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Edited by R. Raymond Issa, Ph.D., J.D., P.E. and Ian Flood, Ph.D.

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Preface

Welcome to Clearwater Beach! It is our pleasure to organize the 2012 International Conference on Computing in Civil Engineering.

This year, we have received many high quality papers. The Workshop has accepted 81 papers from 12 countries in four subject areas, 1) novel engineering, construction and management technologies, 2) design, engineering and analysis, 3) sustainable and resilient infrastructure, and 4) cutting edge development. These papers are the result of a rigorous peer review process starting from the over 140 abstracts we received. Each abstract and each paper were assigned to at least two reviewers. Only the outstanding papers are collected in the proceedings. These papers are also a genuine representation of the very best research being conducted in this community.

We would like to thank the Rinker School of Building Construction and the Conference Department at the University of Florida for their support. The ASCE Technical Council on Computing and Information Technology and its subcommittees have provided guidance and assistance in helping make the conference a success.

Enjoy your stay in Clearwater Beach! Don't miss the beach and the sunshine!

R. Raymond Issa, Ph.D., P.E., J.D., F.ASCE
Ian Flood, Ph.D.
2012 ASCE International Conference on Computing in Civil Engineering

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Building Information Modeling

Evaluation of Existing Sensor Ontologies to Support Capturing of Construction Field Data with Data Acquisition Technologies

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ABSTRACT

Advanced data acquisition (DAQ) technologies, such as smart tags, laser scanners and embedded sensors promise to collect accurate, complete, and timely field data, which is essential to increase the control of construction projects. However, since different DAQ technologies have different capabilities, which are meant to collect different types of data that come with different data processing requirements, construction professionals end up making ad-hoc decisions on which technologies to use in order to capture the required field data. To enable the capture of construction field data in a formal way via mapping required field data to applicable DAQ tools, we identified an initial set of representation requirements for modeling DAQ tools. Based on these requirements, we evaluated and compared relevant sensor ontologies. The limitations and capabilities of relevant sensor ontologies are described in this paper. This evaluation revealed that for the mapping process, there is no single ontology that can be used in its original form to represent DAQ tools. Hence, a representation schema, which builds on various aspects of existing ontologies, has been developed.

INTRODUCTION

Project managers and engineers need to have an accurate and complete understanding of what is happening on a construction site in order to identify and remove information bottlenecks that might result in delay or postponement of construction activities. In order to improve the situation awareness of project managers and engineers, a variety of field data need to be captured. These include: (1) data related to the building components that are being constructed, such as the actual dimensions and material quality of a building component; (2) data related to the construction processes being carried out at construction sites, such as the resource availability and the work progress; and (3) data related to the context under which construction processes are being carried out, such as weather conditions, site layout and so on. In this paper, we refer to the field data that need to be captured as information requirements.

Construction project managers are experiencing incomplete and inaccurate field information due to the current manual data collection methods (Navon 2007). This problem emphasizes the benefit of utilizing DAQ tools to capture field data on

construction sites. Advanced DAQ tools, such as RFID, GPS, laser scanners, and embedded sensors, have the capability to collect and store accurate, complete, and timely field data, which is able to improve the situation awareness of project managers and engineers. However, different DAQ tools have different capabilities and come with different data processing tasks and operational requirements. For example, in order to capture the dimensions of a building component, a variety of DAQ tools, such as laser scanners, total stations and measuring tapes, might be selected. These tools have different capabilities (e.g., accuracy, measuring range, precision), data processing tasks (e.g., a laser scanner requires an additional data processing task to extract the geometric information from the captured point cloud data), and specific operation requirements (e.g., a laser scanner requires the working temperature to be above 32 ºF, whereas a measuring tape can work under 32 ºF). In addition, a laser scanner is able to scan multiple subjects within a certain detection range at once, whereas a measuring tape and a total station can only perform one measurement at a time. Due to the lack of a formal approach to assess the capabilities of different DAQ tools, it is a challenge for project teams to select the applicable DAQ tools to capture the required field data. As a result, there is a need to develop a formal approach to assess the features and capabilities of a variety of DAQ tools, and enable the selection of a set of applicable DAQ tools to capture the required field data (i.e., information requirements).

In order to identify a set of applicable DAQ tools to capture information requirements, one of the essential steps is to create a formal representation schema to describe information about DAQ tools that can support the reasoning necessary to select appropriate tools. There are several research studies actively working on providing descriptive schemas and ontologies for sensors and their properties, such as SensorML, OntoSensor, and so on. These sensor ontologies are different in terms of their objectives, modeled concepts, and expressive powers. The objective of this paper is to evaluate and compare these sensing ontologies, adopt and/or extend them to develop a representation schema to support the mapping between DAQ tools and information requirements.

INITIAL REQUIREMENTS FOR REPRESENTING DAQ TOOLS

In order to identify initial requirements for DAQ tool representation, we reviewed the specifications and operation manuals of different types of DAQ tools (e.g., 3D imaging sensors, automated identification sensors, and localization sensors) to identify common characteristics of DAQ tools to be represented. We also analyzed a large set of information requirements that we identified through interviews and case studies in 3 construction projects to identify unique constraints they impose on the selection of DAQ tools, such as the accuracy of the tools, or the environmental conditions in which the tools are expected to operate. The first requirement of the DAQ tool representation schema is to describe the physical properties (e.g., temperature, humidity, geometry, position) measured by the DAQ tools. Second, since the field data is captured under different site conditions (e.g., temperature, weather, indoor, outdoor), the context under which field data is captured generates constraints on the performance of the DAQ tools that must also be represented. For example, the two information requirements, “check the storage location of steel pipes”

and "check the location of the delivery truck", both require location data. Assuming that the steel pipes are stored in an indoor storage yard, and the truck is operating in an outdoor environment, the applicable DAQ tools to capture these two information requirements could be completely different. For instance, a GPS is able to track the location of the delivery truck in outdoor environments, but it cannot capture the location of the steel pipes due to the satellite signal blockage that occurs in indoor environments. Hence, information about the conditions under which DAQ tools are expected to operate needs to be captured.

Third, specifications and construction methods might generate various constraints on the measurement capabilities (e.g., accuracy, precision, resolution) of DAQ tools. For example, the tolerance manual from PCI (2000) specifies that the tolerance for the length of a precast component is 6mm. Therefore, in order to capture the information requirement "check the length of a precast pier section", the applicable DAQ tools need to have millimeter-level accuracy. Failure to consider these constraints might mislead the selection of appropriate DAQ tools to meet an information requirement. The information related to the measurement capabilities of DAQ tools needs to be represented in the representation schema.

Fourth, a DAQ tool might have specific data processing tasks (e.g., registration and feature extraction processes for a laser scanner) and deployment processes (e.g., installing sensors). In order to help project managers and engineers deploy DAQ tools at construction sites, the representation schema needs to contain the information about the data processing tasks associated with DAQ tools, and how to deploy those DAQ tools on site. Based on these four requirements, we evaluated and compared the relevant sensor ontologies in terms of whether they are able to represent the identified requirements or not. The details of this evaluation are presented in the next section.

EVALUATION OF RELEVANT SENSOR ONTOLOGIES

Ontology is defined as "a specification of a conceptualization" (Gruber 1993), which is composed of three components: (1) the concepts in a specific domain; (2) the properties of and the relationships among these concepts; and (3) the restrictions on the value of the properties and the relationships. Ontology provides a shared vocabulary and a taxonomy to describe the concepts in a domain, and thus can be used to analyze and manage the domain knowledge (Paolucci et al. 2002). A number of descriptive schemas and ontologies have been developed for sensors and their properties. Among these ontologies, we evaluated SensorML, OntoSensor, CSIRO and SSN ontologies within the scope of this paper. The details of these evaluations are provided in the next subsections.

SensorML Ontology. SensorML develops a generic model to describe sensor systems and their measurements (OGC 2007). The basic concept for SensorML is the *Process*, defined with inputs, outputs, parameters, and methods that transform inputs to outputs. *Process* in SensorML is divided into two groups (OGC 2007): (1) *Physical processes*, which refer to the sensor devices, such as detectors, actuators and filters; and (2) *Non-physical processes*, which refer to the data processing tasks

without involvement of physical components, such as feature extraction, data filtering, and so on.

Key concepts represented in SensorML are shown in Table 1. SensorML provides a generic data model to represent the information about sensors, data processing tasks and measurements generated from sensors. In addition, it defines the fundamental data types, such as *Quantity* (i.e., a data type to represent decimal values), *Count* (i.e., a data type that represents an integer value), *Boolean* (i.e., a data type to represent a Boolean value), *Category* (i.e., a data type that represents a value that is a subset of an enumeration), and *Time* (i.e., a data type to represent time). These fundamental data types are useful to specify the inputs and outputs of DAQ tools, so as to support the reasoning with the output data of sensors and required field data in order to find the matches between information requirements and DAQ tools.

Table 1. Major concepts in SensorML and their definitions (OGC 2007)

Concept	Definition of Concept	Example
Physical process	Physical sensor devices	Laser scanner
Non-physical process	Mathematical operations without the involvement of physical components	Feature extraction
Capability properties	Characteristics of the sensor output	Accuracy, resolution etc.
Characteristic properties	Physical properties of sensor devices	Weight and size of the scanners, etc.
Phenomenon/ Observable Property	The observable properties that can be measured by sensors	Geometric information of subjects' surfaces
System	A system which is composed of multiple physical and non-physical processes	Laser scanner + GPS for topographical site survey

OntoSensor Ontology. The objective of OntoSensor is to build a knowledge repository of sensors in order to support sensor selection and discovery (Russomanno et al. 2005). As compared to SensorML, which considers the *Process* as the basic concept, OntoSensor aims to describe the technical specifications of sensors (see Table 2).

Since OntoSensor mainly focuses on describing physical parts rather than processes, it lacks the capability to represent complex data processing chains (i.e., a sequence of data processing tasks). OntoSensor defines the Measurand class to model the outputs of sensors, and represents the capabilities of sensors through the CapabilityDescription and the GenericProperty class. These three classes allow users to query the sensor knowledge repository, and find the sensors that are able to capture the desired data type and have the required capabilities (e.g., day/night operation capability, capability to operate when temperature is under 32 ºF).

Table 2. Major concepts in OntoSensor and their definitions (Russomanno et al. 2005)

Concept	Definition of Concept	Example
Sensor	A sensor device	Total station
Platform	A physical device to which sensors are attached	Tripod
Measurand	The physical properties and quantities that can be measured by a sensor	The coordinates of the measured points
Capability Description	The description of capabilities of sensors and platforms	Day/night operation, measurement time, etc.
Generic Property	The properties of sensors, and has subclasses as: (1) SupportedApplication; and (2) PerformanceProperty.	Supported Application: day/night operation PerformanceProperty: measurement time = 2s

CSIRO Sensor Ontology. The objectives of CSIRO sensor ontology (henceforth called CSIRO) are not only to describe sensors and their capabilities, but also to support the process of searching for sensors and their observations in a sensor network (Compton et al. 2009). CSIRO represents a sensor system using three concepts: *SensorGrounding* (i.e., the physical sensing instruments with their characteristics), *OperationModel* (i.e., the processes of how a sensor performs its measurement), and *PhysicalQuality* (i.e., the physical properties being measured by sensors). Table 3 lists the major concepts used in CSIRO.

Table 3. Major concepts in CSIRO and their definitions (Compton et al. 2009)

Concept	Definition of Concept	Example
Physical Quality	The physical properties that can be measured by sensors	Temperature
Feature	Entities in the real world that are the target of sensing	The room where the temperature sensor is placed
Sensor	A sensor system that contains physical instruments and their associated measurement processes	Temperature sensor with its measurement process
Sensor Grounding	Physical sensing instruments with their characteristics	A temperature sensor with its characteristics such as dimension, weight, operation conditions, etc.
Operation Model	The processes by which a sensor performs its measurement	The process to measure the temperature
Model Result	The properties of the results coming from the *OperationModel* class	Accuracy, latency, resolution, etc.

In terms of supporting the mapping between information requirements and DAQ tools, CSIRO defines the *ModelResult* class to describe the types and properties of the sensor output. However, CSIRO does not provide an extensible way to

represent the measurement capabilities of sensors. It uses different attributes (i.e., withAccuracy, withLatency, withRange, and withResolution) in the *ModelResult* class to specify the measurement capabilities of a sensor. Hence, if an additional measurement capability (e.g., precision or frequency) needs to be added to CSIRO, the structure of the *ModelResult* class needs to be changed internally, which limits the extensibility of the representation schema. As a result, CSIRO has limited ability to satisfy the third requirement of the DAQ tool representation schema to describe the measrement capabilities of DAQ tools.

Semantic Sensor Network (SSN) ontology. Similar to SensorML, SSN considers the term *Sensor* as a process by which an input phenomenon is measured and transformed into an output value (W3C 2010). Therefore, either physical sensor devices or data processing tasks can be represented by the *Sensor* class. The key concepts of SSN are shown in Table 4. SSN gives a formal hierarchical structure and a set of enumerations to describe the property of sensors (W3C 2010). The properties of sensors are represented in three classes: (1) *MeasurementCapability*, which defines the measurement capabilities of sensor devices (e.g., accuracy, resolution); (2) *OperationRange*, which describes the environmental and power conditions within which a sensor is designed to operate; and (3) *SurvivalRange*, which represents the environmental conditions under which a sensor is able to operate without causing any damage to the sensor (e.g., temperature limits of a sensor). SSN is a fairly rich model with various classes to describe the physical devices and processes of sensors. It satisfies the requirements of DAQ tool representation schema in terms of capturing information about sensor capabilities, properties of output data, and the operational conditions.

Table 1. Major concepts and their definitions in SSN (W3C 2010)

Concept	Definition of Concept	Example
Sensor	The physical (e.g., sensor devices) or virtual instruments (e.g., signal transforming).	Accelerometer
Feature of Interest	Entities in the real world that are the target of sensing.	The delivery truck where the accelerometer is attached
Observed Property	The property of the feature of interest that is observed.	Acceleration
Process	A description of how sensors transform the observed property into the output value.	Measure the acceleration
Deployment	The deployment process of sensors.	Attach accelerometer
Platform	A physical object to carry sensors for measurement.	The delivery truck
Operation Range	The environmental and power conditions under which a sensor is designed to operate	Transmission range, power storage capacity, etc.
Measurement Capability	A set of measurement properties of a sensor in a specific condition.	Accuracy, resolution, shift, etc.
Survival Range	The environmental conditions within which a sensor works without causing damage.	Max temperature, minimum temperature, etc.

Comparison of sensor ontologies for supporting the mapping of daq tools to field data. As stated in Section 2, the DAQ tool representation schema is required to describe the information about physical properties measured by sensors, operation conditions within which sensor can normally operate, sensor measurement capabilities, data processing tasks and sensor deployment processes. After critically reviewing the data structures of the four ontologies, we identified that the required information is able to be represented by a combination of these four ontologies and none of these ontologies is able to represent all the required information individually. As seen in Table 5, OntoSensor fails to represent the concepts related to data processing tasks, sensor deployment. CSIRO does not have a relevant class to model sensor deployment. SensorML and OntoSensor are not able to describe the target of sensing. SSN does not define the fundamental data types (e.g., *Quantity, Count, Boolean*) to specify the input and output data of DAQ tools.

Table 5. An assessment for the four ontologies

Concepts	SensorML	OntoSensor	CSIRO	SSN
Sensor	✔ Physical Process	✔ Sensor	✔ Sensor Grounding	✔ Sensor
Entities that are the targets of sensing			✔ Feature	✔ Feature of Interest
Fundamental data types for inputs and outputs	✔ Quantity, Count, Category, Boolean, Time	✔ Classes adopted from SensorML		
Physical properties measured by sensors	✔ Observable Property	✔ Measurand	✔ Physical Quality	✔ Observed Property
Sensor operation condition	✔ Capability	✔ Capability Description	✔ Operation Model	✔ Operation Range
Sensor survival environment	✔ Capability	✔ Capability Description	✔ Operation Model	✔ Survival Range
Sensor measurement capability	✔ Capability	✔ Capability Description	✔ Model Result	✔ Measuring Capability
Deployment	✔ History			✔ Deployment
Data processing tasks	✔ Non-Physical Process		✔ Operation Model	✔ Process

The evaluation results show that there is no single ontology can be used in its original form to support the mapping between information requirements and DAQ tools. With the goals of supporting the mapping process, we developed a representation schema by building on the main concepts represented in the reviewed ontologies, which will be discussed in details in another publication. The developed representation schema covers the following concepts: (1) *Sensor*: the physical sensor devices and their input and output data; (2) *Process*: the data processing tasks (e.g., data transformation); (3) *Capability*: the capabilities of sensors which can be grouped as the measurement capabilities (e.g., frequency, accuracy), operational conditions (e.g., indoor environment) and survival environment (e.g., maximum operation temperature); (4) *Deployment*: the deployment process of sensors (e.g., installing sensors); and (5) *Platform*: a mobile or stationary physical component to which sensors are attached.

CONCLUSION AND FUTURE WORK

In order to improve the value of using DAQ technologies to capture required field data from construction sites, one of the essential steps is to develop a formal representation schema to describe the knowledge related to DAQ tools and support the mapping between information requirements and DAQ tools. In this paper, we have identified an initial set of requirements for such a representation schema, and discovered that the existing sensor ontologies cannot individually satisfy all of those requirements. As a result, we built on the components from the existing sensor ontologies, and developed a representation schema of DAQ tools to support the mapping between information requirements and DAQ tools. This work has built the foundation for further research. We are currently working on developing a set of reasoning mechanisms to reason with the information described in the DAQ tool representation schema and search for a feasible set of DAQ tools to capture a given set of field information requirements over a given time period and space. Also, we developed a library of DAQ tools based on the representation schema that can be used as a testbed for the reasoning mechanisms.

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Framework for Production of Ontology-based Construction Claim Documents

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ABSTRACT

The traditional way of construction project claim document production suffers from tediousness and inefficiency. The manual assembly of claim event history leads to poor reliability of the claim report, due to the claim knowledge gap between experts and clerks. Sharing the team's comprehensive and formal claim knowledge with all of the participants in the claim work flow would result in a more effective way of producing claim documents. This study proposes a system for the ontology-based automatic generation of construction claim documents. The system will extract claim knowledge from all the potential sources into ontology. Software agents supported by the ontology will then complete each part of the claim events history data collection and generation process. The system will also support other functions such as information retrieval, natural language processing and database management. Such a system would efficiently facilitate the claim documents work and become an effective assistant to claim experts.

INTRODUCTION

Currently, in practice, due to the claim knowledge gap between the expert/lawyer and the clerk, the traditional way of claim document production work flow suffers from several drawbacks: inconsistency and unreliability of the claim event history and tedious and inefficient manual work. Those drawbacks tend to undermine the robustness of the claim argument.

To solve this problem, besides the automation of the documents processing work to improve the efficiency, this paper takes the strategy of sharing the comprehensive and formal claim knowledge with all the participants within the claim work flow. To be specific, equipped with the machine-interpretable representation of the claim knowledge, a computer could much better do the clerk's manual claim work. In this paper, following that strategy, an ontology-based construction claim production framework is proposed to address the problem. With a brief literature review on the principle and application of ontology, as well as the research development on

construction claim documents management, the feasibility and applicability of the proposed framework are analyzed. Then, the structure and the methodology of the framework are illustrated, and an example case is given. Finally, the significance of the framework's implementation and the needed future work are also discussed.

LITERATURE REVIEW

Ontology in construction. The most widely accepted definition of ontology is "An ontology is a formal, explicit specification of a shared conceptualization."(Studer et al. 1998). An ontology is represented as a set of concepts within a domain and the description of the relationships between the concepts (Akinci et al. 2008). So, through a well-defined structure, ontologies could serve as a formal representation about a specific body of knowledge in a domain, and this kind of formal representation can be interpreted by computers. That kind of formal representation works as a good methodology for sharing knowledge among certain people and/or computers. Sharing a common understanding of the structure of information among people or software agents is one of the more common goals in developing ontologies(Gruber 1993; Musen 1992).

To be specific, as a kind of knowledge representation, the languages for describing ontologies varies, but with the development of Web technology, the Web-based languages for ontologies which include RDF (Resource Description Framework), and OWL(Ontology Web Language) developed by W3C become more and more popular. Facilitated by the web, those languages fit better in describing ontologies much better in terms of sharing.

In the construction area, research on ontologies application mainly focuses on the following issues: laying a comprehensive foundation for knowledge management, build the industry-wide ontologies for construction, like e-CKMI (e-COGNOS Knowledge Management Infrastructure) (El-Diraby et al. 2005; Lima et al. 2003); Knowledge extraction and representation, for example, domain knowledge extraction from handbooks (Lin et al. 2009), and space representation in construction (Akinci et al. 2002); Interoperability facilitated by ontologies, like the interoperability of process-related application in the Architecture, Engineering and Construction (AEC) sector (Tesfagaber et al. 2003)and the "ontology integrator (Onto-Integrator)" for facilitating ontology interoperability (El-Gohary and El-Diraby 2009). All of these studies indicate that ontologies have a great applicability in the construction realm.

Construction claim documents management. Due to the fact that claims do not arise in every single project, there is no separate role for managing claims in the way that there are estimators, planners and accountants. In practice, the personnel given this role are in most cases decided in an ad-hoc manner (Vidogah and Ndekugri 1998). Therefore, it is very common that the claim clerk always have deficient knowledge and intuition for finding, collecting, and summarizing relevant documents necessary

to make up a solid claim argument. Thus, the knowledge gap mentioned above between clerks and claim experts is the main reason for the inconsistency and unreliability of claim event histories. To solve this problem, a number of expert systems were developed to undertake the legal analysis for certain scenarios: analyzing changes claims (Diekmann and Kim 1992), and analyzing the impact of delays on the contractor's progress (Alkass et al. 1993). However, none of those systems address the issue of accessing and collecting contemporary records of event in order to establish the archive and generate the brief history for events.

To solve the problem of relevant documents omissions in the preparation of claim arguments, some researchers adopted the strategy that it is essential for all project groups to be part of the same document exchange framework, and to enlist or register all their documents within a central web based repository. This framework operates as a document-clearing house for all project groups (Hammad and Alkass 2000). This strategy only puts all the potential candidate documents together to prevent physical loss, but it still does not take the claim body of knowledge into consideration to process that bulk of documents and the sharing of records across the different stakeholders may raise potential risk issue in term of proprietary information considerations.

FRAMEWORK FOR ONTOLOGY-BASED CONSTRUCTION CLAIM DOCUMENTS PRODUCTION

The proposed framework uses the knowledge in the ontology to support the intelligent agents' decision and processing. So, before discussing the structure of the framework, it is necessary to understand how the ontology represents the desired claim body of knowledge. The first step in building this framework is to obtain the desired claim body of knowledge from certain sources, then structure it and make it an ontology. Here we assume that the desired knowledge is already in hand. The methodology of how to build the ontology is the concern discussed here.

To build an ontology, it has to go through the following procedure: defining classes in the ontology; arranging the classes in a taxonomic (subclass-superclass) hierarchy; defining slots and describing allowed values for these slots; filling in the values for slots for instances (Noy and McGuinness 2002). In this case, one important function of this framework is, based on the claim knowledge collected, to identify the facts which could incur a potential claim event. As an illustration, that knowledge about identify claim incurring facts could be structured as shown in Figure 1.

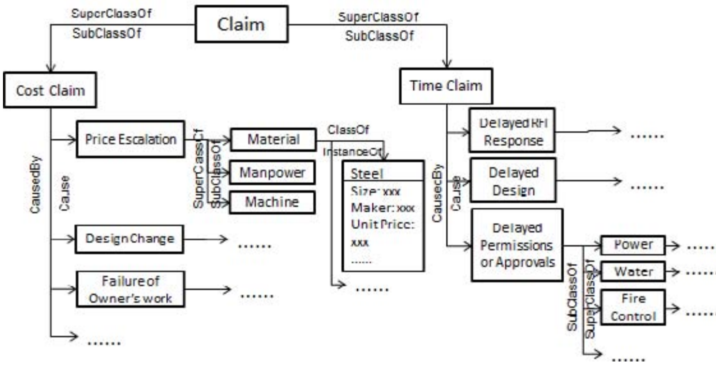

Figure 1. Illustration of the Ontology for Claim Knowledge

Particularly, in Figure 1, the rectangular boxes represent classes, like the classes of "Claim", "Cost Claim", "Time Claim" and so on; the boxes with name and slots inside represent the instances originate from a certain class. For example, the "Steel" instance of the class "Material" is represented by a box with compartments inside. The name of the instance is on the top, and the slots with particular values are listed under the name, like "size: 16mm", "Maker: XX factory", "Unit Price: $XX per Ton" and so on. Thus, a particular construction material used in the project can be presented in a systematic manner for further use; arrow lines represent the relationships between classes or between classes and instances, and the names of the relationships are marked on the either side of an arrow line. For instance, class "Claim" is the super class of classes "Cost Claim" and "Time Claim", and in reverse, "Cost Claim" and "Time Claim" are the sub-classes of "Claim". Further, "Cost Claim" could be caused by the classes of "Price Escalation", "Design Change" and so on, and in reverse, those classes could cause "Cost Claim". That is the initiative or passive representations for a certain relationship in terms of the object we talked about. The same thing happens on the relationship between classes and instances. So, by this methodology, the desired knowledge body could be structured into a proper form as ontology. With the structured body of knowledge, the next step is to describe it by an ontology language. In this framework, Ontology Web Language will be used, i.e. OWL serves to convert the knowledge structure into text material.

By using the above-mentioned methodology to structure the desired body of knowledge into the ontology and describing it in OWL, the foundation for the framework could be laid. Therefore, supported by the ontology representing the desired claim knowledge, the framework would be as shown in Figure 2.

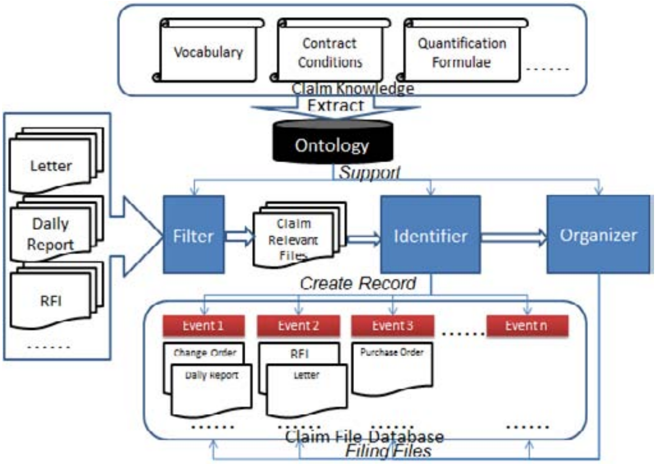

Figure 2. Framework of the Claim Filing Automation

The framework starts from the beginning of the project toward the closing out point. It should cover the period, in which the facts that could incur any claim events are possibly happening, e.g., this is the development stage of all the claim history. Under this framework, the incoming and outgoing documents on a project are read by the "filter", which is one of the intelligent agents in this framework, and then it filters out the irrelevant files and only keeps the claim relevant files. Then those relevant files are passed to the "Identifier" to parse the claim relevant documents into two classes. One class will contain the files which are possibly incurring a claim event while the other contains those which are part of the developing history of an already created event. After that, the "Organizer" will do the corresponding filing work for each class in a certain database: a new claim event will be created based on the first class files and the files will be stored as the first record of that newly created event; meanwhile the files in the second class will be put under the already created event to which the files are associated. All of the decisions made by those agents in this work flow are supported by the knowledge in the ontology. With this work flow running on a daily basis, the project claim record-keeping work is automatically updated while the project is progressing.

EXAMPLE CASE

To illustrate how the proposed system works, an Article "12.2 Not Foreseeable Physical Obstructions or Conditions" of the (FIDIC) 1987 contract document is taken as a piece of claim knowledge to illustrate the example. This article basically requires that if in the construction process, the Contractor encounters a negative physical

obstruction or condition, which is not reasonably foreseen by an experienced contractor, then the part of incurred expense which exceeds the budget should be reimbursed by the Owner. The knowledge of this condition involved in this system could be briefly represented in claim knowledge ontology as shown in Figure 3.

To be specific, take the function of the agent "filter" for example. The essential elements for the definition of this condition include: 1. Unforeseeable by an experienced contractor; 2. Physical; 3. Incurred over-budget expense or over-schedule time happened. If an event satisfies all of these three points, it could be identified as a potential claim event related to this piece of condition. As far as this condition concerned, the three points become the key words to be searched for by the "filter" agent over all the documents' content, in order to identify the relevant claim documents. Any documents containing some or all of those key words or equivalents will be recorded and those documents which are cited or mentioned in them should also be involved.

This case example illustrates that the main challenges in the development of this system consist of but are not limited to the following:

1. The quantitative representation of claim knowledge. It is common that some terms or concepts in contract documents are not exactly specified. For example, like the word "reasonable promptness" regarding the RFI response time limit in the AIA 201 Article 2.2.4. There is not a quantitative definition for this word, which does not fit the proposed system which requires quantitative values. One approach to solving this is to develop the ontology with a proper quantification process to the undefined words or concepts.

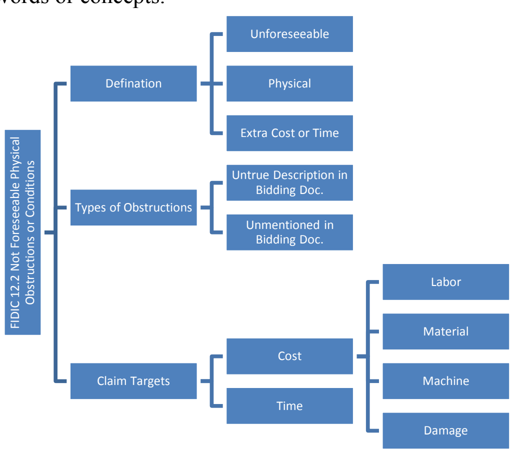

Figure 3. Flowchart for FIDIC Article 12.2
"Not Foreseeable Physical Obstructions or Conditions"

2. Need the cooperation of structured document formatting convention. Since a

significant part of the proposed system depends on the searching over the content of documents, poorly structured contents of documents would definitely undermine the validity and feasibility. Thus, a cooperation of the document formatting is necessarily needed, including standard terminology use, file coding system etc.

SIGNIFICANCE AND FUTURE WORK

By sharing claim knowledge using the claim work flow, this proposed framework would effectively prevent the inconsistency and unreliability of the claim document production that would occur in the traditional way of work. Furthermore, the automation of the document processing activity would efficiently substitute for the manual work, which would save considerable time and improve the accuracy of the product. Thus, the drawbacks of the traditional work flow would be avoided. Moreover, if this framework is implemented correctly, it will become a good assistant to the claim experts/lawyers, as well as to the project managers.

However, in order to implement and validate this proposed framework, there are a lot of other issues that should be worked out. For example, the implementation of some important functions which should be done by some of those agents, like identifying the content of the documents, generating the brief for each claim event history, still need further research. The technologies involved would include, but are not limited to information retrieval, natural language processing, database management, and object-oriented programming.

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i-Con: Geometric Topologies for Semantic Interpretation of Building Components Based on a Semiotic Framework

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ABSTRACT

Construction concept details comprise their geometric features, components or parts, additional or assembled items, and functional characteristics. The concept conditions are the situational conditions or state of affairs, which embrace the concept location, position, site, place, and settings; the status condition, which is the stage of the concept (e.g., completed, installed, delayed), and its relations with other products or context descriptions (e.g,. set by, part of). The details and conditions are minimal ontological definitions of the concept that can be formalized by including logical axioms that use the syntax and vocabulary of a language, and additional semantic relations, which help describe several states of affairs. However, the representations are semantically poor which leads to deficient and accurate interpretations. Furthermore, intentionality is not semantically articulated with the representations. To respond to this need, this research proposes intelligent geometric topologies for construction (i-Con). i-Cons are images that have the virtue of being a symbolic vocabulary. These images have an established use, defined according to qualitative spatial relations, parenthood, and connectedness. Through the use of a mediating technology platform (e.g., a computer graphic application), i-Cons are linked to the virtual representations of the components to assist the user in semantically interpreting them and in efficiently arriving at more accurate conclusions.

INTRODUCTION

Proposed by Peirce (1991), the triadic relationship representation-agent-purpose is a fundamental semiotic categorization for the analysis of knowledge. This investigation builds on this fundamental relation to introduce the intelligent geometric topologies for semantic interpretation of building components (i-Con). This research introduces granularity notion and the cognitive agent's reasoning to begin the analysis and understanding of the fundamentals of the semiotic framework, since there is a strong relation between semantics and the 'grain' size for the interpretation and the reasoning of the representations of building components (Mutis 2007, Mutis and Issa 2008).

The observer's awareness and ability to sensorially experience components of building designs, including symmetries, geometries, patterns, and connections, cannot be explicitly determined. The observer's perception implies a reaction towards the components but not necessarily an understanding of their conditions and context. The challenge is to enhance the observer's experiences as they are directed towards the

building component, by virtue of meaning and sensory-enabling-conditions, to improve reasoning efficiency and reduce ambiguity. Limitations of any perceptual organs and mediation technologies reduce the observers' ability to assert interpretations or to arrive effectively at conclusion.

i-Cons are the result of knowledge engineering analysis aimed to enable efficient reasoning for project stakeholders' interpretations on geometric visualizations (e.g., BIM components, virtual 3D representations). Although, i-con is a vocabulary composed of a set of imagery abstractions for symbol manipulation, they are built on logic to be computable. This logic is based on qualitative spatial reasoning (Cohn and Renz 2008, Freksa 1991) and on formalizations with Region Connection Calculus (Randell, et al. 1992). To secure consistency of the i-Con's images, their primitives (e.g., relationship boundary-interior) are built by borrowing formalisms from mereotopology theory (

GRANULARITY

Granularity refers to what the observer notices. The successful identification of the observed objects is linked to the ability of the observer to detect the smallest units to bind them in a granular structure. The structures afford contrasts that enable the observer to trigger their cognitive capabilities for object recognition. The contrasts (i.e., different light wave and length stimulations) enable the identification of a continuity or boundary of the object. The observer distinguishes entities in the 'real world' through 'grain' sizes, carry out mental operations to map the visualizations to the focuses that serve the observer's purpose, and further translates other granularities and exploits them through cognitive operations as needs dictate (Hobbs 2002).

The granularity notion illustrates the role of the observer's intention to interpret concepts by connecting the observer's intention to represent with the observed representation. The observer perceives distinct and noticeable grains that are to define ideal shapes through senses. These shapes are the observer's "mental schema" that corresponds to the embodied representation of the concept (George Lakoff and Johnson 1999), as a result of cognitive processes. This simple cognitive process allows the observer to infer relevant details and situational conditions. This reasoning refers to the observers' understanding of the representation through the sensory experience, associations to conceptual structures and interpretation of the concept.

The intentionality makes the observer ignore certain details in the configuration of the representation, which are not significant for the interpretation of a concept. For example, Figure 1 illustrates two instances of the views of the storm drainage drawings for a facility. The sketch on the left in Figure 1 represents the view including all the details of the view. The sketch on the right through shapes and lines of different thickness and length represents

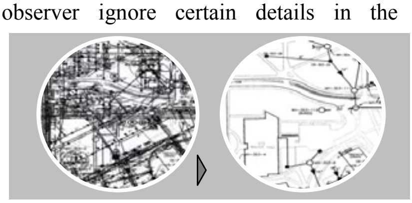

Figure 1. Sketches representing a concept at different granularity level.

the view of a sanitary sewerage concept. This reasoning process and interpretation can be framed with Pierce' ontological categories -firstness, secondness, and thirdness- (Peirce, et al. 2008, Peirce and Hoopes 1991) and the logical status (actual, epistemic and intentional) that arise from granularity during the reasoning process (Sowa 1999). Firstness defines the first pure sensory experience (e.g., the contrast of black and white colors that define the grains and shapes in the drawing). Secondness, it is set by the relationship between the observed, or perceived images, signs, shapes, sounds, among others, and the observer. It involves two or more physical entities or abstract forms (e.g., a proposition that black triangle and an arrow to characterize valves in water pipe systems). Other types of reasoning such as deductions and inductions involve additional steps other than direct analogy to arrive at a conclusion from the sensory experience. Thirdness corresponds to the mediation or the instance of connecting two or more actual entities or abstract forms with conventions. For example, it makes the observer treat the lines in sketch of Figure 1 on the right as sanitary sewerage, by discarding other irrelevant lines, geometries, and details. The sketch has the required granularity for the observer's reasons. If there exist a formal rule that defines the relationship(s) or the signification process through conventions, a process of mediation exists by the nature of this convention.

REASONING AND AFFORDANCES

Gibson (1977) stated that the observers' perceptions are affordances, not qualities of the object. Affordances are invariant combinations of variables of what the cognitive agents notice. Therefore, if an observer experiences the sensory appearance that affords the object and discerns this experience through a reasoning process, plausible interpretations are made. The observer uses cognitive ideal models in memory to associate them to the sensory experiences. These ideal models are cognitive structures or mental symbols that represent particular concepts for the agent. The reasoning process ranges from analogy, decomposition, systemic, comparative reasoning to logical methods that are more constrained and stylized methods (Sowa 2005a), including deduction, induction, and even abduction.

The agent's selection or combination of the reasoning methods depends on the individual agent's needs and ability. Briefly, analogy consists of applying to the present object-representation and conditions the agent's seemingly similar previous experiences (Minsky 1986). Decomposition refers to analyzing the object into its component parts by identifying how they fit together. Systemic method refers to making interpretation about the whole and the relationship of its parts. Deduction refers to applying a general principle to infer some fact. Induction assumes a general principle to subsume many facts, adduction guesses a new hypothesis that explains some fact (Sowa 2005b)

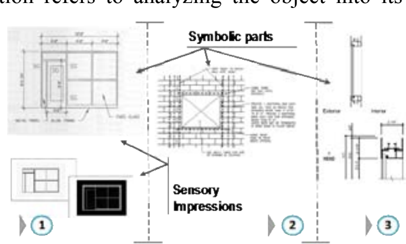

Figure 2. Reasoning on representations.

Figure 2 shows an example of three phases that the agent would experience during the reasoning process to arrive at a conclusion (i.e., make an interpretation of the observed process). In the example, the observer's reason is to focus on an opening to verify their seamless face joints and verify the conditions of installation within a masonry wall (i.e., situational or context conditions). For instance, the observer should verify that at least three wall anchors per jamb will be the installed adjacent to hinge location on the hinge jamb and at corresponding heights on the strike jamb. The observer's intention can be represented in logical proposition that relates the observer to the opening object and to the reason for its installation. The intentionality makes the observer view the object for one specific purpose. For instance, the geometry of step one is an opening to be installed on masonry wall- as it is shown in step 2 in Figure 2.

Intentionality is required to relate the material quality of the object and the observer with the purpose of avoiding contradictory interpretations. For instance, when object is represented by the same geometry with different logical status (e.g., ontology axioms). The representations themselves, a material quality status, do not have intrinsic meaning. The semantics of the representations are motivated by the agent's purpose that makes the agent select relevant details and situational conditions in order to perform the interpretations. This purpose or agent's 'relevance' makes reference to the representation's granularity level or to its affordances, including the details and situational conditions. Conspicuously, granularity states that the sufficiency of details and situational conditions contributes to performing accurate interpretations. In Figure 2 for instance, the intention is to verify that the frame assembly and its parts will accurately be in position into the wall, plumbed, aligned, and braced securely until permanent anchors are set. The observers' intention is to identify its geometry of the opening by contrasting lines (i.e., the dark, inked lines on paper are descriptions of the opening), associate the mental images or conceptual structures to contextual conditions (Step 2), and finally identify the opening parts that secure the door frame's position into the wall (Step 3). Therefore, the ability to associate representations from Step 1 (the opening), Step 2 (the contextual conditions), Step 3 (the opening details - anchors) is linked to the effectiveness of the individual agent's cognition, and the affordances of the representations as they are reconciled the agents' purpose. The agent uses particular reasoning methods or combinations of them as they are needed to arrive to a conclusion.

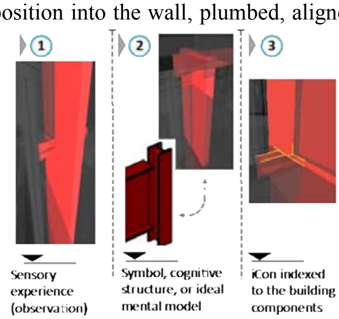

Figure 3. Reasoning on virtual building component representation.

The assumption is that the agents have the ability to connect partial information from multiple documents (e.g., individual representations – opening, masonry wall, and details), find implicit and explicit relationships in the representation through reasoning methods to arrive at conclusions (e.g., provide at least three wall anchors per jamb for the contextual conditions of the observed

opening), and further exploit the relationships in the representation (i.e., semantics) to generate alternative conclusions (e.g., acceptable anchors include masonry wire and masonry T-shaped anchors).

REASONING ON VIRTUAL BUILDING COMPONENTS

The agent's ability is challenged by the quality of affordances and the cognitive agent's faculty to efficiently associate representations. This faculty is acquired through informed symbol manipulation and learning experiences that enable the agent to exercise perceptual knowledge in regard to resolution, details, certainty, context definition, and neighborhood of objects (Bertel, et al. 2006, Freksa 1991). Internal symbol manipulations capabilities and learned experiences are cognitive abilities whose treatment belongs to psychology and cognitive science research. Research, however, can be performed on computing the quality of affordances through the use of mediating technologies in order to streamline the objects' perception, representation, and identification.

For example, the cognitive agent's reasoning on the virtual components (e.g., intersection of steel and beam column of a building structure) can be streamlined through the addition of semantics to the coarse or incomplete features of the components' representations. The significance on assisting the agent's reasoning lies on inferring relationships that are critical, where ambiguity leads to the disruptions in communication meanings in the representation (e.g., functionality of the building components). The value of rendering fine granularities for optimal visualization is not essential to communicate intentionality. Figure 3 shows an example of the cognitive agent's reasoning on the conceptual neighborhood of the virtual building components. The reasoning in the example consists of sensorially experience of the incomplete object, persistently associating the object to the ideal mental schema, and usefully finding the semantics of the objects' situational conditions (e.g., details functionality of the connection).

i-**Cons.** The intelligent geometric topologies for semantic interpretation of building components (i-Con) are images that have the virtue of being a symbolic vocabulary. These images have an established use defined according to qualitative spatial relations, parenthood, and connectedness. The symbolic vocabulary is an artificial language built on three levels of representation: (1) physical similarity, as it is the first referent to one of the entities or to multiple, aggregate, or set of entities (e.g., one or multiple building components); (2) ontological, as in the relationships between entities, including their relationship with the physical space, and (3) semantics, as it defines the actual and possible associations and configurations, including the propositions that define the interpretation of the entities' interaction to situations.

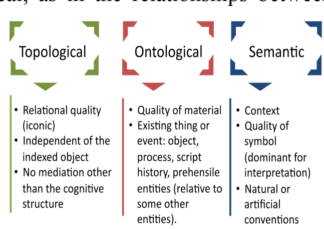

Figure 4. i-Con's representation levels.

i-Cons hold *independence*, which make the symbolic vocabulary independent from a specific situation as it is with syntax in natural language. Figure 4 shows a

summary of the i-Cons' three levels of representation. These levels are aimed to categorize the imagery and to support the i-Con vocabulary associations to an established use. The vocabulary has symbolic meanings. It uses conventions that have the force of operating rules. I-Con's imagery and *symbolic* meaning are complementary to support the cognitive agent's reasoning. Although symbolic meaning is by nature arbitrary, the core of i-Con imagery resembles shapes that hold qualitative spatial relations. For example, an image of i-Con is linked to an established concept of neighborhood, which examines the primitive relations between regions of one object to its physical space or to other objects where their boundaries intersect. An example of the association of i-Con image to the physical object is shown in Step 2 of Figure 3, which is aimed to illustrate the spatial relations of the connectedness of two virtual physical components. The shown topology, an image of the i-Con vocabulary, has a resemblance to the spatial relation of connectedness.

The i-Con symbolic vocabulary has extensions to basic operations that indicate actions (e.g, process, read) and to meanings to support intentionality (e.g., definition of interactions of two objects). These features are aimed at directing the attention to two cognitive agents that are the basic symbol manipulators, the interpreter and source (i.e., a discourse producer and discourse consumer in the natural language domain) on the state of affairs of i-Con's associated physical objects. Figure 5 shows examples of i-Con imagery. In Figure 5(a), each one of the images is part of the i-Con vocabulary framed in the three layers of representation (as shown in Figure 4). The shown topologies have basic emerging semantics and geometric resemblance. For instance as shown in Figure 5(a), the image that resembles a line represents the *existence* of a continuous, discrete object. The ontological representation is the proposition of the existence of an independent, physical object. In propositional logic, this existence is represented through the existential quantifier (∃), which reads as 'there exist an object *y* such that'.

i-Cons' imagery can be placed in any position in a three dimensional Euclidean space, since the i-Cons purpose is to represent the vocabulary through any computer graphics applications that supports three dimensional modeling. Therefore, i-Con imagery represented through computer applications affords 3D image generation and object simulation, including properties such as rotation, intersection, reflection, and refraction. Figure 5(a) shows three positions of the existence, containment, and connectedness i-Con vocabulary in three-dimensional Euclidian spaces. Therefore, i-Con vocabulary has the ability of being identified in a three dimensional space mediated by any computer application.

MEDIATION

Mediation brings an explanatory meaning to the intended physical referent of the i-Con imagery. There is mediation process that gives meaning to the sensory impressions, and subsequently to the image or vocabulary. i-Con imagery is aimed at resembling cognitive valid geometric configurations that are primitive (i.e., have basic semantics that emerge without further intervention of agents, associations to sign systems, or mathematical models). However, i-Con imagery requires a minimum mediation to communicate meanings of the intended physical referent. i-Con imagery are mediated through indexation, by affecting and tying the i-Con vocabulary to an

existing entity (e.g., tying an i-Con image to any structural piece of a building information model). This indexation stipulates that the i-Con image exists by acknowledging the association of the entity to the physical world. Figure 5(b) shows the streamlined reasoning process of the connectedness concept of two building components. The shown i-Con image of connectedness semantics is the two orthogonal intersecting objects. The association to the virtual component and to the physical entity simplifies the cognitive effort to distinguish features of the orthogonal beam-column-beam steel connection.

Figure 5 (a) i-Con imagery (b) i-Con's reasoning on representations

The i-Con resemblance to the object should facilitate an emerging perception of the intrinsic semantics of the i-Con's image in order to reduce the cognitive agent's effort of further mediation. The more use of mediation apparatus or system, the more cognitive efforts, including multiple or combinations of reasoning mechanisms are required to arrive at conclusions. As shown in Figure 5(a), i-Con emerging meanings of containment is primitive and requires minimum effort to respond to the visual contrasts, including the use of further mediation actions through other mediating systems (e.g., use of natural language to define containment). Through the use of mediating technology, i-Con vocabulary is aimed at representing propositions of intentionality by indexing data to the vocabulary.

CONCLUSIONS

This research proposes intelligent geometric topologies for semantic interpretation of building components (i-Con) based on a semiotic framework to streamline the communication of designs, by enabling the agent to observe aspects, details, and geometries through the i-Con vocabulary. The i-Con vocabulary has the ability of being identified in a three dimensional space mediated by any computer application. With the use of i-Con imagery, a reduction of the cognitive agent's effort to efficiently arrive at less ambiguous design interpretation is expected. In addition, i-Con use is aimed to represent propositions of intentionality by indexing data. This feature will further bring an explanatory meaning to the intended physical referent of the building components, since static visual representations (e.g. components of BIM, and 3D images) are limited to the individual's point of view of the design. The successful implementation of i-Con vocabulary has the potential to transform methods of communicating semantics within all range of practices in civil and construction engineering and management projects.

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Exploration and Comparison of Approaches for Integrating Heterogeneous Information Sources to Support Performance Analysis of HVAC Systems

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ABSTRACT

Heating, ventilation and air-conditioning (HVAC) systems account for about 40% of energy used in buildings in the United States in 2008. Analysis of the energy efficiency of HVAC systems requires building-related information, such as building design, HVAC configurations, indoor environment measurements and load requirements. However, since building projects involve multiple disciplines, the needed information is stored in heterogeneous sources, such as design drawings, equipment manuals and sensor networks. It is hence difficult for system operators to collect and integrate the information required for analyzing the performance of HVAC systems. This paper explores the approaches to overcome this challenge of integrating heterogeneous information sources to support the information required for analyzing the performance of HVAC systems. The discussions include a synthesis of the characteristics of integration approaches from various domains, and an analysis of the relationships between the characteristics and the information sources required for analyzing performance of HVAC systems.

INTRODUCTION

Residential and commercial buildings in the United States consumed 41% of the total energy and 73% of electricity in 2008. Heating, ventilation and air-conditioning (HVAC) systems account for more than 40% of the total energy consumption in buildings (DoE 2008; EIA 2008). Improving the energy performance of HVAC systems plays a critical role in saving energy resources and protecting environment (Ellis and Mathews 2002; Castro 2004). Previous research studied performance analysis approaches for HVAC systems. Examples of these approaches include building energy simulation engines (e.g., Park et al. 1985; Crawley et al. 2001), computerized fault detection and diagnosis (FDD) approaches (e.g., Katipamula and Brambley 2005), and supervisory control approaches (e.g., Wang and Ma 2008). These studies show that about 25% - 40% of energy consumed by the HVAC systems can be saved by mitigating component faults and improving control strategies.

However, deploying these approaches in real-world facilities has been inhibited by the difficulties in acquiring information that is required to analyze the energy efficiency of HVAC systems (Luskay et al. 2003; Jagpal 2006).

Analyzing performance of the HVAC systems requires building-related information, such as building layout and materials, HVAC design and configurations, indoor environment measurements and load requirements (Liu et al. 2011). However, since building projects involve multiple disciplines, information is generated using various applications and stored in heterogeneous sources, such as design drawings, equipment manuals, spreadsheets and relational databases. It is hence difficult for system operators to collect and integrate the information required for analyzing the performance of HVAC systems.

In order to utilize the energy saving potentials of performance analysis approaches for HVAC systems, an approach that is able to integrate the heterogeneous sources of building-related information is needed. Previous studies have developed several approaches to integrate heterogeneous information sources. These approaches use different ways to automate the integration process and have various strengths and weaknesses. The objective of this study is to explore and compare the existing approaches for integrating heterogeneous information sources, identify the characteristics of these approaches, and analyze the features of the integration approach for supporting the performance analysis of HVAC systems.

BACKGROUND RESEARCH

With the advancement of information technology, an ever-increasing number of information systems are being used for various business purposes. Information is stored in multiple sources that have heterogeneous data structure, symbolic representation and semantic schemas. Figure 1 shows the common processes of answering an information query using multiple sources (Sheth and Larson 1990).

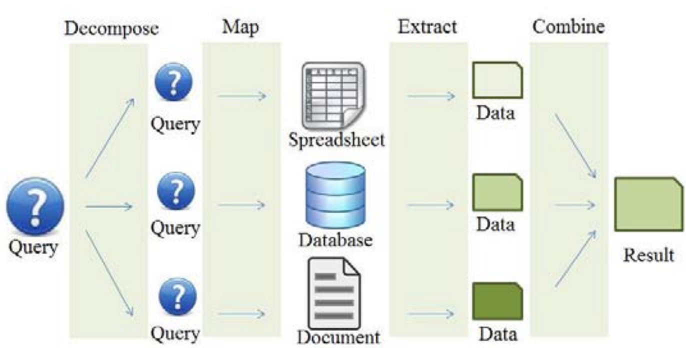

Figure 1. Common processes of answering information queries using heterogeneous sources

Figure 1 shows the four steps in the process of manually retrieving the queried

information from heterogeneous sources. First, users need to decompose the query according to the available data in each source. Second, the decomposed queries need to be mapped to the corresponding data items in the sources. Then, users need to access each source and extract the data values. Finally, the separated data values need to be combined to answer the information query. As more information systems are being used, it becomes more challenging for users to interpret, access, and integrate information from the heterogeneous sources.

Approaches for integrating heterogeneous information sources have been studied in several domains including database management (Sheth and Larson 1990; Chen et al. 2009), information query and retrieval (Chang and García-Molina 1999; Liu et al. 2002), and internet information discovery (Abiteboul 1997; Buneman 1997). Their common objective is to provide a uniform interface to a multitude of information sources so that users are freed from having to manually integrate the sources (Friedman et al. 1999; Bergamaschi et al. 2001). Since these studies have differing objectives and use different types of information sources, they proposed alternative integration approaches to automate the four steps in the common integration process. For example, Figure 2 shows the architecture of two different approaches, which use different ways to automate the information combination step.

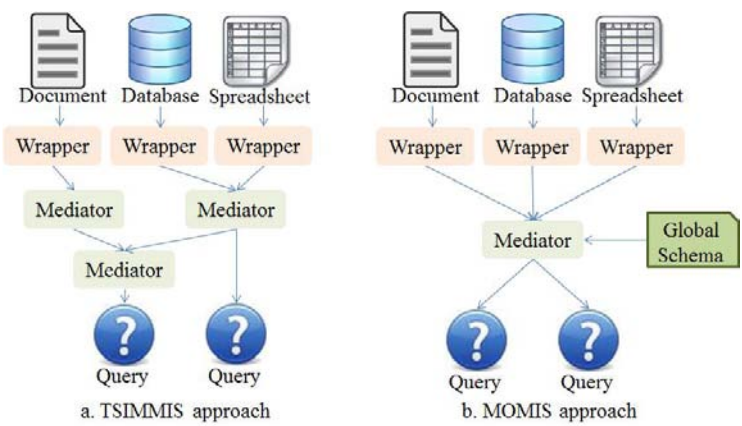

Figure 2. Architecture of TSIMMIS approach (a) and MOMIS approach (b)

The TSIMMIS (The Stanford-IBM Manager for Multiple Information Sources) approach was developed by Li et al. (1998) and utilizes the mediators to extract and combine information from various sources into views, which can be queried by users without knowledge of the sources. This approach starts from identifying the information required by the queries and focuses on developing a formal way to represent the information items in different sources. The other approach, MOMIS (Mediator envirOnment for Multiple Information Sources), was proposed by Bergamaschi and Castano (2001) to integrate the relational databases and file systems. This approach utilizes a global schema to represent the structure of integrated

information. The global schema is developed based on the available data items from the various information sources.

The main advantage of the TSIMMIS approach is its flexibility in developing new mediators to handle new sources or queries. New mediators can be added without affecting the existing ones. However, since the mediators process information separately, ensuring the consistency amongst different information items is difficult, especially when there are a large number of diverse information items. The MOMIS approach has the advantage of managing the consistency of information items since there is a single global schema and mediator. However, adapting new sources or new queries in the MOMIS approach requires modification on the global schema.

The comparison of these two approaches shows that to determine the most appropriate integration approach, features of the integration should be analyzed with the characteristics of different approaches. The goal of this paper is to categorize the characteristics of different integration approaches and compare them with the features of the integration for performance analysis of the HVAC systems.

RESEARCH APPROACHES

In order to analyze the characteristics of the different integration approaches and determine the integration approach for this study, this section synthesizes the characteristics, identifies the features of integration for analyzing performance of the HVAC systems, and discusses the strengths and weaknesses of the different characteristics in relation to the features.

Categorizing characteristics of different integration approaches. According to the different ways that the approaches use to automate the four steps in the integration process, this paper categorized the following four characteristics:

Query-centric and Source-centric approach. Previous studies used two ways to automate the query decomposition and mapping steps. One is the *Query-centric* approach, which starts from identifying the queries required by users and classifying information requirements. Then, sources are identified to support the information requirements. One example of this approach is the INDUS (INtelligent Data Understanding System) approach, which develops a global query schema based on the required queries and then maps the schema to the heterogeneous sources (Senthilvadivu and Duraiswamy 2010). The other way, *source-centric* approach, starts from identifying the information sources that need to be integrated and does not have predefined queries. For example, the Information Manifold approach describes the information items in different sources and provide users a query schema that combines all available information (Kirk et al. 1995).

Mediator architecture and global schema architecture. As discussed in the previous section, the TSIMMIS approach uses a *mediator* architecture to automate the process of information combination, while the MOMIS approach uses the *global schema* architecture. The *Mediator* architecture utilizes multiple mediators to combine information items into views that answer each query. Each mediator generates one view and users need to search for the one to query for. In contrast, the

Global schema architecture combines all information items from heterogeneous sources together and provides one query interface to the users. Users need to follow the global schema and the query mechanism to represent their queries.

Virtual view and Materialized view. The process of extracting and combining data from heterogeneous information sources uses two types of views. The *virtual view* approach extracts and combines data from sources on the fly when it receives query requests. It does not store any intermediate data from the sources to the query results. Both the INDUS and TSIMMIS are examples of this approach. Calvanese et al. (2000) developed an integration approach that maintains the *materialized views* using a data model. This approach extracts and combines information from various sources and then stores the integrated information in its own data model or models. It answers the queries directly using the integrated information, which is updated when the sources change.

New schema and Mapped schema. A schema represents the structure of the information items and is the foundation to develop information combination and query decomposition mechanisms (Lenzerini 2002; Goasdoué and Rousset 2004). The schema can be developed from scratch in the integration approach. For example, the Garlic approach developed by Carey et al. (1995) creates a *new schema* to represent all information items available from the sources. The TSIMMIS approach develops multiple *new schemas* for the mediators to answer an individual query. A different way of developing schemas is to map the original schemas of the heterogeneous sources with each other. For example, The Fusionplex approach provides an method to map information from various sources, such as relational database, object-oriented database and webpages, together to form the integrated model (Motro and Anokhin 2006). Mitra et al. (2000) proposed the ONION (Ontology compositION) approach to map various sources using ontologies.

These four characteristics of the integration approaches have different strengths and weaknesses that should be analyzed with the features of the integration process to determine the most appropriate combination. The next section will discuss the features for information integration in this study and compare them with the strengths and weaknesses of the four characteristics.

Analyzing characteristics of the integration approaches and features for information integration to support performance analysis of HVAC systems. The authors previously discussed the features for a framework that integrates performance analysis approaches for the HVAC systems. Here we present the four features required for the integration framework along with discussions on their relationships to the four identified characteristics of integration approaches:

1. Require high query coverage and extensibility. The primary objective of the integration is to support information required by different approaches. Therefore, the coverage and extensibility of the supported queries are the most important criteria for the integration approach. A *query-centric* approach ensures that all required queries have been analyzed when developing the integration approach. Therefore, it fits the requirement of high query coverage, and would be preferred over a

source-centric approach. Similarly, the *mediator* architecture enables plugging in new mediators for extending queries without impacting the other mediators, while in the *global schema* architecture the schema needs to be modified. Hence, the extensibility requirement calls for the *mediator* architecture.

2. Heterogeneous original schemas. The expected information sources include object-oriented data models, time-series data, relational database, and text files. Their original schemas are very different from each other and it is very challenging to map these schemas with each other. Therefore, this feature favors the *new schema* approach over the *mapped schema* approach.

3. Complex original schemas. The original schemas of the information sources are very complex. For example, the schema for building information contains more than 600 classes (buildingSMART 2010). This feature also calls for developing *new schema* instead of *mapping* the complex schemas. However, because the individual mediators work independently, it is very challenging to use the *mediator* architecture to consistently process information items from the complex original schema. Therefore, the *global schema* architecture better fits this feature.

4. Integrate both dynamic and static information. The dynamic sensor measurements and control signals may change every second, while the building layout and HVAC configuration are updated infrequently. Therefore, a hybrid approach, which includes both *virtual views* and *materialized views*, fits this feature.

To summarize the comparison of the features of the integration in this study and the characteristics of the integration approaches, Table 1 shows the favorable characteristics of each feature where applicable.

Table 1. Comparison of the characteristics of integration approaches and features of the integration in this study

Feature	Query or source centric	Mediator or global schema	Materialized or virtual view	New or mapped schema
1	Query centric	Mediator		
2				New schema
3		Global schema		New schema
4			Hybrid	

Based on the four features of this study, query-centric integration with new schema and hybrid virtual and materialized view approach is the most appropriate combination. However, this comparison does not determine whether mediator or global schema architecture should be used. In order to analyze the trade-off of these two different ways and determine the most appropriate combination of these characteristics, this study will implement a testbed to quantitatively evaluate the performance of the integration approach in both ways.

CONCLUSION

This paper has analyzed the different approaches to integrate heterogeneous information sources for supporting performance analysis of HVAC systems. By comparing the previous approaches for integrating heterogeneous information sources,

this study identified four characteristics of how different integration approaches automate the query decomposition, query mapping, information extraction and information combination processes. The features of the integration process required by this study were analyzed with these characteristics to determine the most appropriate combination. The initial results showed that the query-centric, new schema and hybrid view based approaches fit the features. However, whether the mediator architecture or the global schema architecture should be used was not clear from the results. Next steps of this study include the development of a testbed to quantitatively evaluate the alternatives and determine the most appropriate combination of the characteristics.

ACKNOWLEDGMENT

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Hierarchical Sampling for Efficient and Comprehensive Community Connectivity Analysis: A Michigan Case

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ABSTRACT

Analyzing community connectivity is necessary for identifying construction sites that have various services (e.g., restaurants, supermarkets) within walking distances, so that occupants of the new facilities would not need to use vehicles for accessing those services and thus reduce the carbon footprints of facility operations. Currently, civil engineers need to manually conduct community connectivity analyses on multiple candidate construction sites and recommend the one with the largest number of nearby services. Manual community connectivity analyses are tedious, especially when the engineers need to consider hundreds of locations across an urban area. While experienced engineers may quickly identify some locations with higher community connectivity, such a process is subjective and may compromise the completeness of the solution. To enhance the efficiency of community connectivity analysis while keeping the completeness level of the analysis, this paper explores a hierarchical sampling approach for quickly identifying all locations with high community connectivity across a medium-size city in Michigan. This approach first sparsely sample the urban area (e.g., two miles apart between evaluated locations), and then increase the sampling densities at locations with higher community connectivity based on sparse sampling results. Sensitivity analysis of sampling step sizes are presented and analyzed.

INTRODUCTION

Community connectivity analysis is a critical component of sustainability analysis of candidate sites for envisioned residential and building construction projects (USGBC, 2009). As defined by USGBC, “community connectivity” emphasizes that new buildings are preferably to be constructed in developed site with multiple types of services (e.g., banks, schools, and restaurants) ready in walking distances (0.5 mile), so that occupants of new buildings can have better access to various existing services (USGBC, 2009). Generally, construction sites having more types of different service within 0.5 miles are considered as having better community connectivity. Major types of services having significant impacts on people’s daily life include banks, schools, churches, restaurants, and shopping centers. Easy accessing of these services reduces the uses of vehicles for accessing daily needed services, improves the reuses of established services, and eliminates the needs of setting up

new services. These effects reduce the direct and indirect carbon footprints of new constructions, and improve the sustainability of urban systems (York County, 2009).

In most new constructions, connectivity analyses occur during the feasibility analysis. Engineers search across an area to identify locations with high levels of community connectivity. They manually count the number of types of nearby services for all candidate locations. For large urban areas, the number of candidate locations can be large, and manually analyzing them can take significant amounts of time. For instance, the urban area shown in Figure 1 is of 28.97 square miles, and a comprehensive community connectivity analysis of this city needs engineers to evaluate 0.5 mile grids on this map. Specifically, our experiment shows that an engineer needs to manually evaluate 89 grid locations across this city; assuming that each location requires about 5 minutes, the total amount of time needed for this analysis is around 445 minutes assuming engineers would like to ensure the comprehensiveness of such analysis through an exhaustive approach.

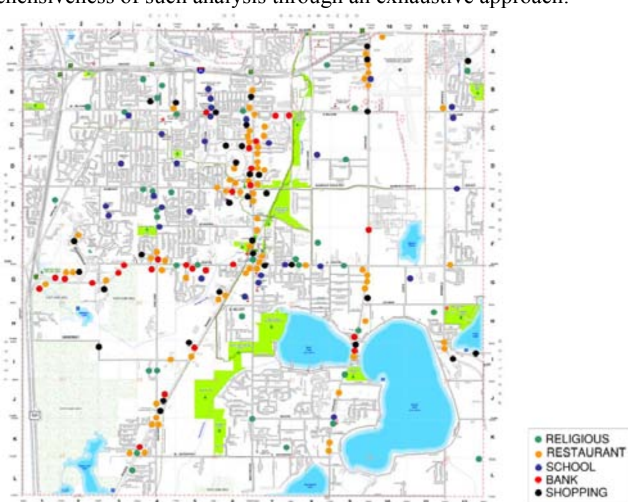

Figure 1. Services across Portage City, Michigan

Analyzing the distribution of services across the city shown in Figure 1, we found that the non-uniform distribution of these services provides some potential of reducing the number of locations that need to be evaluated while keeping a certain level of comprehensiveness of the analysis. We chose to show five types of services in this map (banks, schools, churches, restaurants, and shopping centers) according to our investigations about which types of services among all those listed by USGBC are considered as more significant in LEED (USGBC, 2009). In this city, most services are along two major avenues which are perpendicular to each other and locating in the middle of this city. Such non-uniform densities of service distributions result in non-uniform distributions of community connectivity performances shown in Figure 2. This figure shows 89 locations mentioned above, and labels each location with a

number indicating the number of types of services within 0.5 mile from it. Again, in this map, we considered five types of services identified by us as relatively more significant for LEED evaluations, so the numbers of types of services has a maximum value of 5, and a minimum value of 0. Based on that, we define locations having more than three types of services within 0.5 mile as "*well-connected.*" Figure 2 shows that well-connected locations are mostly along two major avenues of this city, and efforts on evaluating the Northeast and Southwest regions are less effective.

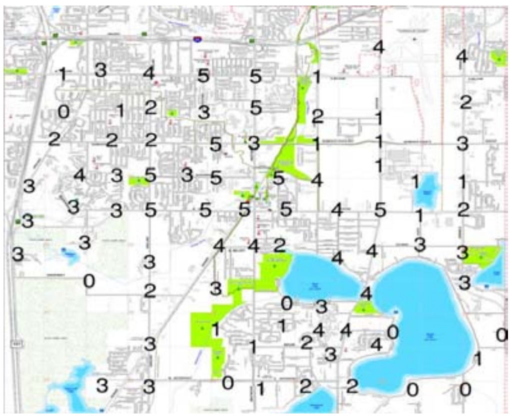

Figure 2. All evaluated locations across Portage City (89 locations in total), and the number of types of services within 0.5 miles from each location

The example discussed above show that 0.5 grid sampling is tedious, even though it provides a comprehensive community connectivity analysis. On the other hand, it is intuitive for engineers to focus on regions with higher densities of services for reducing non-effective evaluation efforts. However, it is difficult to quantify the risks of missing well-connected locations based on the intuitions of engineers, because such intuitions vary person by person, or even time by time. This fact motivates explorations into a hierarchical sampling approach for more efficient and effective community connectivity analysis: first sparsely sample the studied area for identifying regions possibly having more well-connected locations; then increase sampling densities around locations identified as well-connected locations in the first step. This approach can ignore locations having less well-connected locations and thus better utilize the time for community connectivity analysis. A critical issue of better utilizing this approach in practice is to understand how sparse the initial samples should be, and how to increase the sampling densities for minimizing the possibilities of missing well-connected locations while saving time. The following sections discuss relevant studies, research methodology, and evaluation results.

RELATED STUDIES

A number of previous studies explored several aspects on developing walkable

communities, which is related to the community connectivity analysis. Some organizations and researchers developed design guidelines for walkable communities (Bicycle Federation of America, 1998; McNally, 2010). These studies tried to guide urban planners to avoid using low-density development and making the neighborhood not accessible by pedestrians. It addressed the benefits of having walkable community in three aspects: community, environment, and economic. The results of these studies show that well-designed walkable communities promote healthy lifestyle for residents when they are encouraged to walk, and also reduce the needs for using vehicles, gas expenses, and CO^2 emission.

Some researchers focus on analyzing the interactions among the human behaviors and the built environments for improving the community connectivity while reducing various risks, such as traffic congestions and accidents. Shay et al. focused on walking travel, pedestrian safety, and found that services need to be located close to each other and to residential areas. Half mile between trip origins and destinations turn out to be a threshold discouraging walking (Shay, Spoon, Khattak, & Center, 2003). A similar study conducted in Singapore reveal the relationships among traffic congestions, pedestrian safety, and walking decisions of people (Wibowo & Olszewski, 2005).

Urban planning researchers explored the implications of community connectivity from the perspective of land use planning. While exploring multimodal approaches to land use planning, Shinbein found that walking are not an encouraged option for traveling due to disconnections between the origins and the destinations; to address such issues, he clustered the proposed new developments and the mixed-use land for facilitating walkable and biking environments (Shinbein, 1997).

Above-mentioned studies highlight the importance of community connectivity analysis to the design of communities and urban development, while limited work has been done on understanding how to efficiently and effectively sample well-connected locations. Only a few studies are on evaluating network or graph based approaches for urban planning applications (Urban & Keitt, 2001). So far, the authors have not found any previous studies focusing on quantifying the performance of different sampling approaches in terms of comprehensiveness, efficiency, and effectiveness of community connectivity analysis. This study will use real-world data of a city in Michigan to evaluate a hierarchical sampling approach as one step forward.

RESEARCH APPROACH

We design a hierarchical sampling approach to reducing ineffective evaluations, and use data collected for a city in Michigan to evaluate the performance of this approach in terms of three metrics. The three metrics used are: 1) time, which is measured by the total number of locations evaluated; 2) recall, which is the percentage of all well-connected locations that are indentified (equation 1); 3) precision, which is the percentage of evaluated locations that turn out to be well-connected (equation 2). High recall rates indicate the comprehensiveness of a community connectivity analysis, while high precision rates indicate that fewer efforts are invested in evaluating less-connected locations.

$$Recall = \frac{Number\ of\ well\text{-}connected\ locations\ identified\ by\ the\ sampling\ method}{Total\ number\ of\ well\text{-}connected\ locations} \quad (1)$$

$$Precision = \frac{Number\ of\ well\text{-}connected\ locations\ identified\ by\ the\ sampling\ method}{Total\ number\ of\ locations\ evaluated} \quad (2)$$

Table 1 lists two location sampling approaches evaluated in this research: grid and hierarchical sampling. For each approach, we vary the parameters of it and obtain several sampling settings for testing the sensitivity of the sampling performance to the sampling parameter values. For grid sampling, we tested 0.5 mile, 1 mile, and 2 miles grids and observe how the values of three metrics vary with these grid sizes.

Table 1. Evaluated location sampling approaches and parameter settings

Approach Name	**Sampling Setting**	**Definition**
Grid Sampling	0.5 mile grid size	Evaluate grid points that are 0.5 mile apart
	1 mile grid size	Evaluate grid points that are 1 mile apart
	2 mile grid size	Evaluate grid points that are 2 miles apart
Hierarchical Sampling	Hierarchical 1 (H1)	*Step 1*: 2 mile grid evaluation → *Step 2*: Iterative search within 0.5 mile, starting from well connected locations identified among 2 mile grids
	Hierarchical 2 (H2)	*Step 1*: 2 mile grid evaluation → *Step 2*: Search 1 mile from 2 mile grids identified as well connected locations → *Step 3*: Iterative 0.5 mile search starting from well connected locations identified in step 2
	Hierarchical 3 (H3)	*Step 1*: 2 mile grid evaluation → *Step 2*: Iterative search within 1 mile, starting from well connected locations identified among 2 mile grids

We tested three hierarchical sampling settings. The first step of all three settings is to conduct a 2 mile grid sampling based community connectivity analysis. After completing this step, hierarchical 1 (H1) will select well-connected locations identified in the first step, and search 0.5 mile neighborhood of those locations to identify more well-connected locations nearby, and then keep on such 0.5 mile neighborhood searching on newly identified locations until no more well-connected locations can be found (iterative growing of the search). H3 also uses this iterative neighborhood search method, but adopts a 1 mile neighborhood instead of a 0.5 mile neighborhood. H2 is slightly more complicated compared with H1 and H3: after completing the 2 mile grid sampling based analysis, it will search the 1 mile neighborhood of all well-connected locations identified in step 1 and identify more well-connected locations. Then, it keep on iteratively searching the 0.5 mile neighborhood of the well-connected locations identified in step 1 and 2 until no more well-connected locations can be found to grow the search. Overall, these three methods generally use 2 mile grid sampling based analysis results as "seeds" to grow a search tree until no more well-connected locations can be found nearby; "Iterative

search" means once new well-connected locations are found, the algorithm will use them as "new seeds" to grow the search.

EVALUATION RESULTS

The evaluation results include the sensitivity analysis results of the grid size on the performance of grid sampling based analysis, and comparisons of the grid sampling based analysis and the hierarchical sampling based analysis in terms of time, recall, and precision. Figure 3 shows the relationship between the grid size and the recall rate of community connectivity analysis results. This figure shows the results of locations with 5, 4, and 3 types of services within 0.5 mile separately, and also combines the results of these three categories of locations to observe how the percentage of well-connected locations (i.e., locations with three or more types of services within 0.5 mile) that are recovered varies with the grid size.

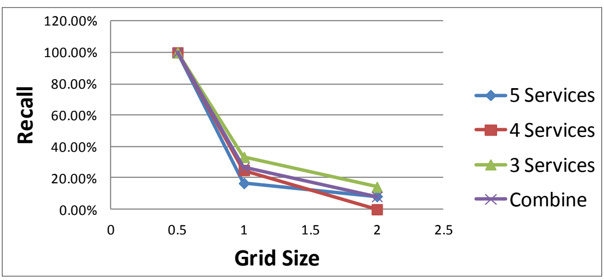

Figure 3. Sensitivity analysis of recall rates to sampling grid size

Figure 3 confirms that the recall rate will decrease when the grids become sparser. An important observation helped us to determine 2 mile as the grid size for the first step of the hierarchical sampling: the recall rate substantially decreases from 0.5 mile grids to 1.0 mile grids, while the decrease from 1 mile grid to 2 mile grid is relatively less. Using 2 miles grid sampling will reduce the number of evaluated locations without substantially compromising the recall performance.

Figure 4 compares the performances of hierarchical and grid sampling based community connectivity analyses. Figure 4a shows that H1, H2 and H3 can identify more well-connected locations than 1 mile and 2 mile grid sampling settings, while consuming more time than them. Compared with 0.5 mile grid sampling, hierarchical sampling results reduce the number of evaluated locations while losing some comprehensiveness. Particularly, H1 can identify 45 well-connected locations while evaluating fewer locations compared with the 0.5 mile grid sampling (68 vs. 89 locations). Hence, H1 misses four well-connected locations among the total of 49 well-connected locations, but saves 13 ineffective evaluations (evaluations wasted on "less-connected" locations).

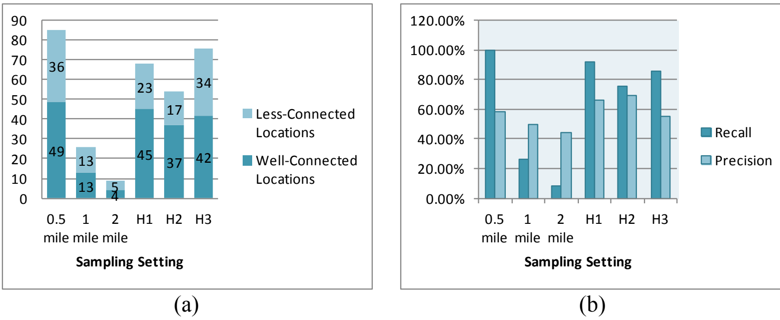

Figure 4. Comparing the performances of hierarchical and grid sampling based community connectivity analysis: (a) time; (b) recall and precision

Figure 4b further confirms that compared with 1 mile and 2 mile grid sampling settings, H1, H2 and H3 can achieve better recall and precision rates. Comparing H1, H2 and H3, we found that H1 (2 mile → 0.5 mile iterative search) seems to have the best overall performance, as it can achieve a recall rate of 91.84% and a precision rate of 66%, which means that it can detect 91.84% of well-connected locations with much better precision than grid sampling settings (58% based on 0.5 mile grid sampling, the best case of three tested grid sampling based analyses). H2 (2 mile → one mile → 0.5 mile) has slightly better precision rate (69%) than H1, but its recall rate is only 75.51%, which is a significant loss of the comprehensiveness. H3 can achieve good recall (85.71%) but waste too much time in evaluating less-connected locations (precision 55%). These observations indicate the overall advantages of the hierarchical sampling approach over the grid sampling approach, while revealing the necessity of conducting more detailed sensitivity analysis to understand why H1 performs the best for the studied city.

SUMMARY, DISCUSSIONS, AND FUTURE RESEARCH

To improve the efficiency and effectiveness of the community connectivity analysis for identifying sustainable construction sites according to LEED, this research explored a hierarchical sampling approach to reduce the total number of locations that need to be evaluated for a given urban area, while striving to keep the level of comprehensiveness of the analysis. Using a mid-size city in Michigan as a case study, we showed that the hierarchical sampling approach can generally achieve recall rates comparable to dense grid (0.5 mile) sampling that samples all possible locations across this city, while achieving higher precision rates. At the same time, we found that different parameter settings of the hierarchical sampling can significantly influence the recall and precision rates of the community connectivity analysis.

In the future, we plan to explore along the following directions: 1) explore methods for automatically determine the optimal hierarchical sampling setting (grid sizes for multiple sampling steps) based on the service distribution information derived from a GIS database; 2) explore how transportation networks corrupt connected communities, and incorporate such considerations into the hierarchical

sampling based community connectivity analysis; 3) evaluate the hierarchical sampling approach on data sets from multiple cities with difference distributions of services, and understand how optimal hierarchical sampling setting varies with different spatial distributions of services; 4) further analyze the needs of different types of buildings, and explore how to incorporate considerations about matching the needs of particular types of new buildings (office building, schools) against the service types into this framework of hierarchical sampling based community connectivity analysis.

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Semi-Structured Data Modelling for a Web-enabled Engineering Application

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ABSTRACT

This paper is part of a larger research project, initiated to leverage the existing NoSQL database storage solutions for creating a platform-independent, fast, scalable and reliable database, capable of efficiently storing and retrieving information for oil & gas/civil engineering projects. This information is usually stored in SQL-based data warehouses to facilitate planning, maintenance or shutdown business processes. The proposed semi-structured database system stores information in JSON format, thus requiring a different approach in structuring, querying and aggregating data. The prototype storage model implemented in MongoDB looks very promising. JSON structure is a convenient way for storing project data, test scenarios show it being faster than a SQL alternative, and flexible schema definition means it is properly aligned with the agile development strategy. This storage approach fulfils the requirements of the project and is expected to be expanded to support ontology-driven storage, knowledge sharing and 3D model integration for a web application.

INTRODUCTION

Traditionally relational database systems have been applied to all data storage problems due to their popularity, wide acceptance of the standard SQL language, strict data management rules and the availability of various open source and commercial products. Current generation of the booming web applications, however, saw the need for new approaches in the data storage area to align with the application flexibility, performance and scalability requirements.

Experience shows that many systems begin their lifecycle small, but once the dataset size increases, they start to suffer from inappropriate design or poor choice of technology. Relational database theory encourages the database to be highly normalized. Using additional database features, such as stored procedures and triggers, helps contain the logic at the database layer thus easing the system management. This in turn comes with a performance hit. A common solution is to provide de-normalized tables/views with pre-joined conditions to speed up the queries that require fast response from the application. But in essence, this defeats the purpose of having a relational database; as such views have to be maintained separately and may introduce data inconsistency (if they fall behind with the data updates).

Relational databases have a history of being difficult to scale when the system performance needs to be increased. Often scaling vertically (by adding more resources to the server) is the only option, but that is bound by the limits of technology and is progressively expensive. When a system needs to be scaled horizontally (adding more servers), the use of joins and transactions actually becomes a burden as it is difficult to implement them in the distributed relational databases (Leavitt, 2010).

Fixed schema in the relational databases and a table format for the data is more suitable for the scenarios where objects have a fixed number of attributes (therefore columns) and data can be easily represented in a table or a set of tables. It is quite difficult to store an object inside one of the table cells, so that the properties of the object are accessible. Such scenario is usually addressed by further de-normalizing the data structure and joining additional tables.

The goal of this project is to create an efficient engineering information integration platform that could be deployed in the cloud and scaled horizontally and vertically as the dataset size increases over time. In this paper, the requirements for the data model and platform will be reviewed. Fitting data storage will be chosen and a few tests will show how it compares to a relational data store.

BACKGROUND

Data model. The data model used in this paper is derived from the field of oil & gas engineering applications, but this approach can be easily applied to other applications, which are using similar data modelling concepts.

Equipment *Objects* in an oil & gas facility usually have a hierarchical structure. One complex component can consist of several sub-components, which in turn can contain items that can be broken into equipment, which may be procured and installed as an assembly or separately. Objects can have associations to other Objects or *Documents*. They can have virtually an unlimited number of attributes, the presence of which is defined by a simplified form of ontology in this field called the *Class Library*.

A Class Library defines the expected attributes for an Object; therefore, if a class named Pump has three attributes, an Object, classified as Pump will also be required to have three attributes. If some of the attributes are missing, the data is considered to be incomplete. One human-readable record representation could look as it is depicted in Table 1, which, in fact, is very similar to the JavaScript Object Notation (JSON) format.

Object – Document and Object – Attribute links are different in nature. Objects can exist without associations to Documents, while attributes only make sense when attached to Objects; these relationship types can be described as many-to-many and one-to-many respectively.

Table 1. Object data format

Presentation format	JavaScript Object Notation (JSON)
Pump P-10115	{ "ID" : " P-10115",
ID : P-10115	"Name" : " Pump P-10115",
Description : Cold water pump, floor	"Description" : "Cold water pump, floor 2",
2	"Class" : "Pump",
Class : Pump	"Attributes" : [
Attributes	{"Pressure" : "80 psi"},
Pressure : 80 psi	{"Type" : "electric"},
Type : electric	{"Voltage" : "380 V"},
Voltage : 380V	…],
….	"Document associations" : [
Document associations	{"Object name" : " Final P&ID DH-10.pdf "
Final P&ID DH-10.pdf	}, …]}
…	

Platform. The engineering information integration database is not intended for the public and will not have thousands of simultaneous users accessing the system. It is required that the system has strong consistency implementation, is able to support large datasets efficiently and works effectively on a single node with the capability to scale the system to multiple nodes. It must perform adequately with read operations and must be able to handle peak moments of intensive read/write operations when a data import job is being executed.

Further discussion will explore the choice of a suitable database system for the task.

NOSQL DATABASE OVERVIEW

The term NoSQL refers to a range of data storage systems, which do not implement the relational data model and do not support SQL query language. With the increasing popularity of online services, companies like Google, Amazon and Facebook have to deal with huge amounts of data. Usually in such cases data consistency is not the primary goal. For an online shopping service it does not really matter much whether the inventory contains 3 or 4 items. What matters is that the service is available and the buyer can put the item into the shopping cart and proceed to checkout. The remaining inventory can be synchronized in the background as long as the correct amount can be retrieved or calculated in a predictable manner.

System availability and scalability is usually of the utmost importance as the number of users and the amount of data associated with them can increase very rapidly in a successful project, so the system has to be designed to scale horizontally in a predictable manner, and perform appropriately on a large number of nodes.

CAP theorem. Brewer's theorem states that it is impossible for a web service to provide Consistency, Availability and Partition Tolerance at the same time (Brewer, 2000). As Merimman (2010) has noted, network partitioning is almost certain in distributed systems, so for most of the time it means that a compromise between Consistency and Availability (Gilbert and Lynch, 2002) needs to be made. As the aim of the project is to provide an engineering information integration database, consistency takes precedence over availability. It is not

desirable to provide obsolete information to the users, as this may impede decision making processes. With so many commercial and open source data storage systems available, it is important to choose the one that is both aligned with the particular data storage problem and addresses key requirements.

Key-Value pair storage

Systems that implement key-value store provide an indexed data structure, where an object (value) can be accessed by a key. While some of these systems are in-memory databases, i.e. Memcached, usually they can be thought as distributed and persistent hash tables (Amazon SimpleDB, Riak, Membase, etc.). Such systems are aimed at providing extremely fast and scalable data stores. While most, if not all, storage requirements can be simplified to fit the key-value paradigm, it is not always optimal to do so. If, for example, objects need to be accessible by several keys, or only a few of the object properties need to be retrieved and updated, it may be more efficient and convenient to use a different data store.

Column based storage. Column based storage systems have been gaining popularity and they have been recognized for their application in data warehouse solutions (Stonebreaker, et al., 2007). Rather than storing object information in rows and retrieving the whole row from a disk (often this means that unneeded attributes are also read from disk), such systems store and retrieve information grouped into attribute columns. Cassandra is a good example of a NoSQL column based storage, which provides a multidimensional column store, while HBase was created as an open source alternative to the Google's BigTable. These systems have been acknowledged to work on a large scale in several big companies (Lakshman and Malik, 2010). Such data storage model does not fit this project however, as it would impose additional difficulties in storing and retrieving the data.

Document based storage. Rather than storing data in rows or columns, systems implementing this kind of storage, organize data by storing it in documents. Such approach has the benefit of being able to store objects with varying number of attributes while attributes with the same name do not have to be of the same type for two different objects. Document storage systems can use additional indexes for fast data retrieval. Such stores can be implemented on top of a relational or object database or directly support semi-structured file formats like JSON or XML. MongoDB and CouchDB are two main NoSQL document based storage systems.

As it was already noted, JSON represents the data model of the project efficiently. Such document (also called semi-structured) storage eases the planning and development of the database schema. Variable number of attributes allows the system development to be aligned with the agile project management. The system can be started small and provide basic functionality initially; over time additional functions can be added as the database layer can be easily extended without taking the existing application offline.

MongoDB was chosen for the particular storage engine because it stores data in BSON (Binary JSON) format. It also provides a SQL-like query language, which makes it easier for developers to interact with the data stored in it. Possibility to have additional indexes on multiple attributes of an object means that several keys can be used to access the information quickly. Map-reduce

functionality provides the capability to run complex queries that require aggregation in the background processes, while GridFS allows storing large files in the database itself.

JSON BASED ARCHITECTURE

JSON format is widely used in web systems as it recognized to be a self-describing, concise (more compact than XML) format for transferring data. With client JavaScript code already present on majority interactive web applications, usage of client side JavaScript libraries like Backbone.js or Knockout.js simplifies the development of rich client interfaces. Having this format at the storage layer, combined with a JavaScript based web server such as Node.js, means that JSON format could be the only form of information needed in the whole path from the database to the client browser.

Modelling data in JSON format in MongoDB has its own advantages and disadvantages. Since the database lacks the functionality of joins, it means that linking data together needs to be done at the application layer. This is partially offset by the rich data model capabilities. As JSON supports hierarchical data structure with deep nesting, some relationships can be embedded inside objects. In a normalized SQL database an equipment Object with attributes would be represented by at least two tables (one for the Object, another one for attribute values), linked by an Object identifier. There would be one issue, as the column data type restrictions do not allow general objects to be stored; they have to be numbers, strings or dates. Thus attributes would be stored as strings, or separate tables for different types of attributes would be needed. In MongoDB this is not an issue as any type of object can be stored as an attribute. Attribute names and values can be stored inside a JSON array, thus eliminating the need for joins and transaction locking (see Figure 1).

As Object – Document association is a many–to–many type of relationship; data would have to be split into at least three tables in a SQL system. In MongoDB the general practice is to choose one collection, which is smaller, and embed object keys from that collection into objects in another collection (see Figure 1). Such approach suggests that this model is best suited for data that does not change frequently. As Abadi (2009) noted, OLTP databases are still better served by proper RDBMS systems, but for data warehousing/analytical storage problems distributed database solutions, which can be deployed in a cloud, may be a good choice.

Since JSON data model contains attribute names in every object, it may be worth noting the size of the record being stored. In general, it is a good practice to make attribute names as short as possible, as this saves space and increases the probability that objects and/or indexes fit into the memory, which is many times faster than the relatively slow disks. If attribute values are very large compared to the attribute names, the performance benefit may not be noticeable, so a proper balance between readability and size is recommended.

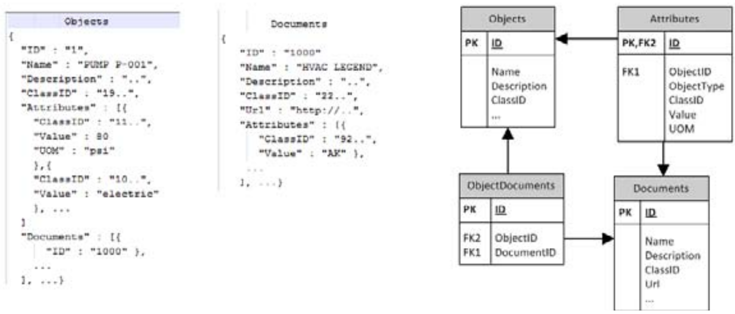

Figure 1. JSON model (left) and relational schema (right) compared

TESTING

Testing was done on Amazon's EC2 large machine instances, each with 2 cores and 7.5GB of memory. As the performance of Elastic Block Storage (EBS) is not consistent, tests were executed three times (on three different virtual machines) and the results were averaged.

MySQL was chosen as a relational database for comparison, as it is also an open source database; it is very widely used and can run on multiple operating systems. The operating system used was Ubuntu 11.10 64bit, MongoDB version was 2.0.2 and MySQL version was 5.1.58. Every MongoDB collection and MySQL table had two indexes – one for the primary key and one secondary index.

Test scenarios were created to emulate a large data process job for importing equipment Objects, Documents and their attributes into the system with a huge number of write and/or read operations taking place sequentially. As it was a prototype test data store model, the numbers should not be treated as absolute values, but rather as relative performance indicators.

The first test was to compare the performance when inserting records into the database. This means that only a single insert operation was executed for both MongoDB and MySQL. The horizontal axis represents the number of equipment Object records in the database. The graph (see Figure 2) shows the consistent performance of both databases with MongoDB being 3-4 times faster than MySQL.

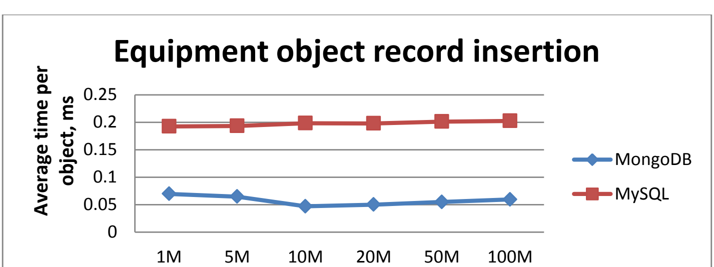

Figure 2. Object Insert Operations

The second test was executed to simulate adding different Document records with attributes and Object relationships to the database. Since the number of Documents is usually a lot lower than the number of Objects, this was represented by having ten times less Document records. Each Document had five attributes inserted and each ten objects were retrieved and had an association to the same document added. While MySQL was faster at querying data from a single table, this scenario still shows it consistently being about 3 times slower than the MongoDB.

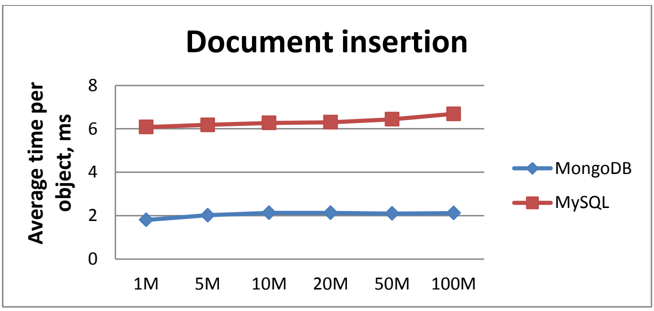

Figure 3. Finding and Inserting Data Combined

The last test was done to get the full object data alongside the associated documents. Since there are no joins in MongoDB, it meant two find operations were executed. For MySQL three select operations were used, two of which contained joins with the attribute table. The graph is different here as MySQL showed very good performance until there were about 5 million object records (50 million attributes). From that point the performance decreased very fast. MongoDB showed a nearly linear performance decrease and outperformed MySQL by a considerable margin on a larger scale.

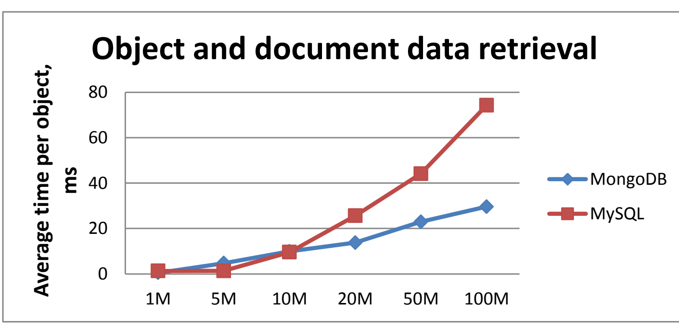

Figure 4. Full Information Retrieval

CONCLUSIONS AND FUTURE WORK

Despite MongoDB being a relatively new database storage system, tests, involving the data model discussed, show it being faster than MySQL most of the time. The outcome of the tests shows that database write operation performance is nearly consistent in the defined scenarios, even when the data store contains 100 million equipment records. MongoDB was faster than MySQL using queries with joins on a large scale for read operations and had a predictable, nearly linear performance decrease as the number of records increased. This suggests that tuning and/or scaling the database for a more consistent read operation performance may be desirable.

Working with JSON object storage appears to be an efficient and convenient way to structure and retrieve data. The prototype test harness aimed to simulate high intensity read/write data import/export operations shows MongoDB a suitable data store. More research will be done to link and store equipment Object relationships to 3D model data. The prototype data model will be de-normalized to fully support the ontology-based Class Library. The platform will be enhanced with additional features to store the information captured by engineers and project managers sharing their knowledge through a web application.

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A Multi-objective Scheduling Model for Solving the Resource-constrained Project Scheduling and Resource Leveling Problems

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ABSTRACT

The project resource leveling problem was proposed to smooth resource usage and reduce resource fluctuation, while the resource-constrained project scheduling problem focuses on minimizing the project duration with limited resources. Solving the two interrelated problems separately is unlikely to result in a globally optimum schedule. The few integrated optimization methods that have been developed favor a predetermined resource profile that may be difficult to achieve. This paper proposes an integrated scheduling method to minimize the project duration and resource fluctuation by using the strength Pareto evolutionary approach II (SPEA II) which outperformed several other multi-objective optimization techniques in solving the resource-constrained project scheduling problem. An innovative chromosome representation scheme for SPEA II was proposed. A set of case studies were tested to compare the optimization performance of the proposed method with the best of the existing techniques. The results showed that the method yields better results than popular methods presented in the literature.

INTRODUCTION

Project scheduling is the basis of decision-making in project planning and management. Resource-constrained project scheduling problems (RCPSPs) were proposed to optimize scheduling under resource constraints. The objective functions of many PCPSPs are to minimize the project duration or to minimize resource cost within a predetermined project duration.

The RCPSPs can be categorized into single-mode and multi-mode approaches in terms of the number of modes in which resources are used or consumed. When activity durations are variable in different modes, the combination of different modes of activities generates varied costs. In this case, the RCPSP may be evolved into a discrete time-cost tradeoff problem (Brucker et al. 1999).

Metaheuristic algorithms, especially genetic algorithms (GAs), have been used widely to solve RCPSPs and its sub-problems. The objective functions of the GAs were usually set to minimize the project duration (Chen and Shahandashti 2009; Goncalves et al. 2008; Hartmann 1998). The chromosomes of GAs have been represented as permutation based, priority rule based and priority value based. Serial and parallel scheduling techniques have been adopted to convert chromosomes into the actual schedule (Kolisch 1996).

Resource fluctuation has been studied mainly within the scope of the resource leveling problem which describes the process of reducing the fluctuations in resource usage over the project duration. Undesired resource fluctuations may cause inefficient and costly implementation of construction, for example, frequently rehiring and releasing workers, lowering production levels and interruption of learning curve effects (El-Rayes and Jun 2009). These implicit costs incurred by undesired resource fluctuations can account for a large portion of resource costs. Heuristic algorithms, such as particle swarm optimization (PSO) and GAs have been adopted to solve resource leveling problems (Chan et al. 1996; El-Rayes and Jun 2009; Senouci and Eldin 2004).

Resource leveling and resource-constrained project scheduling problems are inherently interrelated. A certain schedule having a higher resource cost may have a lower resource fluctuation. However, the two problems have usually been studied independently. Only a few integrated models have been developed to solve the two problems simultaneously (Liao et al. 2011). Resource leveling has usually been addressed in these models by adding a constraint (Senouci and Eldin 2004). These methods favored a predetermined resource profile that may be difficult to achieve (Leu and Yang 1999). In addition, PCPSPs were not fully explored in the integrated models. These studies mainly used a single objective function to minimize project duration, cost, or deviation between resource usage and the defined value (Chan et al. 1996). Only the single-mode RCPSP has been integrated with the resource leveling problem. Therefore, this research aimed to develop a model solving the resource leveling and multi-mode resource-constrained discrete time-cost tradeoff problems simultaneously by using a multi-objective optimization.

PROBLEM DESCRIPTION

The mathematical description of the problem is shown in Eqs.(1)-(4). The problem can be solved by using a multi-objective optimization technique whose objective functions are to minimize the resource cost (i.e., Eq. (1)) and the total project duration (i.e., Eq. (2)). The cost is split into two parts: resource usage cost (*RUC*) and resource fluctuation cost (*RFC*). The constraints include the resource feasibility constraint (Eq.(3)) and the precedence constraint (Eq.(4)).

$$\text{Min } C_{total} = RUC + RFC \quad (1)$$

$$\text{Min } T = max(LF_1, LF_2, \ldots LF_n) \quad (2)$$

$$\text{s.t. } RU_{m,t} \leq R_{m,t} \quad (3)$$

$$FT_i \leq ST_j \quad (4)$$

Where $R_{m,t}$ = the capacity of a resource type k_m at a time period t; $RU_{m,t}$ = the calculated amount of resource m used at a particular time t. FT_i = finish time of activity i whose successor is activity j. ST_j = start time of activity j.

The resource usage cost (*RUC*) is defined as the total cost of the resources used by all the activities in the given activity modes. Resource fluctuation costs (*RFC*) denotes additional costs incurred when resources are newly added or dismissed. Such costs may include training, transportation and bidding costs. El-Rayes and Jun (2009) proposed two metrics: release and re-hire (*RRH*) and resource idle days (*RID*), to measure the level of the resource fluctuation. The *RRH* was calculated from Eq. (5) (El-Rayes and Jun 2009).

$$RRH = H - MRD = \frac{1}{2} \times \left[r_1 + \sum_{t=1}^{T-1} |r_1 - r_{t+1}| + r_T \right] - Max(r_1, r_2, ..., r_T) \quad (5)$$

Where H=total increases in the daily resource demand; T=total project duration; r_t = resource demand on day t; MRD=maximum resource demand during the entire project duration.

In this research, the metric of measuring the resource leveling cost RFC was calculated based on the metric RRH. RFC is calculated by Eq. (6). UHC_m denotes the unit cost of hiring and releasing a resource type m and RRH_m denotes the amount of a hired or increased resource m calculated by Eq. (5). The cost of MRD is also added to RFC to minimize the resource demand.

$$RFC = UHC_m \square RRH_m + C_m \bullet MRD \quad (6)$$

MODEL DEVELOPMENT

The model consists of three modules: the evolutionary multi-objective optimization (EMO), the project scheduling, and the resource leveling (see Figure 1). The fitness values of the EMO are calculated based on time and cost fed by the project scheduling and resource leveling modules.

The EMO module. The EMO module uses the strength Pareto evolutionary approach II (SPEA II) to find a Pareto optimal solution. SPEA II was developed based on the natural evolutionary principle (Zitzler et al. 2001). The previous study showed that SPEA II performed well in RCPSPs (Ballestín and Blanc 2011). SPEA II conducts crossover and mutation as shown in Figure 1. SPEA II uses an external archive containing non-dominated solutions previously found. Non-dominated individuals are copied to the external non-dominated set (see Steps 4-6 of the EMO module in Figure 1). SPEA II uses an enhanced archive truncation method that preserves the boundary solutions. The fitness assignment strategy (see Step 2 in Figure 1) and GA operations (see Step 7 in Figure 1) considers both closeness to the true Pareto front and even distribution of solutions. The non-dominated points are also preserved based on the fitness values.

The encoding approach is illustrated in Figure 1. The first section of the chromosome denotes the priority values which are unique integers in the range from 1 to n (i.e., the total number of activities). The second section denotes the mode of activities. When the two sections are specified, chromosome gene values would be fed into the resource leveling module to generate a genotype (i.e., schedule).

SPEA II calculated fitness using $R(i) + D(i)$ (Zitzler et al. 2001) where $R(i)$ is the function of "strength" which can be derived from cost and project duration and $D(i)$ is density estimator calculated as the inverse of the distance to the k-th nearest neighbor. $D(i)$ is calculated to ensure that the points are evenly distributed along the known Pareto front and to avoid cluster. The fitness values of the non-dominated individuals are less than 1.

The crossover method developed by Hartmann (1998) was adopted to implement the crossover operation in the first section of the chromosome. For instance, the left part of the gene values in child 1 comes from parent 1 and the right part in child 1 is from the parent 2 by the left-to-right scan. The scan makes the right

part of child 1 take the gene values in parent 2 which are different from the gene values in the left part of child 1.

The mutation of the first section of genes is achieved by swapping two randomly selected genes in a chromosome. For the second section of the chromosome, the mutation operator modifies modes at each position with an equal probability. If a position is selected, a random value within the range of the total number of modes is selected.

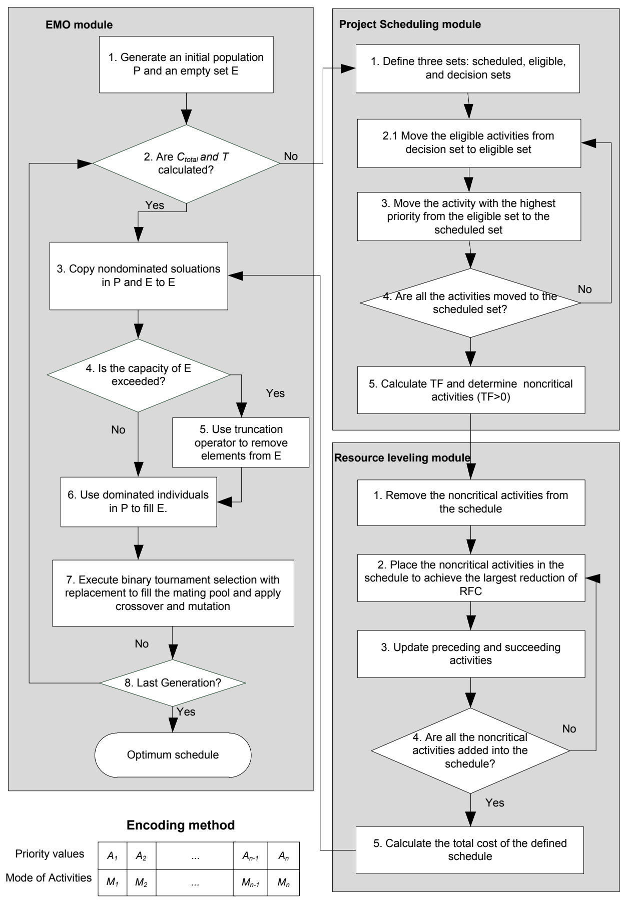

Figure 1. Flow chart of the model

The project scheduling module. The activity and mode lists stored in the chromosome are fed into the project scheduling module to formulate the schedule. Activities are scheduled according to the serial scheme scheduling approach (Kolisch

1996). Three activity sets are established, namely the scheduled set, eligible set, and decision set (see step 1 in Figure 1). At first, all the activities are placed in the decision set. The decision set contains all the activities to be scheduled. The scheduled activity set contains activities that have been scheduled (i.e., starting and finishing time is determined). The activities in the decision set whose precedent activities are scheduled and included in the scheduled set are then moved to the eligible set. Several activities may be moved to the eligible set simultaneously. Only the activity in the eligible set having the largest priority value is selected to be moved to the scheduled set. This activity is added to the project schedule chart and the starting time is adjusted to meet the resource constraint. This process is repeated until all the activities in the decision set are moved to the schedule set. This method is called the backward pass.

The last task in this module is to calculate the total float (TF) for each activity. The following method is used: the backward pass is used to determine the late activity finish times. Then, by deducting the latest finish time by the earliest finish time, the TF of each activity can be calculated.

The resource leveling module. The resource leveling module calculates the project duration and cost as measured by the fitness calculation of the EMO module. The first task is to adjust the noncritical activities (i.e., activities whose TF is larger than zero) to reduce the *RFC*. Where to locate these noncritical activities in the schedule is critical to reducing the *RFC*.

Reducing *RFC* can be achieved by reducing the sum *RRH* + *MDR* (see Eq. (6)). First of all, the noncritical activities are removed from the schedule and form a noncritical activity list (see Step 1 of the resource leveling module in Figure 1). In the subsequent steps, in terms of the priority values of the noncritical activities, each activity will be added into a location where the maximum reduction of *RRH* + *MRD* is achieved (see step 2 in Figure 1). After a noncritical activity is added to the schedule, the start and finish time of other noncritical activities are updated. Following this process, all the noncritical activities are added to the schedule (see step 4 in Figure 1).

In step 3, the noncritical activities are placed by aligning a newly added noncritical activity to existing activities in the schedule. An example is shown in Figure 2. The grey highlighted bar denotes the resource usage of the existing activities in the schedule. Two new activities with oblique lines are added to the schedule. To achieve the maximum reduction of RFC, the two activities should be aligned with the edge of existing activities. Thus, according to Eq. (5), if the first activity may be located at P_1, the reduction of *RRH* is R_1 and if the second activity is added at the position P_2, the reduction is $R_2 + R_3$.

After an activity has been added to the existing schedule, it will be merged into the existing schedule. The next noncritical activity is added based on the newly generated schedule where the maximum reduction of *RFC* can be achieved. This approach uses a greedy algorithm which makes the locally optimal choice at each stage with the intent of finding the global optimum. The sequence of adding noncritical activities depends on the priority values of these noncritical activities. An activity with a highest priority value will be chosen first to add the existing schedule to achieve the maximum reduction of *RRH* + *MDR*.

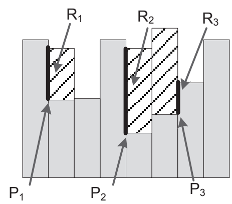

Figure 2. An example of the RRH reduction method

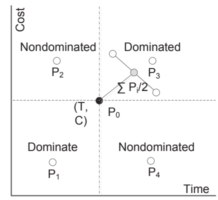

Figure 3. Comparison of (T, C) and calculated solutions.

COMPUTATIONAL EXPERIMENT

The developed model was implemented in MATLAB Version 7.9 using a laptop with a 2.0 GHz CPU and 2G RAM. A similar dataset of test cases originally created for the multi-mode RCPSP were selected from the well-known PSPLIB (Kolisch and Sprecher 1997). Ten cases from the dataset "j10.mm" (available in PSPLIB: http://129.187.106.231/psplib/) were selected (selected case numbers: 1, 50, 100, 150,…450). A baseline model was proposed for comparison with the developed model.

Baseline model. The baseline model has two phases each of which uses the GA algorithm. (a) In Phase I, a number of the minimum project durations were generated. The objective was to minimize the project duration only. This was regarded as a standard multi-mode RCPSP that could be solved by a number of algorithms (Hartmann 2001; Wuliang and Chengen 2009). An archive was included to store the 30 best individuals in the GA simulation. (b) In Phase II, the method developed by El-Rayes and Jun (2009) was used to calculate the minimum cost of *RRH* (corresponding to *RFC*) for each schedule (or individual) preserved in Phase I. Then the minimal total cost (i.e., *RUC* + *RFC*) is calculated.

Referring to Figure 3, assume the black solid point P_0 denotes (T, C) (T= time, C = cost) calculated by the baseline model and was located in the Pareto front line. The point (T,C) can be compared with the white points P_i calculated by the tested model (i.e., the model developed in this research). Four cases may occur after the comparison (see Figure 3): "dominated", "non-dominated", "dominate" and "equal". P_1 dominates the point (T, C) and P_2 is dominated by (T, C). P_0 may dominate many points P_i, thus, the average point is calculated. The percentage error *E* in regard to P_0 is calculated as $\left(\sum P_i / n - P_0\right) / P_0$ where the point P_i is calculated as the tested model and dominated by P_0; n is the number of points dominated by P_0. The grey point in Figure 3 denotes the average position of the two points dominated by P_0.

Experimental results. Two groups of resource unit cost were tested. The resource unit cost was set to 10 for both groups and the unit hiring/releasing cost (UHC) was set to 10 for one group and 20 for another. Preliminary tests were conducted to determine the simulation parameters. The test results showed that the mutation rate was set to be 0.05, which was the same as that recommended by Hartmann (1998), the population and archive sizes were set to 30. The percentage errors *E* were calculated

for each case. It was found that only cases #1 and #2 had errors (see Table 1). Further analysis showed that the reason why most of the errors were zero was that for all the ten cases, more than 80% of the points generated by the tested model dominated the points generated by the baseline model, that is to say, most of the calculated points by the test model were located in the lower left corner of the coordinator system in Figure 3. The reason was that the baseline model did not find the true global optimum individuals or only found the individuals that were inferior to those calculated by the test model. Though the experiment could not guarantee the points generated by the tested model were located on the Pareto front line, the experiment still showed that the tested model had the potential to generate relatively satisfactory results and also had better performance than the baseline model.

Table 1. Errors for cases #1 and #2

Cases with errors	Group 1(UHC = 10)		Group 2(UHC = 20)	
	Time	Cost	Time	Cost
#1	0.0%	1.1%	0.0%	4.1%
#2	0.0%	0.0%	0.0%	1.1%

The time and cost of case #2 are shown in Figure 4. When UHC = 10, the resource usage cost had a larger effect on the total cost and the increase of duration led to a larger decrease in the total cost. The results indicated that the RFC accounted for about 20% of the total cost (UHC = 10) and 25% (UHC = 20). When the duration increased by about 12%, the total cost decreased by 12% (UHC = 10) and 15% (UHC = 20).

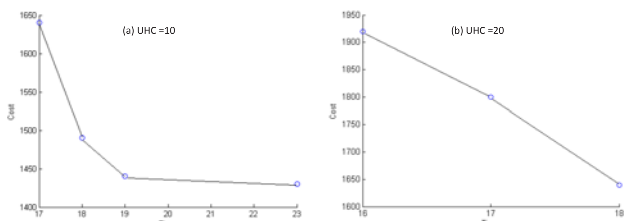

Figure 4. Time and cost for case #2

CONCLUSIONS

This research proposed a time-cost tradeoff model based on SPEAII to optimize the project duration and resource costs by integrated consideration of the resource-constrained project scheduling and resource leveling problems. Ten test cases were selected to evaluate the accuracy of the model by comparison with the baseline model that used the popular methods presented in the literature. The test showed that in two out of the ten cases the errors of the model were less than 5%, and in the other test cases the model generated better solutions than the baseline model. Future work may focus on improvement of the model (e.g., using dynamic unit costs of resources to evaluate the fluctuation cost) and developing models to solve the resource-constraint and resource leveling problems for multiple projects using shared resources.

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A Framework for Construction Workspace Management: A Serious Game Engine Approach

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ABSTRACT

Construction workspace is regarded as one of the main constraints on construction sites. Construction workspaces are generally difficult to proactively plan and manage due to the dynamic nature of a site where workspace requirements keep changing as time evolves. However, project managers are looking for ways to develop proactive site plan for the workspaces required for construction activities as this can impact not only on the cost and project duration, but can also contribute to provide a safer site. This research paper presents an approach for integrating workspace management within the planning process using a serious game engine technology. This paper first illustrates a review of the workspace management practices and advanced visualization techniques in the construction industry. Then, it presents a process framework for an interactive decision support system that integrates workspace planning into 5D planning in order to enable safer, efficient and more productive construction sites. The decision support system will identify schedule conflicts, workspace conflicts and the severity of their conflicts, and workspace congestions on a construction site and allow construction planners to resolve spatial conflicts prior to construction. Finally, the paper shows the current progress in the development of an initial prototype and outlines the future work and research.

INTRODUCTION

Construction projects are complex and dynamic in their nature. One of the main resources and constraints that affect the delivery of construction projects is the space available on site (Dawood et al., 2005). Construction projects are currently characterized by a high degree of fragmentation and specialization, which shape both the work on construction site and the upstream supply chains (Kassem and Dawood., 2012). Construction activities on site are being performed by multiple trades that may require, at any point in time, different workspaces as working areas for labor or working space areas for material storage, people, equipment and support infrastructures. Given the complexity and dynamicity of this problem, project managers cannot often predict solutions by relying on experience only. Current space-time planning techniques involve mainly textual description, hand sketches with site layout templates, bar charts, network diagrams, and 2D/3D scaled visualization models. Current construction planning techniques like Gantt chart, network diagrams, and CPM are proven to be

inadequate for construction execution space planning. Therefore, project managers require a structured approach and new project management tools that allow them to analyze, detect, control and monitor workspace conflicts (Dawood and Mallasi, 2006). A serious game engine is a game designed for a primary purpose other than pure entertainment (Sawyer and smith, 2008). This paper presents a framework that enables the management of construction workspaces within a serious game engine by integrating the traditional planning (CPM), BIM data of construction models and providing real time visual rehearsal of construction workspace.

LITERATURE REVIEW

This section presents an extensive and critical literature review of previous works related to both the workspace management and the advanced visualization technologies used in construction workspace planning. In the context of this research, construction workspace management refers to the workspace generation, the workspace assignment or allocation, the workspace conflict detection and resolution at any time during a construction project. The works reviewed were assessed against a number of features grouped under six main categories which are: physical constraints, workspace planning, construction planning, algorithms, knowledge databases and visualization. The results of this review were plotted into a matrix grid illustrated in table 1. The main findings are discussed in the following two sub sections. For the scope of this paper, only a few works are discussed. For all the other works, readers can refer to the matrix grid and referenced papers.

Construction workspace management. Moon et al. (2009) proposed an integrated approach where workspace are assigned individually for model's objects and linked to schedule activities. They classified the workspaces and allocated workspaces using a semi-automatic generation method based on resource requirements. This approach has significant drawbacks related to the fact that the workspace is assigned using the bounding volume of a selected object and is performed for each object individually. Planners in practice tend also to identify the required workspaces not only based on model objects but also on schedule activities. Finally, their approach is based on AutoCAD rather than BIM and lack strategies for conflict resolution. Dawood and Mallasi (2006) presented a critical space-time analysis (CSA) approach which was developed to model and quantify space congestion and was embedded into a computerized tool called PECASO (patterns execution and critical analysis of site space organization). This was developed to assist project managers in the assignment and identification of workspace conflicts. This methodology uses a structured query language (SQL) to organize the product's coordinates to the required execution sequence, assigns workspaces using layering within the AutoCAD model, and then links workspaces to activities to provide a 4D construction simulation of processes. While this approach is theoretically capable to deal with the dynamicity of construction workspace, it might be difficult to implement in practice as the project planner is required to assign construction workspaces in the design authoring tool (i.e. AutoCAD).

Table 1. Matrix of key research in construction workspace management and advanced visualization system

	Guo, (2002)	Akinichi et. al. (2002)	Dawood et.al. (2005)	Ciribini and Galimberti (2005)	Mallasi and Dawood (2006)	Kazi et.al. (2006)	Hang et.al. (2007)	Chen and Chung, (2009)	Moon et al. (2009)	Wu and Chiu (2010)	This Research propose
Physical											
People				X		X		X		X	X
Technological dependencies	X	X	X	X	X	X	X	X	X	X	X
Workspace Management											
Workspace Assignment											
2D/3D Mark-up on CAD Drawings	X		X		X			X		X	
4D Mark-up tool		X							X		X
Workspace Conflict Detection											
Physical Conflicts on site								X	X	X	X
Logical Conflicts on site					X				X		X
Resources	X		X		X	X		X	X	X	X
Schedule Conflict Detection	X		X						X	X	X
Conflict Visualisation								X	X	X	X
Resolution Strategies	X										X
construction planning											
Planning and scheduling	X	X	X	X	X	X	X		X	X	X
Monitoring and Controlling										X	X
"What-If" modelling					X	X					X
Optimisation											
Computational						X	X	X			X
AI and Knowledgebase algorithms					X						
Database											
Resource and design DB				X	X	X					X
Visualisation											
2D/3D view	X										
4D/VR		X	X	X	X	X	X		X	X	X
Game Engine								X			X

Advancement visualization technologies. Kuan-Chen and Shih-Chung (2009) argued that the construction processes are getting more complicated due to the high number of objects including structural elements and equipments. They proposed an algorithm called “VC-COLLIDE” which identifies conflicts on static or dynamic construction sites and determines the distance between large dynamic 3D objects in virtual construction sites using different scenarios. This algorithm rehearses the operation sequence to detect the collision status in real-time virtual construction processes. However, this method neither accounts for any risk assessment method nor refer to H&S issues such as critical space analysis. Dawood et. al. (2005) proposed an innovative advanced planning tool called “VIRCON” (VIRtual CONstruction) which investigates sequential, spatial, process conflicts and temporal aspects of construction schedules before commencing the work on the site. It allows planners to rectify and trade off the temporal sequencing of tasks with their spatial distribution to rehearse the project schedule. However, this does not visualize the conflicts in the 3D environment and does not refer to safety issues in the space analysis.

The literature review illustrated in this paper clearly showed the importance of proactively managing site workspaces. However, most of the existing research have significant limitations as to their approaches for assigning workspaces; the environment in which workspace management is performed; the lack of a resolution strategy as part of their methodology. In fact, some of the existing researches have attempted to generate and assign workspaces in the design authoring tool to which project planners do not often have access to or do not use. Also, in existing research, the workspace is assigned for each object individually (object by object) which is not often the case and can be impractical for models with a high number of components.

In addition, there are workspaces that cannot be represented using this method such as storage workspaces as they are not associated with any model’s object. Another important limitation of most existing works is that workspace management is separated from the traditional scheduling/planning process and geometric information is imported from non BIM platforms. The framework presented this paper aims at enabling construction workspace management by integrating the traditional planning process (CPM) and BIM data of construction models in a serious game engine and providing real time rehearsal of construction workspaces.

A BIM FRAMEWORK FOR WORKSPACE MANAGEMENT AND VISUALIZATION

Figure 1 presents the process framework to explain 4D/5D modelling, workspace generation/allocation, spatial-temporal conflicts, workspace congestion and resolution strategies. The model data is imported from BIM tools using a number of different file formats including the IFC format (Industrial Foundation Class - rules and protocols that describe the different building objects) and the schedule information from the planning applications using the XML format. Then, the model data and schedule information are linked together to create a 4D model. A 4D model is a visual simulation of the construction schedule that can be enabled once 3D objects from the 3D model are linked to construction activities from the project schedule. The 4D environment considered for the development of workspace management allows for multiplicity linking between objects and activities − more than one 3D element linked to a single activity and vice versa

(Benghi and Dawood, 2008). Once the 4D model has been built in the 4D environment, the processes of construction workspace management can then start. The workspace management will be enabled through a number of processes and sub processes including workspace generation process, workspace and schedule conflict detection process, workspace congestion detection process, and resolution strategies process. Each of these processes will be discussed briefly in the following sub- sections.

Workspace generation. This process starts with the allocation of resources (workers, equipments and materials) and the identification of the required support infrastructures to each activity that affect the dimension, position and type of workspace. The framework assumes that project planners are capable or have access to such information once the construction method has been defined. This metadata information is then used to assign the workspaces through a 3D mark up within the 4D environment. A bounding box will then be created as a result of the 3D mark-up process. All the different types of workspaces defined earlier can be assigned with a number of options that allow to editing the workspace attributes such as its volume, shape and position. The positioning of the workspace within the 4D environment can be obtained using a transformation matrix. Once the workspace has been generated and positioned, it can then be linked to one or more than one activity in the schedule. In order to enable the subsequent processes for workspaces management, the attributes of each workspace, the model element(s) and activity(ies) to which the workspace was allocated, are stored in a relational database. Once this process has been completed, the workspace conflict detection process can be started.

Workspace-Schedule conflict and workspace congestion algorithms. A schedule conflict is referred to a situation where a schedule presents a number of overlapping tasks. A workspace conflict may occur only for overlapping tasks sharing the same space. Therefore, the schedule conflict is a preliminary condition that requires to be checked prior to the workspace conflict. Therefore, the first step in the workspace conflict detection process (figure 1) is to check the schedule conflicts. An intersection test aims basically at detecting the physical clash or geometric conflict among the workspaces associated with the conflicting activities. This conflict can be detected by carrying an intersection test in each of the Cartesian direction (X, Y, Z). The intersection test utilizes a direct comparison of the individual coordinate values of the Axis aligned Bounding Boxes (AABBs). In particular, it compares the minimum and maximum coordinates values along each axis. Workspace congestion is a situation that occurs when the resources allocated to an activity such as labours, materials and equipment requires larger workspace than the available workspace while there are no physical conflicts between the workspaces. Workspace congestion is checked in all cases independently from the occurrence of schedule conflicts and/or workspace conflicts as it may occur also for a single activity which individually occupies a workspace. The process for checking workspace congestion is illustrated in figure 1.

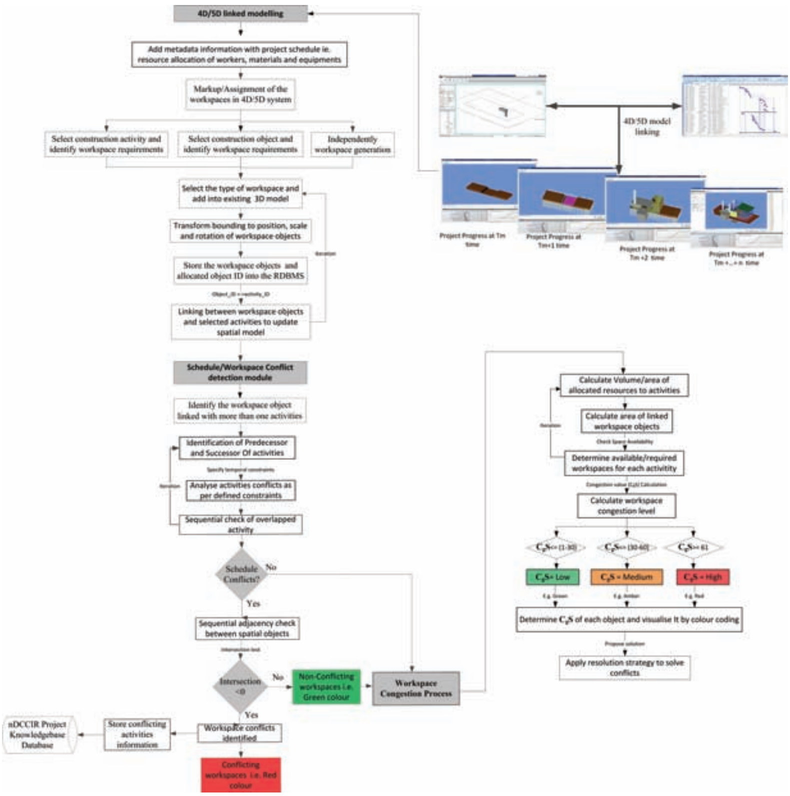

Figure 1. Overview of Process Framework

Resolution of workspace conflicts and workspace congestion. The resolution of workspace conflicts and workspace congestion represents the last process of construction workspace management where data from previous processes are utilized to resolve conflicts. Although this stage is one of the main aims of construction workspace management, much of the previous research was limited to identify workspace conflicts without tackling resolutions strategies. Bansal (2011) and Guo (2001) included in their methodologies conflict resolution processes that utilize the conflicting activities and the sizes of overlapping construction workspaces. The system will help the decision making process for the following resolution strategies:

- **Adjust/Control schedule:** this resolution strategy can be used to resolve schedule and workspace conflicts. The SC value provided for all activities not only help the project planner to focus his resolution strategy on the affected activities but also gives quantitative information about the amount of overlap.

- **Adjust/Control physical location:** this resolution strategy is used for workspace conflicts/congestion and consists in redesigning, controlling or adjusting the positioning/orientation of workspaces within the model.
- **Changing the direction of work progress:** many activities and works on construction site can be started from different directions (e.g. south – north rather north – south). Therefore, project planners can resolve workspace conflict by simply changing the direction of work progress.
- **Hybrid approach:** it is a trade off of the three above strategies.

The outcome from this development is an interactive multidimensional planning tool which allows users to rehearse different real time scenarios of the construction processes before the construction starts. By adopting the proposed methodology and integrating workspace management issues with the traditional planning process, it is hoped that workspace management can be significantly improved on construction site. Once all sub-process of framework developed, industrial pilot case studies will be conducted, in collaboration with practitioners, to test the effectiveness of the system and assess the best ways for its implementation.

CONCLUSION

One of the main resources and constraints that affect the delivery of construction projects is the space available on site. This paper presented a framework that allows a comprehensive management of construction workspaces by integrating workspace management with the traditional planning process (CPM) and the BIM model in a serious game engine in which construction workspace management is being conducted and rehearsed in visual real-time mode. The result of the review showed that existing research have significant limitations as to their approaches for assigning workspaces; the environment in which workspace management is performed; the lack of resolution strategies as part of their methodology. One of the most important limitations is that workspace management is separated from the traditional scheduling process, the geometric information is imported from non BIM platform, and the workspace management is performed within the design authoring tools. The paper showed the framework organized into a number of processes that explains the workspace generation and allocation process, the workspace conflict detection process, the workspace congestion identification process, and conflict resolution process. This is in line with the principles of nD project management where the ultimate scope is to give project planners the capability of rehearsing the different construction options before the construction starts in order to enhance the efficiency and productivity of construction processes.

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A Machine-Learning Classification Approach to Automatic Detection of Workers' Actions for Behavior-based Safety Analysis

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ABSTRACT

About 80-90% of accidents are strongly associated with workers' unsafe behavior. Despite the importance of worker behavior measurement, it has not been applied actively in practice due to its time-consuming and painstaking associated tasks. For measuring and analyzing worker behavior, vision-based motion capture has recently been proposed as an emerging technique that requires no additional time or cost. In line with motion tracking that extracts 3D skeleton motion models from videos, this paper proposes motion classification techniques for automatic detection of workers' actions. The high-dimensional motion models (e.g., 78 variables in this study) that result from tracking are transformed into a 3D latent space to reduce the dimensions for recognition. To recognize motions in the 3D space, this paper applies supervised classification techniques for training the learning algorithms with training datasets where unsafe motions are labeled, and then classifying testing datasets based on the learning. As a case study, motions during ladder-climbing are tested. The results indicate that the proposed approach performs well at automatically recognizing particular motions in datasets. Thus the measured information has great potential to be used for enhancing safety by providing feedback and improving workers' behavior.

INTRODUCTION

Computer vision-based sensing and tracking for site data acquisition are active research areas in construction. Due to the increasing prevalence of surveillance cameras on a jobsite, as well as the cost-efficient and easy-to-obtain nature of data collection with these cameras, vision-based monitoring has been applied for progress measurement (Brilakis et al. 2011; Golparvar-Fard et al. 2009), productivity analysis

(Gong and Caldas 2010; Bai et al. 2008), quality management (Zhu and Brilakis 2010), and safety (Yang et al. 2010). For safety, in particular, a vision-based approach to motion tracking has recently been investigated for the behavior analysis of construction workers (Li and Lee 2011; Han et al. 2011). For example, Li and Lee (2011) extract 3D human skeleton motion models from site videos for ergonomic analysis of workers' movements, and Han et al. (2011) apply a dimension reduction technique to high-dimensional motion data for recognizing particular motions (i.e., unsafe actions). These techniques allow automated behavior data collection for health and safety, and also provide a way to understand workers' safety behavior by analyzing their actions. Thus, observed behavior data have the potential to be used not only to detect workers' unsafe actions and provide feedback on their safety behavior (McSween 2003), but also to evaluate safety performances as a positive indicator (Hinze and Godfrey 2003). The previous studies—which state that about 80-90% of accidents are strongly associated with worker's unsafe behavior (Helen and Rowlinson 2005; Salminen and Tallberg 1996; Heinrich et al. 1980) and that behavior measurement is statistically correlated to accident records (Krause 1990)—indicate the significant importance of behavior monitoring for safety management.

Despite its potential benefits for safety enhancement, the detection of unsafe actions in motion data still remains challenging for three reasons. First, motion data are high-dimensional. Motion data contain angular information between body joints. To represent motions, many body joints need to be tracked; for example, 25 body joints (e.g., head, neck, hip, arm, leg) are selected in this study, and each body joint has 3 degrees of freedom (i.e., x-y-z rotations). The high-dimensionality of motion data thus causes difficulties for data analysis. The second reason is that every time a particular motion happens while performing, it widely ranges in variation and speed. The irregularity of motions can produce inconsistent results when one recognizes particular motions. Accordingly, robust methods that can systemically compare the similarity of motions are necessary to improve the accuracy of motion analysis. The third reason is that motions change over time. Unlike a pose at a moment (i.e., a data point), an action is represented by a sequence of data points. Motion recognition hence involves time series data analysis, and these characteristics of motion data make it difficult to recognize particular actions in a large amount of data.

To address these issues, this paper investigates machine-learning techniques to classify motion datasets for identifying specific actions. We collect motion data including actions during ladder-climbing, and recognize specific actions (e.g., stepping up the ladder, working on a ladder, and stepping down the ladder) by comparing the similarity between motion datasets.

BACKGROUND

Motion capture is a process to track and record body movements (Moeslund and Granum 2001). During the last decades, motion capture technologies have been actively developed and widely applied for various fields including entertainment, sports, military, and medical research. In construction, motion capture has also been proposed as an emerging means for measuring workers' behaviors, which has not been carried out actively in practice due to the limitations of field observation (Han et

al. 2011). For example, our industry partners stated that they no longer observe worker behavior because of its time-consuming and painstaking tasks involved in the measurement and the large amount of data required for avoiding biases. In our recent study (Han et al. 2012), we thus investigated how vision-based motion tracking can be used for safety; specifically, critical unsafe actions are first defined based on accident records, motion data for the unsafe actions and site videos are collected from a lab and a jobsite respectively, 3D skeleton motion models are extracted from site videos, and then both motion models—from a lab and a jobsite—are mapped onto the same space to identify the unsafe actions.

In addition to the mapping of motion data, this paper explores motion classification to automatically and systemically identify unsafe actions. For time series classification, the Hidden Markov Model (HMM) and the Dynamic Time Warping (DTW) are the most popular and widely used methods (Kotsifakos et al. 2011). The HMM is a generative model that represents the relationships and structure of sequential data, and has been used for various applications such as speech recognition (Kotsifakos et al. 2011). Nevertheless, it is generally required to determine the size of the model (i.e., the number of image frames for each action) beforehand, though the size of a motion model varies with each action (Okada and Hasegawa 2008). In this respect, the DTW that measures similarity between sequential datasets (Jeong et al. 2011) is applied in this paper. The DTW is used to measure the distance and identify an optimal match between two sequences, even the lengths of which are different, and thus two motion datasets that may vary in time and speed can be classified. Thus by using the DTW, the distances between a pre-defined training template (e.g., ascending, working, and descending) and testing datasets are computed, and the one with the smaller distance is classified into the same class as the template.

DATA COLLECTION

As a test case for motion classification, both training (i.e., template) and testing motion models were collected through a lab experiment in this study. Motion datasets were gathered using a motion capture system (e.g., Vicon motion capture system) at the University of Michigan 3D Lab. A performer wearing a special black suit attached reflective markers on his/her body joints (Figure 1.a); thus, the system easily tracks the movement of markers with multiple cameras and produces accurate motion data. A 3D skeleton model is then obtained, as shown in Figure 1.b. This model contains the information on angles between joints changing over time. In this study, 25 body joints in Figure 1.c are tracked using the system, and hence the motion data has 78 dimensions in total (i.e., 75 angles for joints and 3 global pose angles). The datasets are comprised of motions during a ladder-climbing; in construction in 2005, falls from a ladder accounted for 16.0% of fatalities and 24.2% of injuries involving days away from work (CPWP 2008). The datasets contain 25 cycles of ladder-climbing, and each cycle consists of 3 action classes: stepping up, working on a ladder, and stepping down. As a result, the motion datasets are classified into the three classes using the DTW.

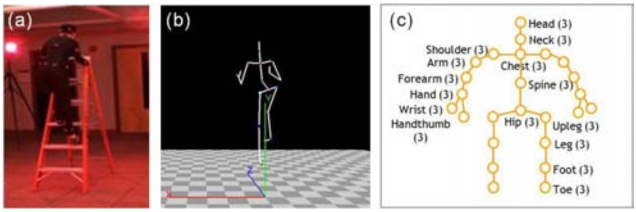

Figure 1. (a) Motion capture system, (b) body skeleton model, and (c) body joints (Note: the number represents the degree of freedom)

FEATURE EXTRACTION

To analyze the high-dimensional data and improve the accuracy of classification, a dimension reduction technique is first applied to extract primary features from the collected data. In our experiment, the classification results were inaccurate when applying to raw data. The dimensions, initially numbered at 78, were hence reduced to 3 using kernel principal component analysis (kernel PCA) (Schölkopf et al. 1998). The kernel PCA is a powerful method that computes the kernel matrix (e.g., polynomial kernel in this study) for non-linear mapping, and uses the eigen-decomposition to reproduce data (Cunningham 2008). This method is thus useful for extracting primary features that have large eigenvalues in the decomposed eigenvector space, as well as for reproducing non-linear data such as motion data. This means motion data, including various sub-actions, could be efficiently transformed onto a low-dimensional coordinate in our previous study (Han et al. 2011).

To determine the target number of dimensions that can represent most of the data without loss of information, eigenvectors and eigenvalues were computed and compared. As shown in Figure 2.a, the first 3 eigenvectors have large eigenvalues. This means that in the eigenvector space where raw data are mapped, most data can be represented with these 3 axes (i.e., 3 eigenvectors); thus 3 dimensions were selected for dimension reduction. Then, a training dataset (i.e., one cycle of ladder-climbing) was mapped onto a three-dimensional space (Figure 2.b), and mapping parameters were learned in this process. The parameters were tested with subsets of training data (i.e., three classes: step up, work, step down, as shown in Figure 2.b), and the data points in the subsets were mapped onto the exact same points. In addition, the colored points in Figure 2.b reveal where the three classes of motions are located in the space. Based on the mapping parameters learned and tested, testing datasets (i.e., the other 24 cycles of ladder-climbing) could successfully be transformed to the same space, as well (Figure 2.c). Each cycle of motions is distributed, but is located mostly within a narrow range.

MOTION CLASSIFICATION

Using the transformed datasets that have only three dimensions, motion datasets are classified into three actions (i.e., stepping up, working, and stepping

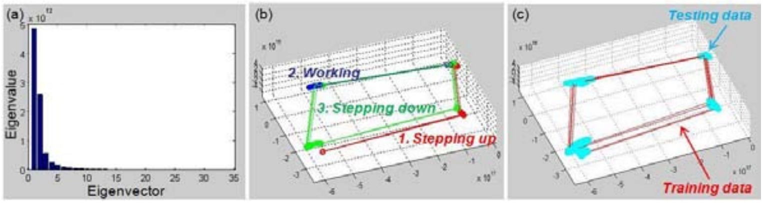

Figure 2: (a) Eigen-decomposition, (b) mapping with training data, and (c) mapping with testing data

down). Among 25 cycles, one was used as a template, and the other 24 were used as testing data and thus were classified with the templates. In other words, one cycle of motion datasets was first divided into three data subsets corresponding with the three actions, and each subset was used as a template to measure the similarity with training datasets. The DTW was used to calculate the distance between each template and the three subsets of training data; it was regarded as similar when the distance between two sets of sequential data was short. Eventually, actions are recognized by identifying the template with the smallest distance to the dataset; for example, when the distance between a dataset and a stepping-up template is the shortest among three templates, the dataset is classified as stepping-up.

To measure the performance, classification errors—which are percents of incorrectly classified datasets—were calculated through 25-fold cross-validation (i.e., among 25 cycles, each is iteratively selected as a template in turn, and validation is performed for the other 24 cycles in each iteration). Table 1 presents the mean errors for the three templates when using each cycle as a template. The cross-validation results reveal that the classification algorithm provides 76% of the average accuracy.

The results also indicate that the accuracy can be improved up to 93% when using suitable motion data (e.g., the 13th cycle dataset in the table) as a template. In this regard, selecting a template is critical for recognizing specific actions in motion data. Thus for accuracy improvement, actual motions of construction workers on a jobsite can be sampled and utilized to find an optimal template for target motion detection. This strategy may also help resolve an issue on motion variances that differ from individual to individual by using specific workers' motion samples to detect the one's motions. The fact that the number of workers on a particular jobsite is limited and that the scope of motion detection in this study is limited to pre-defined motions (e.g., critical unsafe actions such as carrying a tool and material up the ladder) may facilitate the motion template selection. In addition, an optimal template can efficiently be determined among the samples through cross-validation to reduce classification errors, as identified in Table 1. Consequently, the proposed classification approach has great potential to robustly and systemically detect specific actions.

DISCUSSION

The proposed motion analysis can be used for two aspects of safety management. Straightforwardly, feedback on behavior can be provided for employees

Table 1. Errors Through Cross-Validation

Cycle	1	2	3	4	5	6	7	8	9	10	11	12	13
Error (%)	0.25	0.27	0.27	0.29	0.24	0.32	0.32	0.23	0.09	0.27	0.24	0.19	0.07
Cycle	14	15	16	17	18	19	20	21	22	23	24	25	Mean
Error (%)	0.20	0.29	0.23	0.25	0.29	0.16	0.21	0.23	0.29	0.33	0.23	0.31	0.24

based on the measurement. Feedback is very efficient for improving safety behavior (Komaki et al. 1978), thus leading to a reduction in the number of unsafe actions, and eventually to a reduction in the number of incidents and injuries. The previous study that found that near-miss incidents such as unsafe actions are precursors of accidents (Phimister et al. 2000) also indicates the importance of behavior in safety. Further, at-risk conditions that cause workers to take unsafe actions can be identified and removed in advance through active feedback and communication.

Second, behavior measurement can be used to assess ongoing safety performances (Hinze and Godfrey 2003). Motion recognition techniques are available to count the number of unsafe actions for periods of time, and the measured frequency and types of unsafe behavior may help determine what corrective managerial actions (e.g., training, education, or the use of scaffolding rather than a ladder) need to be taken. Motion recognition techniques also suggest the extent to which efforts and time for safety are needed to improve performance. For this purpose, the constant monitoring of workers would be highly effective, but a random sampling of motion data can be adopted in the case of activities being out of range of fixed cameras.

CONCLUSION

The objective of this paper is to assess a motion classification approach to detecting specific actions in motion data that can be obtained from site videos. For motion classification, high-dimensional motion data are first transformed to a low-dimensional coordinate to improve the accuracy of classification. Then, we label particular actions in training datasets, and measure the distance between the labeled actions and testing datasets in the low-dimensional space. The dataset with the smallest distance is classified into the same action. The results indicate that the proposed approach performs well at automatically recognizing particular motions in datasets. In this way, workers' behaviors can be measured without significant human effort and cost. The measured information thus has great potential to enhance safety by providing feedback on workers' behaviors, and by determining proper management strategies for behavior modification.

In our future studies, we will investigate motion sampling to extract representative templates from site videos. Motions of multiple performers in various position (e.g., using a right or left hand first when ascending, or grasping a rung or side rail) will be collected and tested for template selection. Furthermore, motion detection in streaming data will be studied beyond classification with sets of motion data. An approach using a threshold of the distance may be taken to determine the similarity between a template and streaming data points (i.e., classifying as the same

actions when the distance is less than the threshold). Eventually, our ongoing project will include the extraction of motion data from site videos, the verification of the proposed method for the motion data, and the detection of unsafe actions in the video streams. In this case, the proposed approach will rely on the accuracy of the extracted motion models; however, advanced motion modeling techniques such as a Gaussian Process Dynamical Model (GPDM) (Wang et al. 2005) may facilitate smooth embedding of high-dimensional motion data in a dimension reduction process and reduce the variation of motions caused by inaccurate 3D motion model extraction.

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RBU: A Model for Reducing Bias and Uncertainty in Multi-Evaluator Multi-Criterion Decision Making

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ABSTRACT

Decision-making in fields such as politics, engineering and healthcare, shapes the world and how it evolves. Both public and private organizations face challenges when making decisions. Two examples occurred with the Minnesota Department of Transportation in 2007 and the U.S. Department of Energy in 2008. Losing bidders for a bridge-rebuilding contract and a liquid-waste cleanup project, respectively, protested the agencies' awards on the basis of evaluation methods and selection criteria. Multi-evaluator multi-criterion (MEMC) decision making can be controversial if bias or uncertainty find their way into the final decision.

In a previous study, the authors of this paper developed a model that reduces the effect of uncertainty resulting from an evaluator's insufficient expertise in a particular criterion. This paper builds on the previous study by also correcting for potential favoritism or bias. It presents a more comprehensive mathematical model that supports MEMC decisions and protects decision-makers from criticism. The methodology includes: (1) proposing a probabilistic model and its assumptions; (2) developing an iterative algorithm; (3) testing the algorithm and analyzing its convergence; and (4) revising the model based on the results. Tests of the model show it performs better than the simple average method on 100% of the simulations.

INTRODUCTION

When making a decision, one often considers more than one criterion. Additionally, more than one evaluator is often needed to reduce potential biases and/or uncertainty. Such decisions are called *multi-evaluator multi-criterion* (MEMC) decisions. Decisions need to be unbiased when comparing alternatives, in order to make the right conclusion and maximize benefits from the process. The decision making process must also be transparent, particularly in public settings where taxpayers' money is involved. Even with transparency, decision making can still be controversial and can lead to loss of public trust and added legal costs. In a previous

study, we developed a multi-evaluator decision making model that reduces the effect of uncertainty resulting from an evaluator's insufficient expertise (El Asmar et al. 2011). The current paper builds on it by presenting a comprehensive mathematical model for MEMC decision making that also corrects for bias in the evaluators' scores. The model is intended to support selection decisions and protect decision makers and their agencies from potential criticism.

Management science literature on MEMC decision making can be classified into two categories: multi-criterion (MC) decision making and multi-evaluator (ME) decision-making. While there are many studies on MC decision making, especially in the construction literature, few address the problem in the context of MEMC. Other studies focused on weighting the criteria, as opposed to maximizing the benefits from having more than one evaluator. Evaluators' possible bias and lack of experience have not been adequately addressed.

OBJECTIVES AND SCOPE

The MEMC model's main purpose is to assist in the decision making process when selecting among many alternatives by using a mathematical method to perform fairer evaluations. This purpose stems from the fact that current MEMC decision making methods can be controversial and can lead to project delay, loss of trust, and increased legal fees, as was recently demonstrated in the examples mentioned in the *Abstract*. ME decision making can yield different levels of uncertainty in the scores due to varying degrees of the evaluators' expertise. Another problem is the potential for biases of the evaluators either for or against certain alternatives. These two issues make it necessary to reconsider the traditional averaging method of aggregating the evaluators' scores. A mathematical model is essential for detecting and reducing the effects of both bias and uncertainty in the evaluators' scores. A previous study (El Asmar et al. 2011) introduced a mathematical model of ME decision making that can measure the evaluators' expertise by detecting the uncertainty from their scores, and reduce the effect of uncertainty on the decision. It considered two dimensions: (1) *multiple alternatives*, and (2) *multiple evaluators*. A third dimension, (3) *multiple criteria*, should be added to allow for consideration of potential evaluator bias. Therefore, the proposed new and more comprehensive model has two objectives:

A. To detect and reduce any possible evaluator favoritism or bias, and
B. To detect and reduce the effect of possible uncertainty, or lack of expertise.

The model can be used in decision making problems that deal with multiple evaluators who review multiple alternatives based on multiple criteria. However, the scope of this study is limited to the areas of bias and uncertainty in the scores given by the evaluators. The proposed model is only concerned with estimating the "ideal" scores from the actual raw scores of the multiple evaluators; it does not consider how these scores are used to make the final decision. Therefore, it can be applied in situations where different decision models (other than the linear weighted model introduced in the following section) are used. Similar to the traditional linear weighted model, we assume that all assessed criteria are independent, i.e., they measure distinct aspects of the requirements. Because consensus scoring is not within the scope of this study, we assume that each evaluator scores the alternatives

independently. Another assumption is that the combined knowledge of the evaluators is greater than the individual knowledge of any single evaluator.

A MATHEMATICAL MODEL FOR BIAS AND UNCERTAINTY

A decision maker needs to select one of several alternatives $i = 1, 2, \ldots, I$. The decision should be made according to certain criteria $j = 1, 2, \ldots, J$. Each alternative is assumed to possess a certain utility value V_{ij}, taking values between 0 and 1, and giving the score of criterion j for alternative i. To evaluate the utilities V_{ij}, the decision maker takes the opinion of a number of independent evaluators $k = 1, 2, \ldots, K$. Each evaluator assigns a utility score U_{ij}^k (also between 0 and 1) reflecting his or her perception of V_{ij}. A common procedure is to give an estimate $\widetilde{V}_{ij}$ of V_{ij} by the average of all U_{ij}^k over the k, i.e.: $\widetilde{V}_{ij} = \frac{1}{K}\sum_k U_{ij}^k$. Using the above estimates $\widetilde{V}_{ij}$, there are different methods for selecting the "best" alternative. The most commonly used is the linear weighted model, where Criterion j is given a weight w_j, and the alternative i with the highest score $S(i) = \sum_{j=1}^{m} w_j \widetilde{V}_{ij}$ is selected. In this section, we introduce the mathematical model for MEMC decision making to reduce bias and minimize the effect of uncertainty in the traditional method. We first assume that all scores U_{ij}^k are between 0 and 1.

Transforming the Scores. Bias or uncertainty can lower a score of 0.9 to 0.7 or 0.5, but it can raise it to at most 1. Therefore, to deal with the scores U_{ij}^k in a symmetric way, we need to transform them to the real line $(-\infty, \infty)$, where large deviations on both sides are possible. We let T be a continuous increasing function that maps the real line $(-\infty, \infty)$ to the open unit interval (0, 1), so that its inverse T^{-1} exists, and we let $X_{ij}^k = T^{-1}(U_{ij}^k)$. For definiteness, we choose T to be the cumulative standard normal distribution function given by:

$$T(x) = \frac{1}{2}\left[1 + erf\left(\frac{x}{\sqrt{2}}\right)\right] = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x} e^{-\frac{1}{2}x^2}dx$$

The function T has the advantage of transforming the standard normal random variable Z into a random variable $U = T(Z)$, which is uniformly distributed on (0,1). Similarly, if U is uniformly distributed on (0, 1), then $Z = T^{-1}(U)$ follows a standard normal distribution. The model assumes all of the evaluators' scores take values in the open interval (0, 1). The intuition behind this is that evaluators can never really believe an alternative deserves 0 or 1 (nobody is perfect and nobody is worthless). However, since some evaluators actually do give extreme scores, one can explain this by round-off error due to the fact that evaluators do not give exact real numbers like 0.9857… and are likely to round-off that score to 0.99 or to 1.0.

Defining Bias and Uncertainty. The first step in the model development is to give precise mathematical meanings to the concepts of *bias* and *uncertainty*. The

key assumptions are listed.

- For each alternative i and criterion j, a true "ideal" score V_{ij} exists. These are the scores we want to recover. Similar to the evaluators' scores, we assume $0 < V_{ij} < 1$. The transformed values of the ideal scores are denoted by $Y_{ij} = T^{-1}(V_{ij})$.
- For each i, j and k, the transformation $X_{ij}^k = T^{-1}(U_{ij}^k)$ is a random variable which deviates from Y_{ij} according to the formula:

$$X_{ij}^k = Y_{ij} + \delta_{ij}^k$$

The evaluators' scores are given by:

$$U_{ij}^k = T\left(T^{-1}(V_{ij}) + \delta_{ij}^k\right)$$

- For each i, j and k, δ_{ij}^k is a "noise" random variable representing both the evaluator's uncertainty and bias. The expected value $E(\delta_{ij}^k) = \mu_{ik}$ does not depend on j. We define μ_{ik} as the *bias coefficient* of evaluator k toward alternative i. The reason for this assumption is that a bias in the scores of evaluator k toward or against alternative i is modeled by an average positive or negative shift of the transformed ideal scores Y_{ij}, for all values of j. The existence of the criterion dimension j allows for detection of evaluator k's potential bias toward or against alternative i. Therefore, the *bias coefficient* of evaluator k toward alternative i is independent of the individual criterion being evaluated.
- $Var[\delta_{ij}^k] = \sigma_{jk}^2$ does not depend on i. We define σ_{jk}^2 as the *uncertainty coefficient* of evaluator k regarding criterion j. Since an evaluator might have a certain amount of experience in a particular criterion, this assumption implies that he or she can score all alternatives with an uncertainty that only depends on that criterion. In other words, the uncertainty coefficient of evaluator k regarding criterion j is independent of the individual alternative being evaluated. This assumption is vital for our ability to estimate uncertainty.
- For different triples (i, j, k), the random variables δ_{ij}^k are independent. This is explained by the fact that even for a fixed evaluator and fixed alternative, the "random" deviations of the scores of various criteria from the ideal scores are independent of one another. One possibility is to assume δ_{ij}^k is normally distributed, reflecting the fact that the uncertainty is the result of many independent factors. However, the model does not need this assumption.

The challenge is to estimate the true scores V_{ij} from the different scores U_{ij}^k given by the evaluators, or equivalently estimate Y_{ij} from X_{ij}^k.

Minimizing Bias and Uncertainty. To estimate Y_{ij} from X_{ij}^k, we will try to minimize the effect of the different "noise" random variables δ_{ij}^k. Let us first assume that we are given the values of the mean μ_{ik} and standard deviation σ_{jk} of δ_{ij}^k. Each X_{ij}^k is a random variable with mean $Y_{ij} + \mu_{ik}$ and standard deviation σ_{jk}. Guided by the commonly used estimate $\tilde{V}_{ij} = \frac{1}{K}\sum_{k=1}^{K} U_{ij}^k$, we employ the more general linear weighted

estimate: $$\tilde{Y}_{ij} = \sum_{k=1}^{K} \omega_{jk} (X_{ij}^{k} + c_{ijk}) \quad (1)$$

where ω_{jk}, called the *knowledge weight*, represents the weight of evaluator k attributable to his or her experience on criterion j. Since we also know that the evaluators might have biases, we add the correction term c_{ijk} to their scores. The addition of the correction terms and the weighted averages are performed in the space $(-\infty, \infty)$ rather than in the unit interval (0, 1).

For the above general estimate (1), the correction terms and the knowledge weights that give the best estimate of the true scores U_{ij} are given by the formulas:

$$c_{ijk} = -\mu_{ik}, \qquad \omega_{jk} = \frac{1}{\sigma_{jk}^2} \bigg/ \sum_{k=1}^{K} \frac{1}{\sigma_{jk}^2} \quad (2)$$

Using these formulas guarantees the following:

a) The expected value of the estimate equals the true score $E[\tilde{Y}_{ij}] = Y_{ij}$.
b) The variance $Var[\tilde{Y}_{ij}]$ is the smallest possible among all choices of knowledge weights. Moreover, the smallest value of $Var[\tilde{Y}_{ij}]$ is given by: $1 \bigg/ \sum_{k=1}^{K} (1/\sigma_{jk}^2)$.

Since $1/\sigma_{jk}^2$ may represent the experience of evaluator k with criterion j, the above statement guarantees that the maximum value of the experience in the estimate $Var[\tilde{Y}_{ij}]$ equals the sum of the individual experiences of the evaluators.

Estimating Bias and Uncertainty. If the values of Y_{ij} were known, and since $\delta_{ij}^{k} = X_{ij}^{k} - Y_{ij}$, we can find statistical estimates of $\tilde{\mu}_{ik}, \tilde{\sigma}_{jk}$ using the formulas:

$$\tilde{\mu}_{ik} = \frac{1}{J} \sum_{j=1}^{J} \delta_{ij}^{k} = \frac{1}{J} \sum_{j=1}^{J} (X_{ij}^{k} - Y_{ij})$$

$$\tilde{\sigma}_{jk} = \sqrt{\frac{1}{I-1} \sum_{i=1}^{I} (\delta_{ij}^{k} - \tilde{\mu}_{ik})^2} = \sqrt{\frac{1}{I-1} \sum_{i=1}^{I} (X_{ij}^{k} - Y_{ij} - \tilde{\mu}_{ik})^2} \quad (3)$$

By fixing i and k, the set $\{\delta_{ij}^{k} \mid j = 1,2,.., J\}$ can be thought of as a sample of size J taken from distributions with the same mean μ_{ik}. On the other hand, fixing j and k, the set $\{\delta_{ij}^{k} - \mu_{ik} \mid i = 1,2,.., I\}$ can be thought of as a sample of size I taken from distributions with the same standard deviation σ_{jk}. The factor $(I-1)$, or any other correcting factor for unbiased statistical estimates, will not affect the calculations of the experience weights ω_{jk} of Equations (2). Now, since we only have the estimates $\tilde{Y}_{ij}$, we can use $\tilde{Y}_{ij}$ to get rough estimates of μ_{ik}, σ_{jk} by Equations (3), while replacing Y_{ij} by their estimates $\tilde{Y}_{ij}$. Thus, we have a recursive problem:

a) To find estimates $\tilde{Y}_{ij}$ of X_{ij} using Equation (1) we need the correction terms c_{ijk} and the knowledge weights ω_{jk}. These can be found using Equations (2) with the means μ_{ik} and the standard deviations σ_{jk}.

b) The estimates of the means and standard deviations $\tilde{\mu}_{ik}, \tilde{\sigma}_{jk}$ could be evaluated from Equations (3) using the estimates $\tilde{Y}_{ij}$ we get in step (a).

The Iterative Method. This problem can be solved by iteration. The basic idea is to start with the simple averages of the evaluators' equally-weighted scores as $\tilde{Y}_{ij}$, which we use to estimate $\tilde{\mu}_{ik}, \tilde{\sigma}_{jk}$, from which we can get better estimates $\tilde{Y}_{ij}$, which are then used to improve our estimates $\tilde{\mu}_{ik}, \tilde{\sigma}_{jk}$ etc., until all the values stabilize. The algorithm is best explained by the flowchart in Figure 1, where we drop the tilde (~) signs to simplify our notation. Other than the evaluators' scores U_{ij}^k and their transformations X_{ij}^k, all the variables are estimates that change in each iteration.

Convergence Discussions. The objective of the algorithm is to estimate the scores Y_{ij}, from which the true scores V_{ij} are calculated. After experimentation, the following problems are encountered. First, the biases μ_{ik} sometimes diverge together to +∞ or −∞, causing the scores Y_{ij} to diverge to −∞ or +∞. A solution to this problem is to require that after each iteration the biases sum to zero. Second, we almost always get nonzero biases μ_{ik} for a fixed alternative i. Thus, it is reasonable to ignore biases μ_{ik} that are small relative to others. Third, it is possible that one of the ω_{jk} converges to 1, which results in a domination of evaluator *k* in finding an estimate of Uij. This

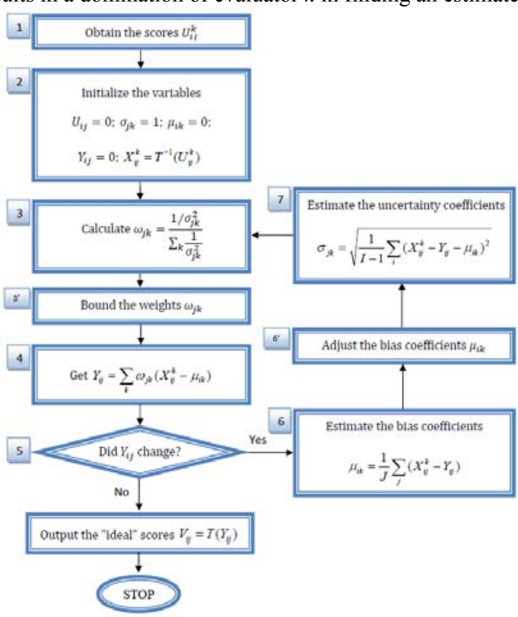

Figure 1. Flowchart of the Iterative Method

problem is solved by imposing an upper bound on the knowledge weights, while still making sure that $\sum_{k=1}^{K} \omega_{jk} = 1$. A suitable value is *2/K*, giving the informed evaluator twice as much power to influence the final scores.

MODEL TESTING AND VALIDATION

We evaluate the model with two kinds of data. The first is an example where we generate input scores, add random variation and bias to them, and then input the imperfect scores to the model to try to recover the real scores. The second is an application to some real-life data.

Recovering Real Scores. In this example, four evaluators score five alternatives based on three different design criteria: quality of the design, safety, and schedule. The ideal scores that each alternative deserves on each of the three criteria are preset to specific values: alternative A will be set to the lowest score, alternative B will score a little higher, and so on up to alternative E scoring the highest out of all five. The scores are obtained by adding a random number to each ideal score. The random numbers are uniformly distributed with means equal to the biases to reflect that evaluator 1 is biased toward alternative A and against alternative E. The standard deviations are set to represent the situation where evaluators 1 and 2 are the most knowledgeable in all three criteria; evaluator 4 is less knowledgeable in the area of safety; and evaluator 3 is less knowledgeable in the area of schedule (see Table 1).

Table 1. Recovering Real Scores - Input Values and Assumptions

	Alternatives Ideal Scores					Evaluators' Uncertainty			
Criteria	A	B	C	D	E	E_1	E_2	E_3	E_4
C_1	0.10	0.30	0.50	0.70	0.90	0.05	0.05	0.1	0.1
C_2	0.20	0.40	0.60	0.80	0.95	0.05	0.05	0.05	0.4
C_3	0.10	0.20	0.30	0.40	0.50	0.05	0.05	0.4	0.05

After the scores are generated, we (1) calculate the plain averages of these scores, and (2) use the generated scores as inputs to the model to obtain the output. Then we compare the final scores – both from the model and from the plain average – to the preset ideal scores, to compare the traditional average with our model. The results demonstrate that our model gives final scores that are closer to the real scores than the simple averages in 100% of the simulation trials. The improvement in the quality of the results of our proposed method, as compared to the traditional averaging method, is between 36% and 79% with average improvement equal to 61%. This is also an improvement over our previous model (El Asmar et al. 2011), which realized better final scores in 89% of the simulations.

Application to a Real Dataset. A potential application of the model is the design-build team selection of the bridge replacement project for the collapsed Mississippi River bridge of Interstate 35W in Minneapolis, Minnesota. Table 2 shows (1) the averages of the six evaluators' original scores given to the four alternatives based on nine evaluation criteria, and (2) the modeled scores. The technical criteria are scored out of 100 points. When comparing the methods, the similarity of the technical scores adds support to the correctness of the selection decision made by

MNDOT, and dismisses the claims made by protesters. This example was featured in a previous paper (El Asmar 2010) that motivated this paper. The authors refer the interested reader to that paper for more information about the specific problem and the importance of the decision context.

Table 2. MNDOT Case Study

Criterion Number	Average Scores				Modeled Scores			
	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 1	Alt. 2	Alt. 3	Alt. 4
1	57.17	60.33	94.17	71.67	57.42	60.46	95.36	71.04
2	57.00	71.17	88.00	70.50	54.40	72.58	86.67	68.62
3	85.67	76.33	86.00	74.33	85.56	77.45	83.82	75.36
4	57.83	77.83	79.00	66.33	59.17	80.66	83.86	70.65
5	68.33	63.67	*97.83*	63.83	68.17	67.80	98.30	66.94
6	49.00	61.33	*97.17*	56.33	52.06	64.47	98.49	61.04
7	5.83	43.00	92.50	67.00	0.36	48.55	93.30	71.03
8	27.67	63.17	93.00	59.33	25.12	60.09	95.04	59.08
9	72.00	75.67	92.33	71.67	73.81	78.16	95.77	73.87
Total	**55.98**	**65.91**	**91.38**	**67.88**	**55.78**	**67.97**	**92.63**	**69.61**

CONCLUSION

The decision making model presented here can detect and minimize bias as well as extract the maximum knowledge from the scores given by evaluators with various degrees of experience. It is applicable to many real-life situations and gives the decision maker a basis upon which to proceed with a selection decision. The decision-maker can use the model results in different ways, from total reliance on the outputs to a combination of the outputs with other quantitative variables, such as cost, in making a final decision.

Tests of the model show that it performs better than the simple average method in 100% of the simulations. It reduces the errors by an average of 61%, compared to the simple average method. A limitation of the model is that it can only handle scores that are between *0* and *100%.*

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Identifying Scheduling Inefficiencies for Industrial Projects using the Flowline View: A Case Study

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ABSTRACT

Industrial construction projects are typically very complex in nature both technically and from a construction management perspective. These projects typically involve a large number of very specialized, highly skilled, and diverse role players. The skill set requirements for the resources (both manpower and equipment) make it very costly, and in many cases impossible, to accelerate or delay key tasks. The scheduling in this context focuses on achieving a near continuous work flow for key trades. This paper presents the study, from an owner's perspective, of schedule analysis for a highly repetitive industrial project. Due to highly specialized equipment needs, delays or unnecessary accelerations on this project results in huge added costs per day for the owner. The study uses a location based scheduling approach, the Flowline methodology, as a visualization tool to identify scheduling inefficiencies which cannot be identified using the existing CPM based schedule for the project. Although productivity data is considered an essential input for linear scheduling in general, this study demonstrates that the Flowline methodology can be used by an owner even without access to trade productivity data. The results can be used to strategically release work packages to avoid unnecessary added costs.

INTRODUCTION

Industrial construction projects are technically complex and typically involve a large number of skilled crews performing complex subtasks. These crews usually represent various conflicting trades and their management requires sufficient understanding of the posed time-space conflicts. Coordination of these crews and scheduling of work to attain the desired productivity rates, especially for skilled crafts, is not a trivial exercise. The scheduling and coordination tasks are further complicated for projects that are highly repetitive in nature. Traditional scheduling techniques, like the Critical Path Method (CPM), are mainly activity driven and do not provide the necessary constructs to model spatial constraints and functional workflow requirements for projects. Such emphasis on activities alone can lead to problems in management of resources, both labor and material, during the construction phase (Arditi et al. 2002). Graphical and linear scheduling techniques, like the Line of Balance (LOB), provide some additional functionality that can enable decision makers to model the repetitive nature of work. Application of these methods to scheduling for construction projects is widely published in literature with earliest

works reported on the use for scheduling of linear construction projects such as highway construction (Johnston 1981; Chrzanowski and Johnston 1986) and for repetitive building construction projects (Carr and Mayer 1974). However, the adoption of the technique for scheduling of linear repetitive construction projects has not been widespread in part due to the lack of availability of commercial tools and access to reliable productivity data (Duffy, Oberlender et al. 2011).

Linear scheduling is convenient way to portray repetitive activities and offers additional feature of identifying activities that might result in a conflict (Hinze 2008). A relatively newer variant of the method, Flowline scheduling (Kenley and Seppänen 2010), is a location based scheduling method that is gaining traction in the building construction industry. The Flowline scheduling relies on mathematical models based on quantities, locations, crew sizes, and various productivity rates to enable detailed modeling of repetitive tasks. The Flowline technique works best in a collaborative environment where knowledge is shared throughout the construction supply chain and is incorporated during the planning stages of the project (Seppanen 2009). However, this productivity information is often not readily available to the end consumer of the schedule, e.g. an owner. The availability of reliable data, and access to such data, is especially challenging for projects where an owner has engaged a design/construction entity on a Lump Sum Turnkey (LSTK) contract basis. The contractor in such a contracting model is mainly concerned with finishing the job under budget and useful suggestions to improve overall productivity can be ignored (Dozzi et al. 1996).

In the absence of reliable data, the use of the technique for an analysis of production related inefficiencies would be rather fruitless. This paper presents a different use of the Flowline based techniques as a schedule visualization tool: specifically to identify scheduling inefficiencies (as opposed to production inefficiencies). A case study is presented that highlights the use of the technique to identify areas of concern for the owner where any delays or even unnecessary, unintended accelerations can cost large sums of money on a daily basis. The key contribution of the work presented in paper is that such analyses can be performed, without any resource or productivity related information, using the basic CPM schedule activity data alone (durations/dates).

The next section provides a brief overview of the Flowline methodology and how it can be used for identifying scheduling inefficiencies. The methodology followed for the research and the scope of the study is presented next. The paper proceeds with a detailed discussion of the case study for a large industrial project that is composed of many repetitive sub-units. A results and conclusions sections highlights the impact of the Flowline location based technique and how it can be useful even in the absence of detailed productivity data.

FLOWLINE SCHEDULING

A variety of scheduling methods are adopted for construction projects. Kenely and Seppanen (Kenley and Seppanen 2009) proposed a typology for scheduling methods in which they distinguish between scheduling techniques based on the approach used to model the construction activity. CPM and PERT are classified as activity based scheduling techniques whereas the location based techniques are

distinguished based on the emphasis on unit or location production. Location based methods focus on continuity of work through various units for the project. While for unit production methods emphasis is on achieving a steady production rate for repetitive units, Flowline scheduling falls under the location production category where the emphasis is instead on completing the work sequentially in various physical locations. The unit production methods do not discriminate between individual units and hence lack the flexibility to manage projects where each unit is different and where completion order of individual units is a constraint. In contrast, the Flowline scheduling method focuses primarily on work being performed in individual locations.

To model work being performed in individual locations, the Flowline method relies on information about quantities, crews, and productivity for different construction processes for each location. Flowline method adopts a location breakdown structure (LBS) to keep track of information for the individual locations. The durations for the activities within each location are then derived based on these basic inputs and the resources assigned to these related activities are modeled to "flow" between various locations. This flow of resources is modeled using a single "Task". The notion of the Task is a powerful construct as this allows for rapid modeling of repetitive work however such constructs are missing from the CPM technique. Modeling of task continuity as a basic feature is another powerful feature of the flow line methodology which cannot be modeled using the CPM approaches. Figure 1 represents a Flowline view of a schedule showing various continuous and non-continuous tasks.

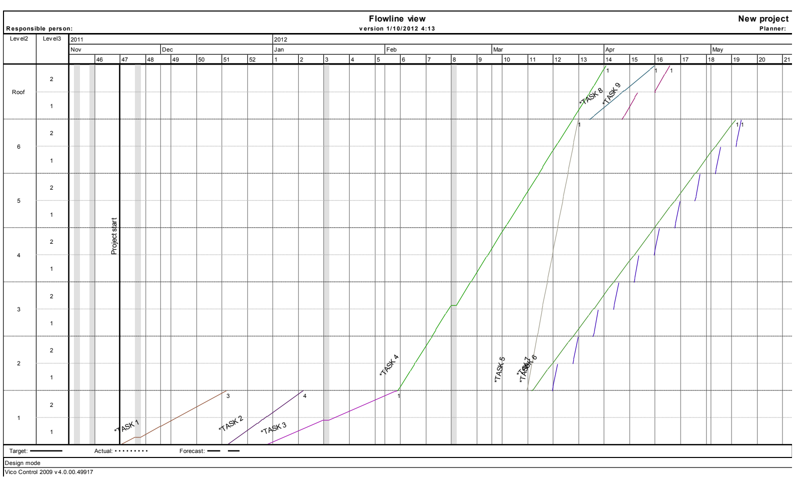

Figure 1. A Flowline schedule generated using Vico ® Control 2009 Software showing various continuous and non continuous tasks scheduled in various locations for the project.

SCOPE AND METHODOLOGY

A case study based methodology has been used to explore the use of Flowline scheduling as a visualization tool. The case study was conducted from an owner's perspective where the owner would like to shield itself from added costs due to inefficient scheduling. No productivity or resource data was available for the complex technical activities comprising the project. The CPM based schedule for only a part of the project was transformed into a Flowline based schedule without logic links between tasks. Only a part of a single work package was considered to demonstrate the power of the visual representation. The transformation was more of a "sketch" on a Flowline view as opposed to being a complete Flowline schedule. In the context of Flowline scheduling, such sketch modeling is akin to a simple bar chart based representation of a portion of a CPM schedule (no links between tasks). To simplify the modeling, the start and finish dates for each task were computed using the start date of the first constituent activity and the finish date of the last constituent activity. Each task being modeled here is carried out by a crew dedicated for that task alone.

CASE: FABRICATION/INSTALLATION OF OFFSHORE PLATFORMS

Project Background. The project under study involves fabrication of platforms and jackets on-shore and transporting them off-shore and installing in various oil fields, presenting a scenario of repetitive activities for a large number of units. All the platforms are similar if not identical and are taken up in batches of 10 or 15. The platforms are of the same design and are repeatedly fabricated and installed at different locations. The variation for units arises due to the topography of the seabed for the offshore fields as different locations in the fields may require a different length of legs for the jacket (base) of the platform.

Off-shore projects being unique, acquisition of resources (such as marine vessels) is not only costly but very difficult. This makes workflow continuity imperative i.e after installation of one platform, installation barge should move on to the next platform without any discontinuity. Further, off-shore operations, unique as they are, are always subject to weather delays, and other logistical constraints such as ongoing drilling activity in the vicinity.

For the particular project presented in this study, fabrication of platforms is carried out on-shore in a fabrication yard usually three or four at a time in order to maintain the continuity for off-shore installation. The yard is laid out with four bays and the layout is such that each facility is set up in one location. Designated crews (manpower and Equipment) for tasks like Pre-fabrication, assembling and erection move from one location to another. It is important for these crews to move with minimum conflict and idle time. Moreover, since they perform same activities at different locations, improvement in their learning profiles and enhanced productivity is expected with the continuity of work. However, productivity data is either not kept or is mostly with the contractor and is not available to an owner for any analysis.

Acquiring off-shore resources, as mentioned earlier is a logistical nightmare. These resources are booked years in advance and once acquired keeping them busy is another daunting task. Standby costs are usually in six figure US$ per day if continuity is not maintained. In case the continuity cannot be maintained or the work

runs into the weather risk window, additional mobilization and de-mobilization costs are incurred that are enormous.

In such situations, facilities are released in batches of 5 or 6, so that installation of these facilities can be accomplished in one campaign. This puts a lot of pressure on the on-shore fabrication activities as many activities have to go in parallel. In such a scenario, a planning approach that focuses on the efficient usage of the critical and costly resources and reduces idle time and that recognizes the repetitive nature of the tasks being undertaken would be apt for the project under study. It also becomes imperative to select a scheduling technique that not only gives better overview like identifying inefficiencies but ensures work flow continuity which would also lead to productivity improvement due to repetitive task being undertaken. However, due to the dominance of activity based scheduling techniques, the contractors typically rely on CPM based schedules which do not support any of these desired capabilities.

Constraints and Objectives. Since this study is being presented from a Client's perspective, the aim is to effectively manage and control the release of work packages (sets of oil platforms for fabrication and installation). The focus of the owner is on efficient utilization of the off-shore resources like installation barge and associated vessels with minimum standbys and avoidance of multiple campaigns by maintaining continuity of facilities installation. In addition to the off-shore challenges, difficulties arise when the on-shore activities get ahead of the off-shore installation. The next-to-be-installed platform is loaded on to a barge as soon as it is ready and shipped out to sea just in time. Any early completion of the platform would result in a fabricated platform sitting on a barge waiting to be shipped out. Any synchronization issues there result in substantial additional costs per day for the idle barge borne by the owner.

The fabrication and installation schedule for the platforms is driven primarily by the drilling schedule for the offshore oil fields which represents an external constraint. This drilling schedule is fairly dynamic and any changes in the drilling plan can have serious ramifications for the scheduling of on-shore activities. Although all platforms are virtually identical, the jackets are quite variable and hence the activities related to the jackets are presented here.

Use of flowline for schedule visualization. The master schedule for the project is built by the contractor using the Oracle ® - Primavera ® scheduling software which uses the CPM approach. Activities for the fabrication and installation of steel jackets for one work package (consisting of four jackets) were considered. Individual activities from the CPM schedule were grouped into tasks and were consolidated such that each task represents the time window in which its constituent activities are scheduled. Figure 2 shows the Flowline sketch for the selected activities where roughly 500+ CPM based activities are shown as around 100 tasks. Although these tasks represent the work as continuous, the activities which make up these tasks are not necessarily scheduled to be continuous in the original master schedule. The tasks can be seen with varying slopes which indicates that the production rates for individual tasks were not considered by the contractor while scheduling these tasks.

Each of these tasks is carried out by a specialized crew that moves on to the next work package when released. The activities on the top represent the off-shore activities as indicated by the LBS and can be seen as fairly streamlined.

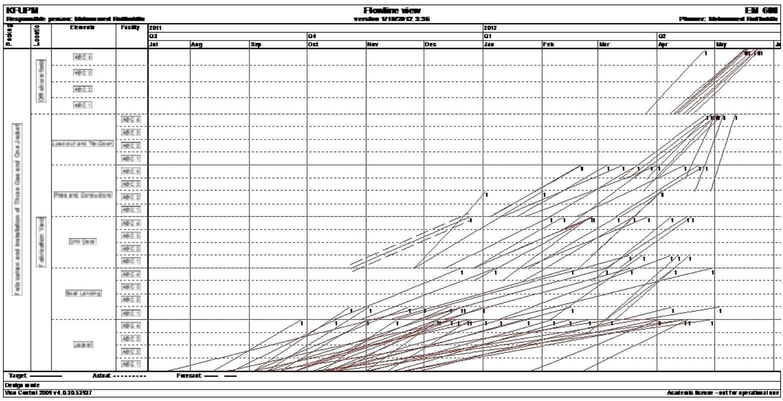

Figure 2. 100 Tasks representing around 500+ activities and the 300+ logic links that CPM based schedule uses to ensure sequential progress for related activities. Off-shore installation activities are shown on the top right corner.

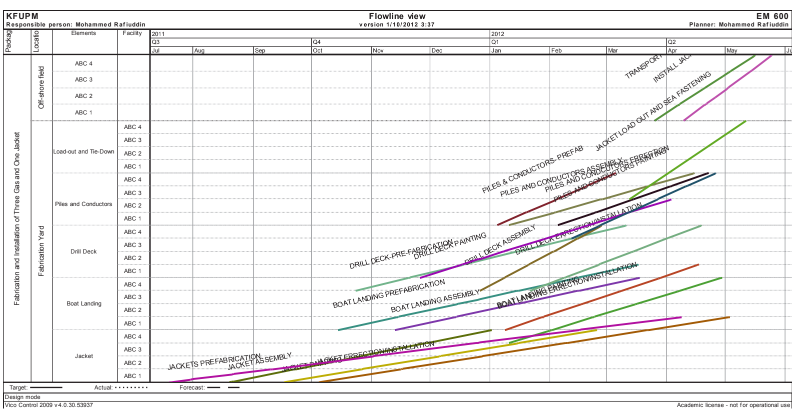

Figure 3. 19 Summary Tasks representing the activities for the Jackets for four facilities. Off-shore installation tasks are the last three tasks shown.

The schedule, as shown in Figures 2 and 3, represents substantial inefficiencies in the form of idle time for crews and inconsistent productivity for different crews. In addition, many tasks are intersecting representing potential time-space conflicts. Figure 4 visually represents the time zones in which the owner would incur substantial additional costs for any delays or accelerations. Identification of

these potential time space conflicts (Figure 2, 3) is difficult using the CPM view of the schedule. The Figures are essentially a graphical layout of "time windows" for the tasks (without any productivity related information) yet these views convey information beyond what a CPM representation can show utilizing the same information.

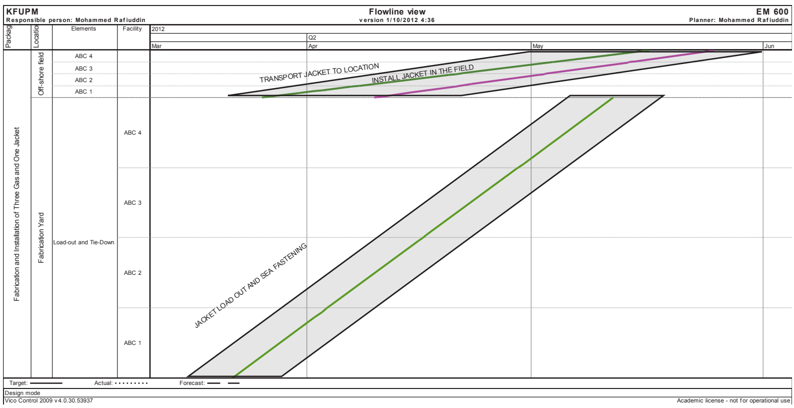

Figure 4. Manually highlighted time zones around the offshore and directly related onshore activities indicating time periods where the owner can incur extra costs

DISCUSSION

The case presented here highlights the use of the location based tools as a schedule visualization mechanism for owners involved in high stake repetitive projects. The owner can use the sketches to identify potential of performance shortfalls by the contractor without any access to the detailed execution plans or productivity rates. The Flowline view consolidates the CPM schedule and is a very powerful communication tool. Although the emphasis of the study was to identify potentials for the owner is to maximize utilization of offshore resource, its visible from the Figures above that the on-shore activities carry substantial inefficiencies that can potentially de-rail the laid out plans by the owner. The drilling schedule can be used as a milestone in the Flowline schedule and tasks can be scheduled towards that milestone. The owner can use the information to strategically release work packages to avoid weather risk periods and to limit the number of campaigns needed for a work package.

CONCLUSIONS

This case study presented here was performed from the perspective of an owner. The study recognizes the difficulties owners face in getting access to Contractor productivity data and the detailed execution schedule. Hence the scope of

the study was limited to the proper utilization of the more costly and scarce off-shore resources through visualization of the timing of on-shore & off-shore activities. Equipped with additional analyses of the existing data, the owner can decide to strategically release work packages and minimize the owner's exposure to costly delays and accelerations.

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An Expert System for Construction Decision-making using Case-Based Reasoning

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ABSTRACT

During the early stage of a construction project, decision-making happens frequently due to the decisive effect to the whole project. It is necessary to compare with actual data of other projects because every construction project is unique. For this, a decision-maker utilizes mountains of solution which can be collected from other projects. Case-based reasoning, which is the process of solving new problems based on the solutions of past experiences, is widely utilized for decision-making of construction project. This research suggests an expert system for decision-making of construction project using case-based reasoning. To verify the method, this research utilized the model which was built and case studied based on Korean military barrack projects.

INTRODUCTION

During the early stage of a construction project, decision-making happens frequently due to the decisive effect to the whole project. It is necessary to compare with actual data of other projects because every construction project is unique. In this respect, an expert system, which is a computer system that emulates the decision-making ability of a human expert, has been studied and utilized many times over the past years (Jackson, 1998).

What ultimately determines the success of the expert system is how knowledge of specific areas to formulate and program. However, it is very difficult to represent expert knowledge because it has many possibilities for errors. Because the

human thinking process to solve a problem is complex and unwieldy, it is hard to store expert knowledge in the system. In this overall perspective, various methodologies which can mitigate these problems have been considered to be an important subject in expert system.

In order to solve the problem, a decision-maker utilizes mountains of solution which can be collected from other projects. Case-based reasoning, which is the process of solving new problems based on the solutions of past experiences, is widely utilized for decision-making of construction project.

The present paper deals with the problems regarding how convert expert knowledge to the system. In order to approach the problems from a different angle, this research suggests an expert system for decision-making of construction project using case-based reasoning. To verify the method, this research utilized the model which was built and case studied based on Korean military barrack projects.

PRELIMINARY STUDY

Expert systems. An expert system, which is one of the applications of artificial intelligence, is a interactive computer program incorporating judgment, experience, rules or thumb, intuition, and other expertise to provide knowledgeable advice about a variety of tasks (Gasching, 1981). By using expert's knowledge and problem solving process, expert systems are designed to solve any problem currently solved. Expert systems have many useful features when compared to human expert. They are permanent, easy to transfer, easy to document, consistent and affordable (Waterman, 1986).

An expert system consists of two main components: the knowledge base and the inference engine. The knowledge base is the collection of facts and rules for decision-making. The inference engine is the part of the system that decides which facts and rules to apply when trying to make a decision (Waterman, 1986).

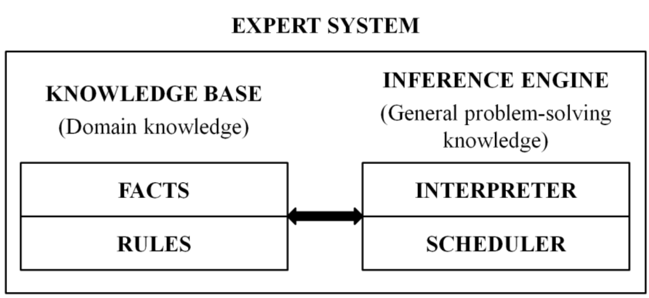

Figure 1. The structure of an expert system (Waterman, 1986).

Case-based reasoning. Case-based reasoning is a problem solving approach that it utilizes solutions of past experiences to solve problem. A new problem is solved by finding a similar past case, and reusing it in the new problem situations (Aamodt, 1994). Case-based reasoning contains two main assumptions, which are that similar problems have similar solutions and once happened problem tends to come about again (Watson, 1994). It is widely utilized in the construction field such as construction design, decision making, scheduling and cost estimating, which need to consider past experiences and knowledge.

Case-based reasoning may be described by the following four processes; 'the four REs' (Aamodt, 1994).

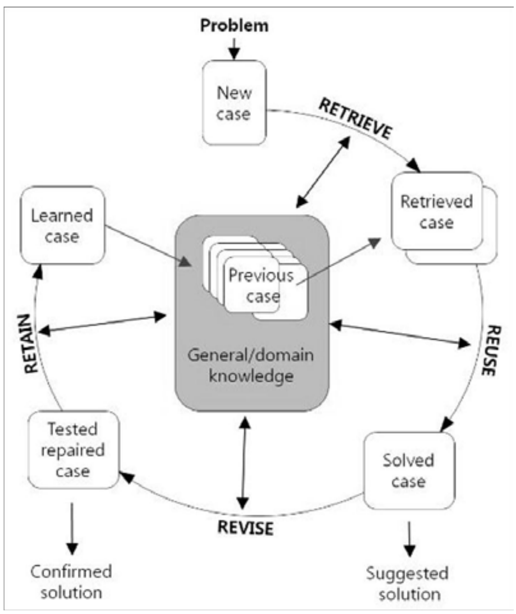

Figure 2. The Case-based reasoning cycles (Aamodt, 1994).

- RETRIEVE the most similar case.
- REUSE the knowledge in that case to solve the problem.
- REVISE the proposed solution.
- RETAIN the part of this experience for future problem solving.

GA-CBR Model. The previous researches in this laboratory suggest case-based reasoning cost models utilizing genetic algorithms (Ji et al. (2009) and Park et al. (2010)). The dependent variable (estimating target; cost, duration, etc.) of a specific case can be formulated by appropriately weighting its attributes.

$$C_i = X_{i1}W_1 + X_{i2}W_2 + \cdots + X_{ij}W_j \tag{1}$$

where, C_i : the dependent variable of *i*th case
X_{ij} : the value of *j*th attribute of *i*th case
W_j : the weight of *j*th attribute

When this relationship is expanded to a set of general cases, it is described by the matrix formula below.

$$\begin{pmatrix} X_{11} & \cdots & X_{1j} \\ \vdots & \ddots & \vdots \\ X_{i1} & \cdots & X_{ij} \end{pmatrix} \times \begin{pmatrix} W_1 \\ \vdots \\ W_j \end{pmatrix} = \begin{pmatrix} C_1 \\ \vdots \\ C_i \end{pmatrix} \tag{2}$$

In order to make a range of weights from 0 to 1, assuming that all attributes and the dependent variable are normally distributed, they are converted to a standard cumulative normal distribution.

$$\begin{pmatrix} x_{11} & \cdots & x_{1j} \\ \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} \end{pmatrix} \times \begin{pmatrix} w_1 \\ \vdots \\ w_j \end{pmatrix} = \begin{pmatrix} c_1 \\ \vdots \\ c_i \end{pmatrix} \tag{3}$$

where, c_i : the dependent variable of ith case (standardization), $0 \leq c_i \leq 1$
x_{ij} : the value of *j*th attribute of *i*th case(standardization), $0 \leq x_i \leq 1$
w_j : the weight of *j*th attribute, $0 \leq w_j \leq 1$

Attribute weights are optimized to minimize the sum of the absolute value of the distance by genetic algorithms.

$$\begin{pmatrix} c_1 \\ \vdots \\ c_i \end{pmatrix} - \begin{pmatrix} x_{11} & \cdots & x_{1j} \\ \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} \end{pmatrix} \times \begin{pmatrix} w_1 \\ \vdots \\ w_j \end{pmatrix} = \begin{pmatrix} d_1 \\ \vdots \\ d_i \end{pmatrix} \tag{4}$$

optimizing w_j for $\min \sum_{k=1}^{i} |d_k|$

where, d_i : distance of case *i*th

Similar cases are retrieved from the database by utilizing attribute values and attribute weights. By calculating this, the dependent variable of a target case is estimated.

This method can attain reliable results based on genetic algorithms. However, calculation time is longer than other methods such as gradient descent method and multiple regression analysis.

EXPERT SYSTEM USING CASE-BASED REASONING

Various reports have been published on the expert system over the long period of time. However, there have been few studies on the combination of expert systems and case-based reasoning. In the expert system which is proposed in this research, the four-RE cycles for case-based reasoning works as a logic for the inference engine. The knowledge base is composed of the expert weight and the case library. The sets of attribute weight, which is reflected the expert's thought for decision-making, are stored in the knowledge base for the expert system. Additionally, previous cases which include problems and solutions are also stored in the system.

Process of the expert system using case-based reasoning. Figure 3 shows the process of the expert system using case-based reasoning. In order to solve the present problem, a user input building information to user interface. Based on expert weights, similar cases are retrieved from case library and the solution of similar cases are proposed for present problem. If necessary, the proposed solutions are modified and repaired. Finally, the solution of the present problem is retained as a new case in case library for future problem solving. The process of case-based reasoning is divided into two main parts of the expert system and the user interacts with the expert system by using user interface.

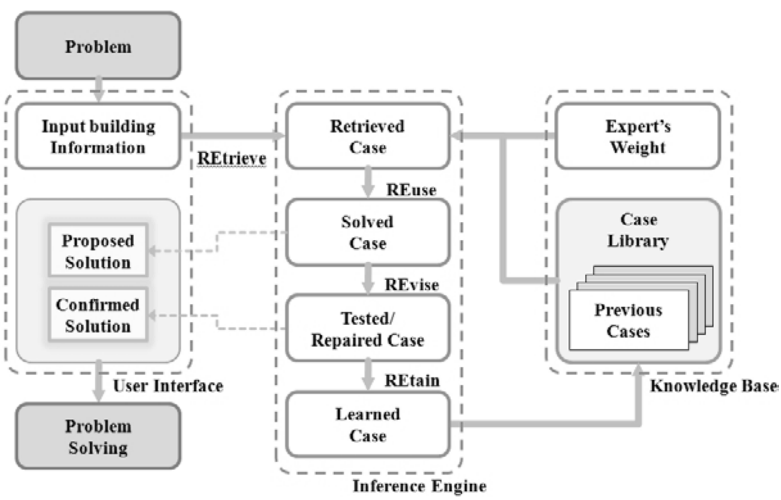

Figure 3. The process of the expert system using case-based reasoning
Method of Calculating Expert Weight

In order to apply expert knowledge to the system, a nearest neighbor of each case will be set up by experts. The decisions will be based on the expert's past experiences and his specialized knowledge. Attribute weights are calculated by using weighted Euclidean distance as follows.

$$d_i^{(w)} = \left[\sum_{j=1}^{n} w_j^2 \left(x_{pij} - x_{qij}\right)^2\right]^{\frac{1}{2}} = \left(\sum_{j=1}^{n} w_j^2 x_{ij}^2\right)^{\frac{1}{2}} \quad (5)$$

where, $d_i^{(w)}$: the weighted Euclidean distance of *i*th case
w_j : the weight of *j*th attribute
x_{pij} : the value of *j*th attribute of *i*th original case
x_{qij} : the value of *j*th attribute of *i*th solution case

Attribute weights are optimized to minimize the sum of the weighted Euclidean distance by genetic algorithms.

$$\text{optimizing } w_j \text{ minimize for } \sum_{i=1}^{m} d_i^{(w)} = \sum_{i=1}^{m}\left(\sum_{j=1}^{n} w_j^2 x_{ij}^2\right)^{\frac{1}{2}} \quad (6)$$

Through this process, expert knowledge is modeled as combinations of attribute weights. It is stored in knowledge base and utilized for retrieving a similar case in case-based reasoning.

CASE STUDY: KOREAN MILITARY BARRACK PROJECTS

Experiment design. The validation of the model was executed to examine reliability using data of Korean military barrack projects. In the total of 115 cases, 10 test cases were selected using simple random sampling and remaining 105 were used to make case library. These are used to feature counting model, multiple linear regression analysis model, the GA-CBR model (Park, 2010), and the model based on this research. It is assumed that the suggested model can be improved in terms of accuracy when comparing average absolute deviations of accuracy rate are relatively lower than another one. Stability of the model can also be examined by comparing standard deviations of absolute deviations.

Data analysis. The cost data of Korean military barracks projects were distributed from 2005 to 2008. In order to remove errors due to time, all the cases were normalized to year 2008 with the historical cost index (KICT). Four attributes were extracted by interviewing experts and its weights were calculated as follows. In the feature counting model, all the weights of attribute had a same value (0.2500). In the multiple linear regression model, regression coefficients were used to weight values and they were calculated by SPSS statistical program. In the GA-CBR model and the suggested model, GA software, Evolver 4.0 was used to find the optimal weights. Conditions for optimization by genetic algorithm are as follows. Initial population is 50, mutation rate is 0.1, crossover rate is 0.05 and stopping condition is that trials reach 5,000,000. In the suggested model, average of weights which were extracted

by ten experts was used. The attributes weights which were calculated by these methods are listed in Table 1.

Table 1. Calculated attribute weight values.

Attribute	Expert System	Feature counting	MRA	GA-CBR (Park, 2010)
Capacity	0.0326	0.2500	0.0021	0.0055
Number of Floors	0.0153	0.2500	0.0840	0.0335
Gross Floor Areas	0.8996	0.2500	0.7317	0.9453
Building Areas	0.0524	0.2500	0.1822	0.0171

Results and discussions. The results are drawn from Table 2. Although it is slightly different depending on individual case, the proposed model was resulted in an overall lower absolute deviation. However, standard deviation of absolute deviations was resulted upper than the MRA model and the GA-CBR model. These results represent that the suggested model is improved in terms of accuracy, nevertheless, in terms of stability; the model needs to be improved.

Table 2. Calculated attribute weight values.

(absolute deviation, %)

Case	Expert System	Feature Counting	Multiple Regression	GA-CBR (Park, 2010)
1	12.8	28.3	12.4	4.4
2	12.8	5.1	12.6	10.5
3	5.3	14.3	7.2	2.6
4	18.9	17.0	18.9	18.9
5	0.8	11.1	9.3	9.3
6	12.9	3.2	10.3	16.0
7	6.2	7.8	6.2	6.2
8	11.2	4.0	11.2	11.2
9	0.8	6.1	11.0	5.2
10	9.5	51.6	11.9	13.0
Avg.	9.1	14.8	11.1	9.7
S.D.	5.8	15.0	3.5	5.2

CONCLUSION

This research has attempted to establish the new methodology for expert systems using case-based reasoning. It reflects the expert's opinion to retrieve similar case. This new methodology applies case-based reasoning to expert systems and it can be named 'case-based expert system'. To verify the method, this research utilized the model which was built and case studied based on Korean Barrack projects. It is shown that accuracy is improved compared to the existing models, however, stability

left lots of room for improvement.

This research lays the foundation for future work on the case-based expert system. As the research is limited to cost estimating for Korean Barrack projects, applying to other kinds of decision-making problem and building projects should be required. Moreover, improving stability by applying other methods is necessary. It will be developed by applying expert classification which can give importance between experts.

ACKNOWLEDGEMENTS

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Cognitive Design of Learning Modules for Field Management Education

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ABSTRACT

This paper presents the use of experts' knowledge for design of field management instruction. Learning scenarios and supporting tools are developed through cognitive analysis of construction superintendents. In particular, a safety supervision tool was designed to simulate jobsite conditions and aid learners' decisions. By providing a robust context, higher education construction students are presented with an opportunity to practice decision making and observe the existing relationships of the domain. This helps students to understand how their knowledge fits into the big picture of field work before they step into a jobsite.

INTRODUCTION

In this research, cognitive analysis is used to support the design of educational modules for field management. The purpose is to improve the effectiveness of instructional content delivery. A safety supervision module is presented in this paper to describe the process of bringing experts' knowledge into instructional tools. The topic of safety was selected given its impact on project performance. The pedagogical objective of the module is to evaluate safety of construction operations given particular jobsite conditions.

The safety module is being implemented through a tablet PC application created specifically for this project. This system is designed to support learners' decision making in a simulation of actual jobsite conditions. Through these learning tools, students are exposed to knowledge that is integrated in the context of a realistic environment of practice.

In this way, students can observe where their skills fit in the job. For example, scheduling is usually taught as a standalone activity, and its relationship to other jobsite activities is difficult to grasp. In the richer context of this exercise, scheduling is used to control the results of field supervision and provide input for work planning, both before and after performing supervisions. In contrast to lecture settings, applicable concepts and information are presented in a way that responds to work requirements. Such organization of information inherently expresses the function of information in the project.

In order to document superintendents' mental models of work, a technique of cognitive analysis called Applied Cognitive Work Analysis (ACWA) is used (Elm et al. 2003). Mental models account for the relation between actual work activities,

decisions and information dimensions that superintendents find necessary to complete their work successfully. These dimensions are embedded in learning tools that guide students' attention to the aspects of work that impact the outcome of the exercise.

The next section of this paper reviews aspects of expertise in the context of field management education. Following sections describe the methodology for using cognitive analysis as input for the safety module and then the resulting design after using such methodology. Afterwards, a discussion is presented on the application of this module in existing educational settings. The last section presents final conclusions.

BACKGROUND: ACQUIRING EXPERTISE

According to Klein and Militello (2005), expert practitioners have mental models of how the primary causes in the domain operate and interact. They have a sense of typicality allowing them to recognize familiar or typical situations, know a large set of routines, and have perceptual skills for making discriminations and detecting problems. As noted by Clark (2008), experts "see" with different eyes and have the ability to represent problems in a manner that leads to effective solutions.

Developing expertise requires extensive practice. For field managers, expertise is acquired through thousands of hours at the jobsite. Previous to having such practical experience, there is little opportunity for novices to observe the impact of their decisions at work and develop the thinking skills necessary for job performance. In this sense, traditional field management education would benefit from a context to practice decision making that can increase practical knowledge before graduation.

Identification of relevant aspects of the job from cognitive analysis methods, make it possible to develop supporting tools and scenarios for education. These instructional components can bring learners closer to the development of their mental models of the work. The feasibility to develop cognitive analysis for construction field managers and use the results of analysis for evaluation of information tools (O'Brien et al, 2011) speak for the viability of this methodology.

METHODOLOGY

Development of this research was conducted in three parts. The first part concerns the identification of the relevant aspects of work. These aspects include work objectives, decisions and information concerning jobsite safety, as available in three ACWA studies of construction superintendents (details available in Mondragon and O'Brien (2011)). In the second part, the structure of the learning scenario is determined, based on the aspects of work previously identified. The third part consists of determining the functionality and information content of the supporting learning tools. Once the work aspects and the structure of the scenario have been defined, it is possible to focus on development of supporting tools.

LEARNING MODULE DESIGN

Use of ACWA. Figure 1 shows a Functional Abstraction Network (FAN), which is a product of ACWA that represents the relationships between work objectives and mental processes. This figure includes a detailed view of three boxes, called goal-process nodes, related to safety supervision. Figure 1a shows that one of the objectives of work is to maintain field safety and that the process to attain this goal includes performing safety supervisions in the field. Figures 1b and 1c show objectives that support safety supervision, such as supervision of field work and update of schedule documents.

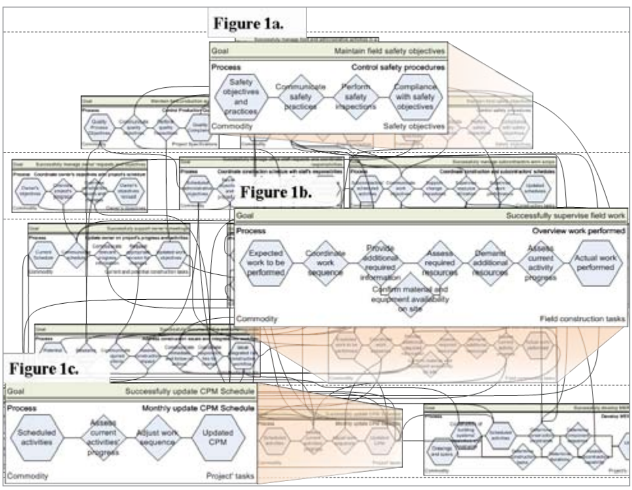

Figure 1. ACWA's FAN diagram showing a superintendent's work objectives and associated processes

Table 1a.

CWR-G4.1 Monitor recurrent safety issues
IRR-G.4.1.1 Compliance with safety program objectives IRR-G.4.1.2 Safety coordinators attaining objectives IRR-G.4.1.3 Continuing safety trends …

Table 1b.

CWR-P12.5 Monitor workers' safety practices with respect to safety requirements for each activity and the project
IRR-P12.5.1 Safety trends and recurrent issues for current work conditions IRR-P12.5.2 OSHA specifications for the task IRR-P12.5.3 Work procedures for the task IRR-P12.5.4 Job Hazard Analysis IRR-P12.5.5 Capacity to complete schedule …

Table 1c.

CWR-P13.1 Monitor subcontractors' capacity to complete tasks on schedule
IRR-P13.1.1 Start dates in CPM Schedule IRR-P13.1.2 Finish dates in CPM Schedule IRR-P13.1.3 Expected manpower for activity IRR-P13.1.4 Actual manpower for activity IRR-P13.1.5 Site space available for activity …

Table 1. Examples of Cognitive Work and Information Requirements related to each section of Figure 1

Decisions and information related to safety are contained in the list of cognitive work and information requirements. This list is developed for each node and indicates the decisions that are necessary to engage in each process and attain each goal. Similarly, the information requirements determine the information that is necessary to make each decision. Table 1 shows some of the requirements that correspond to each of the goals in Figure 1. These requirements are about a quarter of the total number for each box, however they are representative of the safety-related information needed in each instance.

Development of the learning scenario. In a real jobsite, superintendents are responsible for safety of field activities. Having knowledge of safety regulations allows them to detect and mitigate unsafe work conditions. Similarly, the safety module is set up for students to develop such background knowledge, then use this information to assess a set of construction operations, and finally take the information gathered from construction tasks and use it to update their control documents. Thus, students are expected to learn basic construction safety requirements before doing the exercise. Then, a specific jobsite scenario is provided for students through a set of documents and tools.

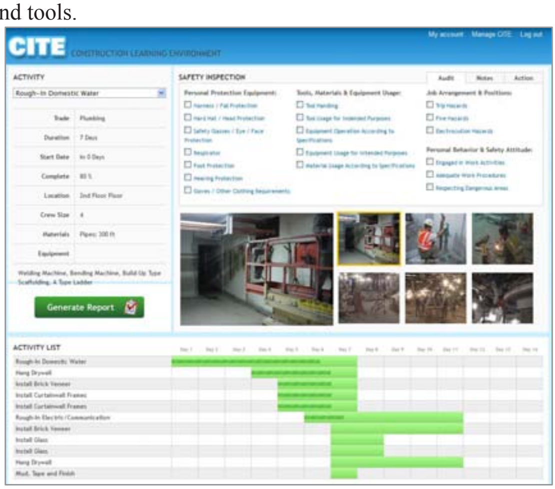

Figure 2. Screenshot of the computer-based system developed for safety inspection

Information corresponding to background knowledge and jobsite scenario is determined by IRRs. In the case of background knowledge, safety requirements are related to OSHA standards, and can be easily accessed through different resources available on the internet. In the case of the scenario, information must be determined by the instructor. For example, IRRs indicate that crew size, space availability, and start/end dates of the activity are relevant for assessing safety conditions (Table 1c). The instructor can develop the scenario by adding values to each dimension. Those values allow for a large number of possible results. In this case, authors developed a scenario consisting of ten construction tasks in a commercial building undergoing

interior work. Details for each task included specific crew size, materials, durations, and other information indicated in the list of IRRs.

Development of supporting tools: Tablet PC system. The scenario is presented to students through different documents and tools. As part of the pre-exercise information, students are provided with a schedule, a floor plan, latest safety trends, and a table of details for each of the tasks in the schedule, such as resources, materials or crew sizes, as was explained in the previous section.

The tablet system is primarily concerned with jobsite activities that are occurring in present time. The simulation consists of a set-up of sensors spread through a building, each of which represents a construction task for a project. Sensors interact with the tablet PC to present users with changing jobsite conditions over time. The application interface shows textual information from nearby tasks and multimedia content to represent safety practices for each task. Also, the interface contains input controls that allow the user to make decisions regarding problems with safety practices. The scenario conditions during the simulation are presented through multimedia content in the tablet system.

Figure 2 shows a preview of the safety application. The left box contains information for the activity that is being evaluated. Such information provides a description of jobsite conditions that are important for safety practices, such as crew size, equipment and material usage, and trade; a schedule can be found below, providing additional information. The right box contains options for performing safety audits for each activity. Groups of options are available for evaluating jobsite conditions, together with images and videos corresponding to nearby activities. Figure 3 shows possible actions that can be taken to address safety issues.

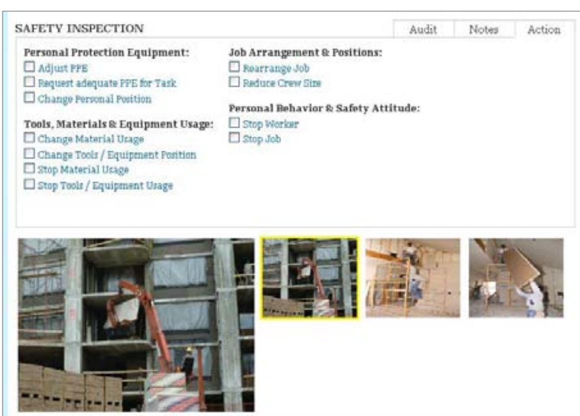

Figure 3. Options included in the safety application for addressing safety issues

Figure 4. Report provided by the safety application

The information content in the application's interface is taken from required information found in ACWA results. Each relevant dimension is added a value, or a set of values, to provide content to the interface. For example, options for safety audit decisions (figure 2) and action decisions (figure 3) respond to a specific information requirement (see IRR.-P12.5.2 in Table 1c). They are also based on actual safety audit forms used in commercial construction sites. In this way, students are given the opportunity to perform cognitive work inspired by realistic information availability.

Module deployment. The simulation itself is meant to have a duration of 30-60 minutes. Prior to the simulation, students are expected to develop some background knowledge on detection of unsafe jobsite conditions, as well as actions to mitigate these conditions. Students are provided with documentation for reference regarding task safety inspections, pre-task safety planning, and safety regulations. Going through this material should not present a problem to higher education engineering students.

The workflow of the exercise consists in walking around the simulated jobsite, approaching each sensor and obtaining the information for a task. Then, students evaluate the multimedia content for each task. Once this is completed, a report can be generated to provide students with a summary of the conditions found and the decisions they made. Figure 4 shows a sample of the report obtained after evaluating a drywall hanging task. The content of the report is then used to update the construction and safety trends in the final section of the module.

DISCUSSION

Cognitive design of learning modules is a useful approach to encapsulate a realistic job context in which students can apply their knowledge. Other educational

approaches have been used for the same purpose of providing students with a real life scenario, or background, for problem solving. In classroom settings, Problem-Based Learning has been applied with experiential learning objectives. In work settings, apprenticeship programs have been developed to guide novices through initial stages of work; a particular method, known as cognitive apprenticeship, can be used to decrease time required to develop expertise. In the rest of this section, it is discussed how the cognitive design approach can enhance other educational methods by improving the presentation of job dimensions.

PBL is developed around a meaningful ill-structured problem that does not have a single correct answer. A scenario is provided for students to work on a solution. They are expected to put their knowledge to use and be self-directed learners (Hmelo-Silver, 2004). The latter assumption plays an important part in successful learning outcomes of PBL, as problems and scenarios are not detailed. Students are expected to make sense of a critical condition and determine what is relevant to the problem and what potential courses of action are. This poses a limitation to the development of a mental model of the domain. Cognitive-based learning modules have the potential to aid this situation. The context made available, as well as the tools used in the modules, inherently reflect some of the domain's relationships. This is knowledge that is not always available, even to self-directed learners. And this type of support is compatible with the presentation of a single critical problem

Cognitive apprenticeship is an approach to training where problems and learning aids are developed based on cognitive task analysis of practitioners in the domain. Using this knowledge, learning occurs in the context of actual work under the guidance of a live or automated mentor, as with a real apprenticeship, but inefficiencies of real apprenticeship are reduced by instructional control over the type and sequence of problems (Clark, 2008). For example, by using real routine problems and cognitive models for different levels of expertise, Gott and Lesgold (2000) found viable to reduce the amount of time necessary for learners to attain the performance level of experts. In this case, learning modules can also aid in presenting information for the users. Scenarios and instructional tools can guide learners through initial actions of the domain. This has the potential to simplify the development of cognitive apprenticeship programs, as they may reduce the need for guidance from the mentor.

CONCLUSIONS

Cognitive analysis studies can provide practitioners' knowledge and expertise in a way that is useful input for several aspect of instructional design. The development of learning tools is of particular relevance to transmitting the structure and relationships of the domain to learners. While there is much knowledge at high abstraction levels, artefacts and supporting documents are at the front of delivering instructional content. Therefore, it is important to carefully design these in the context of actual job activities, in a way that shows the reason for their usage and contents.

Developing a mental model like that of the superintendents takes time and practice, but presenting students with a model of the job relieves the difficulty of developing the model by themselves. There is an opportunity to include this type of

learning modules in higher education curricula, as well as professional training programs. The relationships made available through scenarios and tools enhance the development of cognitive skills of expert practitioners.

Future work on this module requires deployment and evaluation of usability and learnability. Additional modules will be developed to present students with more objectives of field management, as opposed to strict safety supervisions. As suggested by the results of cognitive analysis, it is important to increase the interaction between users and the opportunities to practice communication of relevant information.

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Using a Virtual Gaming Environment in Strength of Materials Laboratory

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ABSTRACT

Imagine a student in a materials lab pressing a switch to begin a tension test on a steel specimen. For a few moments nothing appears to happen. Suddenly, with a loud bang, the specimen breaks and the test is over. Now imagine the student pressing the backup button and watching as the two halves of the specimen are magically reconnected. The student chooses to repeat the test but this time, knowing where things get interesting, the student chooses to view the test in slow motion so they may observe the transition from elastic deformation to inelastic deformation and the necking down of the specimen before it fails. Clearly, this is not your father's Tinius-Olsen machine. This student is using a simulated testing environment that offers safe and inexpensive learning opportunities. This paper demonstrates the effectiveness of using 3D games-based virtual lab simulations in the Strength of Materials Lab for Civil Engineering students. Virtual lab characteristics such as easy access to the information, visualization, and simulation capabilities allow auditory, visual, and kinesthetic learning environments to emerge. The effectiveness of this approach is measured using quantitative and qualitative analysis and compared to student performance in the traditional physical laboratory.

INTRODUCTION

Given the high cost of Strength of Materials laboratory equipment and the large class sizes, most universities cannot afford to set up multiple versions of the same experiment. The rapid emergence of new technologies and the finite useful lifetime of existing equipment add to the continuous need for replacements. Virtual labs utilize small computer applications that are available for free; therefore, virtual labs can cost "virtually nothing".

The games-based virtual 3D simulations of engineering laboratories improve learning, reduce costs, and improve access to the course. By leveraging cyber learning and innovative visualization techniques, the virtual laboratory experiments allow learners to explore engineering phenomena in new ways that are not safe or cost-effective in physical, real-world laboratories. Such virtual learning environments go beyond computer lab simulations by creating a more immersive environment that places the students "inside" the experimental setup.

The immersive learning experience has been shown to foster creative thinking in students. This type of thinking leads to higher rates of achievement in all areas of study. Creativity tests in the USA, using Torrence's Creativity Test (CQ test), have shown a steady decline in creative thinking in USA students (Bronson 2010). Creative thinking is a result of divergent thinking that is then synthesized into convergent thinking, where one narrows down multiple possibilities, and chooses the one with the best possible outcome. Called Bi-lateral Mode, this type of thinking has been proven to happen more often in creative thinkers. Low CQ results in recent tests confirm reports in neuropsychology that youth today learn differently as a result of their lifelong exposure to digital interfaces. It is important that educational models be created that support and engage student learners in a way that parallels the way they learn with new technologies.

There is a wide, fascinating, and growing field of research in the use of computer games in education (Malone, 1980). Video games are a significant cultural influence and are useful in improving design strategies (Good and Robertson, 2004; Knudtzon et al., 2003), enhancing and motivating learning (Denis and Jouvelot, 2005) and (Steiner et al., 2006), and increasing the success of job skills training (Greitzer et al. 2007). While traditional educational environments and institutions may fail to properly motivate and situate learning, utilizing best practices of psychology and motivation theory, games-centric learning environments offer potential to meet the needs of competence, autonomy, and relatedness to enable students' success (Denis and Jouvelot, 2005). Research also shows that some video game players of certain game types achieve better scores in critical thinking, strategy development, and problem solving tests than non-players (Malone, 1980).

Most undergraduate engineering students can be categorized as Digital Natives, which are people who have been exposed to digital interfaces and digital games since birth. Neuroscientists indicate that neural pathway development has changed in modern persons more dramatically than any time in history since humans first learned to use tools (Small & Vorgan, ed. Bauerlein, p. 2). Digital natives have sharpened cognitive abilities and are adept at rapid information processing by reacting to visual stimuli (p.12). Researchers have shown also that people respond to the idea of learning via a "game" differently depending on whether they played games (specifically video games) while growing up or not (Zyda, 2005, p. 25). One goal of the virtual lab is to appeal to digital natives' embrace of learning through games. In 2002 the release of the game America's Army proved to benefit both recruiting and field training for the US armed forces. While the entertainment aspect of that game was its initial goal, the pedagogical impact it had was significant to the Army's needs. The term "serious games" has been used to describe gaming projects similar to this virtual lab. Serious games, "involve pedagogy: activities that educate or instruct, thereby imparting knowledge or skill" (Zyda, 2005). Researchers show that there is substantial evidence that game experiences affect digital-game natives positively and the effects will benefit society as a whole. The Strength of Materials Virtual Lab embodies this concept fully. Future iterations are slotted to include detailed animations/movie clips showing the potential results of failed tests. This will add to the gaming nature of the program, appealing to digital natives, while fully retaining the pedagogical structure and outcomes.

Neuroscientists have also identified that creative and expressive aesthetics facilitate emotional engagement and creative thinking. Furthermore, focusing on specific visuals using "expressive cues" during audience engagement isolates attention while stimulating emotional cues with specific aesthetics such as color, texture, focal points, etc. (Power, 2009). Since emotion drives attention, the interface helps to create and link between gestalt oriented recognition (gestalt referring to the creation of meaning as defined by a combination of memory, attention and emotional response) and interest with the users. The gaming and motion picture industries have been at the forefront of 3D graphics and responded to these research findings in the past decade. These industries have taken a turn away from purely naturalistic/realistic representation of reality and now embrace expressive, simplified, fluid and theatrical rendering in entertainment. The reason for this is the overwhelming evidence that expressionistic and abstracted visual displays translate to clearer context and a more meaningful experience with the story or game (Power, 2009).

Zeki (2008) states that a type of creative play offered in an environment such as this stimulates imagination and "invites participation in constructing meaning" (p. 115). In a pedagogically focused game interface, this is accomplished through the infrastructure of the developers, (in this case the three areas of research our team come from), the cognitive design of the game, and the immersive aspect of engagement (Zyda, 2005). The mimetic nature of this type of learning environment is designed to be semi-realistic. Instead of extensive realism, simplification of the visual environment increases attention and focus, and becomes an invitation for investigative learning (Terzidis, 2008, and Powers, 2009).

Virtual laboratories have been developed in a number of engineering and scientific disciplines such as geotechnical engineering (Arduino et al. 1999 and Budhu, 1999), triaxial testing (Budhu, 2000), and instructional control (Bhandari and Shor, 1998). Some virtual laboratories use two-dimensional schemes of the engineering laboratory (Arduino et al. 1999; Bhandari and Shor, 1998), while others used Virtual Reality Modeling to simulate a real laboratory (Budhu, 2002). (Kukreti et al. 2002) developed two-dimensional computer simulations of Strength of Materials course laboratory materials. Now there is a significant opportunity to incorporate more interactive, immersive 3D simulations to invigorate engineering education and make learning more engaging. Current graphics and programming technology enable more sophisticated virtual modeling with broader appeal to undergraduate engineering students.

With the games-based virtual labs, we are guided by the motivation theory associated with games in education and how this influences learning. Inspired by Malone's assertion that challenge, fantasy, and curiosity are the keys to making a game fun (Malone, 1980), we see a significant correlation between these ideas of what makes a game fun and what makes a motivating, empowering, and successful games-based curriculum of study.

This virtual game lab interface is designed to stimulate investigation, allow for exploration of the objects involved in the test, and creates alternative outcomes from inaccurate measurements (in later versions). In this virtual lab, the concepts of visual stimulation, emotional engagement, and creative play work in unison to

provide a virtual gaming environment and stimulating pedagogical experience that ultimately fosters creative and critical thinking.

VIRTUAL STRENGTH OF MATERIALS LABORATORY DETAILS

The Virtual Laboratory is an interactive environment of 3D objectives for creating and conducting simulated experiments. The 3D objects are composed of different formats and include text, colors, sound, images, shapes, animations, video, and graphics. Many options are available when utilizing computer based virtual simulations. We can customize the virtual lab experience to the instructor's preferences and highlight specific key points. While many different laboratory exercises can benefit from the use of virtualization, this paper discusses two Strength of Materials laboratories:

Tensile Test	Various "unknown" materials can be tested to see how they react when tension is applied; based upon the deformation of the material when it is pulled, the student can determine the type of the material. Any type of material can be simulated and tested.
Torsion Test	Various materials and interconnection types can be simulated; as various torsional forces are applied, the student can examine the elasticity, yield sheer strength, ultimate sheer strength, and how the materials rupture.

The 3D lab simulation has three different views – namely, the lab view, the data view, and the report view.

The Lab View was created to provide the user with: 1. general information about the test which includes (a) importance of the test and the expected learning outcomes (b) step-by-step instructions on how to conduct the test (c) how to use the virtual program. 2. Selecting and setting up a specimen in the testing machine. 3. Application of loading 4. Observation of results 5. Guiding the interpretation of gathered data 6. Providing feedback throughout the testing.

Two types of materials have been used, A36 structural steel and T6061 Aluminum. After selecting the material student will have to use the virtual caliper to measure the specimen diameter and length. Following the identification of the specimen type and shape, the user is guided to set up the test specimen in the testing machine by dragging the specimen to its final location and tightening the grip's screws and bolts into their correct position. Once this is accomplished satisfactorily, the user begins the test by adding loads incrementally or continuously. The user has the option to indentify the various parts of the apparatus by virtually touring and walking in the room, zooming in and out on specific parts of that particular piece of equipment, or watching the demo video prepared for this purpose. Furthermore, in this view, students can position a virtual camera to examine spaces within the machine neither possible nor safe in a real laboratory. A student could easily focus on key pieces of the apparatus by pressing a "take me there" button. The 3D version has the ability to focus on specific, close-up views of key parts of the lab setup and can determine whether the test was set up accurately and correct any misalignment of

materials. Additionally, the calibration of measurement instrumentation is just as in the real world laboratory. The Lab views of both torsion test and the tensile test are illustrated in Figures 1 and 2.

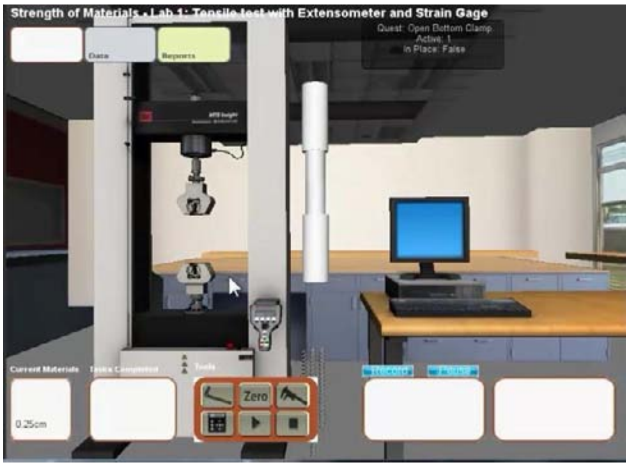

Figure 1. Lab View – Tensile Test

Figure 2. Lab View – Torsion Test

The Data View automatically records the test results in a table format and gives the user the option to graphically plot the results in XY scatter. This allows the user to observe the relation between stress and strain and easily distinguish the elastic region and the plastic region. As the results are being recorded in the data view, the student can watch the test running on a small window as shown in Figure 3.

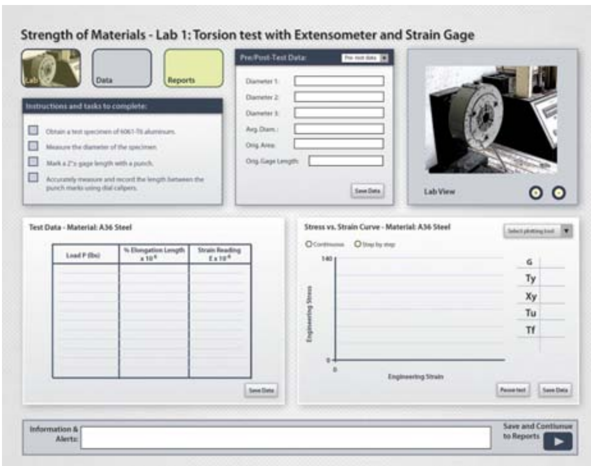

Figure 3. Data View

The virtual laboratory allows for measurements to be gathered even in cases where an experiment was not properly set up, so students can learn from both their successful or improper lab experiments. Furthermore, our virtual lab allows for random error factors that fall within the range of acceptable experimental error as not all experiments should produce the same results, but results should be within an acceptable range of values.

The user can observe a summary of the results in the Report View as shown in Figure 4. A guide is provided to help the student to interpret the results and do all the necessary calculations. The user has the option to save the results in a txt file. Students can use Excel to open the txt file and use the saved results to plot best-fit curves and analyze the results. The outcome of this analysis can be compared to properties of known materials, and a student will be able to identify what materials were used in the experiments. In the tensile test, a user is expected to calculate the modulus of elasticity, the yield stress, the ultimate stress, and the fracture stress. Modulus of rigidity and the yield shear stress are the main output of the torsion test.

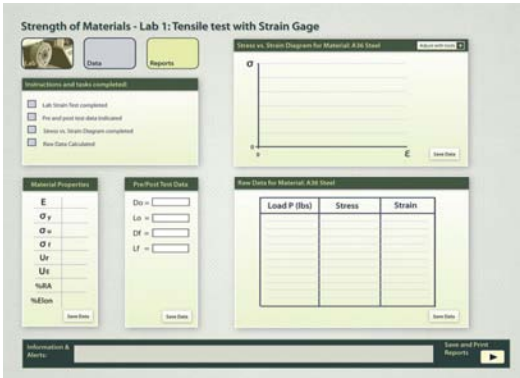

Figure 4. Reports View

CONCLUSION

3D Virtual Strength of Materials Laboratory and other virtual laboratories provide a number of benefits to students by increasing accessibility to the lab experiments (virtually unlimited); eliminating most lab testing material costs; providing more 'hands on' experience in seeing the physical results of often abstract data play out in a virtual animation; affording multiple scenarios and views of the materials tests that would otherwise be inaccessible to students in the lab as well as giving much needed unique and advanced experience to engineering students. Aesthetics has a direct effect on emotion, instinctive responses to activities, and positive and negative reflection on a situation. For educational experiences, this is an important factor in maintaining not only attention and interest, but can ultimately affect retention rates in programs like engineering. Peaking interest and total time spent on learning engineering in these virtual environments will play a role in the overall achievement of engineering students. This ensures a head start in the global engineering market, and makes available more financial and educational benefits and opportunities.

AKNOWLEDGMENT

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Developing 3D Safety Training Materials on Fall Related Hazards for Limited English Proficiency (LEP) and Low Literacy (LL) Construction Workers

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ABSTRACT

Construction has been one of the most dangerous industries, with fall being the most common type of hazards. Meanwhile, about one fourth to one third of the industry's taskforce is composed of Hispanic workers, many of whom lack proficiency in English, and/or have limited literacy. Limited literacy and lack of English proficiency are not specific to Hispanic workers and serve as critical barriers in effective safety education and training. The paper presents the developmental efforts and lessons learned of six 3D visualized and scenario-based training case materials that use minimum amount of text descriptions. Common cases that involve construction fall hazards from the National Institute for Occupational Safety and Health (NIOSH) Fatalities Assessment and Control Evaluation (FACE) program were analyzed and modeled in a 3D video game platform referencing the effective training strategies from Occupational Safety and Health Administration (OSHA). Using 3D simulated virtual job sites in safety training is expected to reduce the required level of language proficiency and literacy, and increase the understanding as well as learning interests of those in construction who can't speak or read much English.

INTRODUCTION

Occupational safety is imperative in construction. In the U.S., there are more than 1,000 construction work-related fatalities each year (BLS, 2009a). Construction has historically been one of the most dangerous industries in the nation, with fall being the most common type of hazards that caused occupational injuries. Falls accounted for the largest number of fatalities in construction in 2004 contributing to approximately 36 percent of all fatally injured workers (BLS, 2004). This statistic has not significantly improved with falls contributing to 34 percent of the fatally injured workers in construction in 2009 (BLS, 2009b). These statistics have supported numerous efforts made over the years to develop and deliver training programs specific to fall protection.

Meanwhile, the demographic distribution of construction workers now includes about 25% to 35% (Platner, 2011). Hispanic workers are calling for safety training materials to be available in Spanish as well. However, a quick look at

OSHA's fall protection website for construction revealed the scarcity of such resources. Merely translating training materials developed for English-speaking workers into Spanish is not sufficient to make them useful for the Hispanic/Latino construction workers (Evia, 2011), because many of these workers have limited literacy in Spanish as well as in English (Ruttenberg and Lazo, 2004). Therefore, in addition to low English proficiency, lack of literacy is another critical barrier in effective safety training and is an issue that extends beyond the Hispanic group to include a larger constituent of the workforce (Wallerstein, 1992). In addition, adult educators are often unprepared to deal with adult literacy issues (Lytle *et al*, 1992). The *use of visual aids* and *the facilitation of peer discussion* during training have been recommended when developing and delivering safety training to Limited English Proficiency (LEP) and Low Literacy (LL) construction workers (Ruttenberg and Lazo, 2004). These two strategies are also advocated by OSHA as the best practices for working with LEP or LL construction workers.

In an effort to (1) recognize the fall hazards, (2) promote safety training among LEP or LL construction workers, and (3) expand the implementation of the above-mentioned training strategies, the authors obtained a one year financial support from OSHA to develop 3D visualized and scenario-based fall protection training cases for the construction industry. As the project is still an ongoing effort, purposes of the paper are to introduce the developmental process for the training case materials and to highlight issues encountered when modeling the cases. Although the materials developed target particular groups of construction workers, the materials can be broadly adopted to engage all learners in the recognition, avoidance, abatement, and prevention of fall-related safety and health hazards.

SELECTION OF CASES

Tapping onto the existing resources, real-world examples of fall related accidents from the National Institute for Occupational Safety and Health (NIOSH) Fatality Assessment and Control Evaluation (FACE) program were chosen for the training case development. Each FACE example comes with the background information about the reported fatal accident, investigation report describing the accident, accident prevention recommendations, and sometimes images or graphs of the accident location.

Several criteria were considered for the initial selection of these FACE examples. The *first* selection criterion considered was the most common locations where fall hazards usually take place. Although a fall could happen at almost any locations, even at the ground level (due to floor openings or bad housekeeping on site), roofs, ladders, and scaffolds were identified as the three most common "hazardous locations" that should be addressed in the training materials. Inputs from two research-participating subject experts further reinforced the validity of the criteria. The *second* selection criterion was typical fall-triggering hazardous scenarios associated with working on roofs, ladders, and scaffolds. For example, over-arching or improper positioning are typical scenarios that make workers fall from ladders. The *third* selection criterion was the construction trade that takes up a higher proportion of fall fatalities among the targeted workers. For example, the five most widespread occupations of Hispanic construction workers are roofers, carpenters,

drywall installers, ironworkers, and painters (BLS, 2009a). Selecting cases to reflect typical work activities (e.g. using a ladder to paint the interior of a structure) engaged by these trades would make the developed training materials more relevant to targeted populations.

After looking into the recent fall related examples from the NIOSH FACE program and applying the three case selection criteria, the authors were able to narrow down 15 candidate examples as displayed in Table 1. To diversify the training materials, cases that represent different job set-ups (e.g. extension ladder versus A-frame ladder) were further identified for the final six cases, as indicated by the asterisks next to the case number in Table 1.

Table 1. Candidate NIOSH FACE Fall Fatality Examples

No.	Location	Activity	Scenario
1*	Pitched roof	Roofing	Toe-board break
2*	Roof opening	Removing roof panels	Stepping backward on a roof opening covered only with insulation
3	Roof edge	Installing plywood sheeting	Slipping
4	Roof edge	Helping roofer	Trying to prevent a bundle of shingles from sliding off a roof edge
5	Roof opening	Roof repairing	Stepping on an exposed ceiling tile
6	Extension ladder	Ascending the ladder	User slipping off the ladder
7*	Extension ladder	Attaching wood block	Over-reaching
8*	Extension ladder	Doing touch up painting and installing roof tie-downs	Ladder tip over
9	Stepladder on a rolling scaffold	Drywall finishing	Scaffold rolling
10	Step ladder	Window Cleaning	Worker working backwards on ladder facing window, ladder tipping
11	Job-made elevated work platform	Framing	User slipping
12*	Wheeled scaffold	Hanging sheetrock on a wall	Scaffold moving back and victim losing balance
13	Scaffold plank	Carrying debris from roof to truck through scaffold plank	Slipping
14*	Top stage of a tubular scaffold	Painting	Slipping off unsecured boards on scaffold
15	Scaffold	Bricklaying	User improper positioning

PAPER PROTOTYPING AND TESTING

Before the authors devoted full resources to the development of the training cases, one NIOSH FACE case (case #7 in Table 1) was prototyped on paper, as an example, for feedback and for informing the development process. The example was about a worker attaching a wood block to a balcony ceiling on top of a step ladder. The balcony was located adjacent to a trench and the worker slipped, falling 10 feet off the ladder into the trench and had a fatal head injury. Additional assumptions such as the time pressure and nearby tools (either appropriate or not) to help get the job done were made to enrich the example. Figure 1 shows the original prototype in a six grid comic style. The prototype also contains two learning assessment questions that are not displayed in Figure 1.

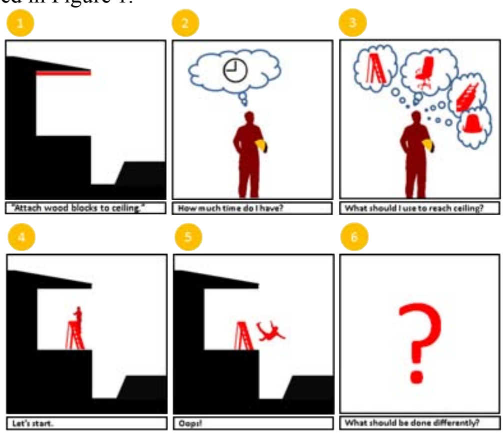

Figure 1. Prototyped NIOSH FACE Case for Evaluation

The paper prototype was evaluated in two focus group sessions, each last between 35 to 40 minutes with the participation of a subject expert and two targeted workers. In each session, a subject expert would first walk the recruited workers through the prototype in a mock-up training delivery fashion and then ask the workers what they like or dislike about the prototype. As the prototype mimics the logic and highlights of the full developmental effort, working with a focus group as such helps obtain feedback from the potential audience and confirming their learning styles as well as preferences. The evaluation also helps verify the logistic requirements (e.g. the sequence of training points to be crossed) for safety trainers. Specific lessons learned from the paper prototyping and testing are discussed below and Figure 2 displays the revised NIOSH FACE example prototype after the focus group evaluation.

First of all, the lesson learned is to avoid trivial information and to simplify the modeled work activity in order to gain clarity. Although NIOSH case information about the modeled work activities derived from the NIOSH FACE cases is sufficient to develop training scenarios, not enough detail is available from these examples to fully disclose the activity specifics. For example when walking through the paper

prototype, workers participating in the focus group sessions had quite a few questions about why the wood block had to be attached to the ceiling and what the dimensions of the wood block were. These uncertainties could be disruptive to the training and can be avoided by making the work activity very straight forward. For this reason, the activity “attaching a wood block” was revised into “changing a light bulb” during case development without changing the key learning objectives.

Secondly, the dimensional perspectives have to be included in the case. It is essential to build in the dimensional perspectives about the work set up (e.g. height of the ceiling) for workers and trainers so that they can visualize and identify the potential fall hazards. This could be achieved by spelling out the specific dimensions or, in a more subtle way, by providing a point of reference in the modeled cases (e.g. placing a six foot ladder on the working platform). For the same reason, construction tools, equipment, or materials should also be graphed in accordance to their relative sizes. Therefore, understanding the work practices and having a common sense about the feel and look of construction tools (e.g. a six foot ladder comes with 5 rungs because the typical spacing between ladder rungs is one foot), equipment (e.g. outriggers for tall mobile scaffolds to maintain the scaffold stability), or even materials are important to the successful modeling of the training cases.

Thirdly, it is favorable to mix in safety culture assumptions such as the pressure to get the project completed or supervisor’s attitude toward safety to enrich the cases and intertwine with the modeled work activity. Although the original prototype has touched upon the issue of safety cultures at a couple of places, additional assumptions would be appreciated. This will help present the cases in a non-linear way and encourage peer discussion during training delivery.

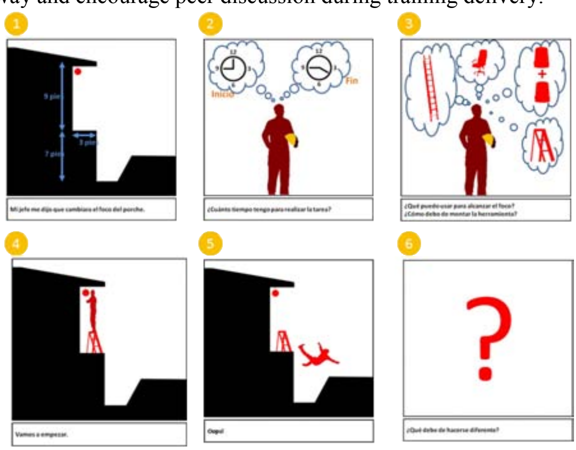

Figure 2. The pictorial prototype for the revised NIOSH FACE case

METHODOLOGY FOR THE PICTORIAL PROTOTYPING

A formal methodology for using a NIOSH FACE case to develop a pictorial prototype has been defined by the authors based on the procedures and lessons

learned during paper prototype testing. Pictorial prototypes, such as the one represented in the figure 2, can then be used as a starting point for 3D modeling. The methodology encompasses 10 steps as explained below.

First in step 1, the description of the case to be modeled is extracted from the case source for review. This includes the background information about the case, investigation detail that describes the process in which the case happened, accident prevention recommendations, and sometimes images or graphs of the case location. Then in step 2, a long description of the case is developed based on the information provided by the case source. The long description includes all the detail (e.g. dimensions, materials used, or tools adopted) important for the pictorial prototyping and 3D modeling. In step 3, after the initial two steps, the expert feedback is sought after to make reasonable assumptions when ambiguities reside in the long description. This step is optional and can be waived in situations where the development team is aware of all aspects of the fall fatality case to be modeled. In step 4, learning objectives, both generic and trade-specific, are defined. In step 5, the scenario to be modeled is largely established, based on the long description of the case, expert feedback (if any), and defined learning objectives. In step 6, assumptions about the case are made in terms of the physical dimensions of the job set up, types of the materials or tools used, and safety culture. In step 7, testing questions relevant to the learning objectives are determined for learning outcome assessment. In step 8, a short description of the case is developed to accompany the pictorial prototype and eventually the 3D model for the trainees so that only minimum amount of reading is required. Also in this step, the pictorial prototype is drafted to narrate the story of the case graphically. In step 9, the case along with its long description, learning objectives, assumptions, assessment questions, short description, and figures are presented to the subject experts for final evaluation and comment. Lastly in step 10, the case is revised and finalized based on experts' feedback from step 9.

The pictorial prototype produced by the above mentioned methodology facilitates the 3D modeling by providing the modeler with snapshots of the events that have actually happened over the case and thus, the 3D models can be created based on a shared understanding of the case among the project participants. In this way, only a part of the 3D modeling is left to the imagination and interpretation of the 3D modeler.

THE 3D MODELING PROCESS

The popular game development platform, Unity, has been chosen to develop the cases' 3D models for its capability to deploy on multiple platforms, compatibility with many 3D rendering tools, affordable platform and library object cost, relatively lower demand of hardware resources, well documented user manuals and developer forums, and ease of use. The research assistant for the project was able to learn about the platform from scratch, create and load a simple 3D structure into the platform, plug in a 3D mechanical valve previously developed by using Google Sketch-Up, add in a simple interactive function into the platform, and finally publish a web application of the model all in 2 days without exercising much programming skills. Figure 3 shows the preliminary 3D modeling output for the tested prototype.

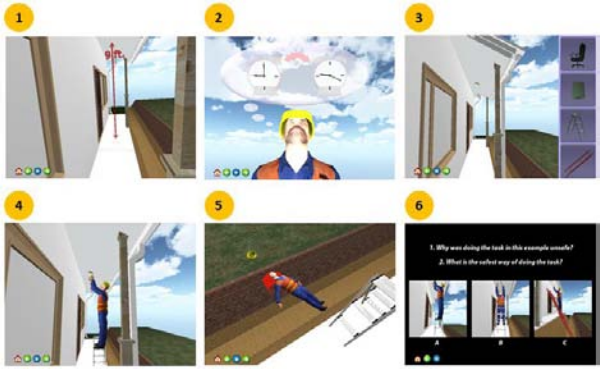

Figure 3. Screen shots of the preliminary 3D model for the tested prototype

Although the 3D modeling process just commenced, it encountered some issues that require special attention. The first and foremost issue is the hand-off of case information between the pictorial prototype development and 3D modeling. The pictorial prototypes provide the background information and specific dimensions for the on-site set ups but they do not describe the color, textures, shapes and sizes of remaining tools, equipment, or materials. The pictorial prototype is also not meant to illustrate the surrounding environment and thus creates a fuzzy boundary that needs to be clarified in the 3D modeling process. As the pictorial prototypes are prepared in the 2D format, the 3D viewing aspects (e.g. from what angle should the job set up be presented and what are the transitions between the different view angles) are lacking and need to be further determined during 3D modeling.

CONCLUSION

Construction has historically been one of the most dangerous industries in the nation, with fall being the most common type of hazards that caused occupational injuries. It is therefore not hard to understand why a significant number of fall protection training materials and efforts have been continuously developed over the years. Meanwhile, about one fourth to one third of the industry's taskforce in the U.S. is composed of Hispanic workers, many of whom even have limited literacy in Spanish. To this end, not only low English language proficiency but also lack of literacy are critical barriers to effective safety education and training. Effective training strategies for LEP and LL construction workers are the *use of visual aids* and *peer discussions*. The authors secured one-year OSHA funding for developing visualized and scenario-based fall protection training materials, which would support the first training strategy. Focus groups and training pilot sessions are planned as a part of this project to control for the effect of using visual aids on the occurrence of peer discussions.

Many real examples of fatal fall incidents were selected from the NIOSH FACE dataset and then narrowed down to six cases that will be developed into a 3D environment. Prior to the 3D development, a paper prototype was created and tested

to help layout the methodology for defining the cases. As a result, a 10-step working process was established to guide the pictorial case development, which upon completion provides fundamental case information for the 3D modeling process. The use of a paper prototyping for exploration and testing was an invaluable experience for the project. Although the 3D modeling process just commenced, the authors have learned that the hand-off of case information between the pictorial prototype development and 3D modeling is not as complete as expected and still requires additional communication and coordination. It is envisioned that after one of the cases is fully modeled in 3D, existing methodology for creating the pictorial prototype will be further modified to support specific information needs of the 3D modeling process and inform others in the research community who are also interested in 3D visualized training and education material development.

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Simulation of the Policy Landscape of Transportation Infrastructure Financing Using Agent-Based Modeling

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ABSTRACT

The existing deteriorating condition of infrastructure systems in the U.S. needs to be improved by expanding innovative financing options. In this paper, a hybrid agent-based/system dynamics model is created to simulate the micro behaviors of the players (namely, the state Departments of Transportation, private institutional investors, and the general public) in this financing process, and aggregates the effects of these micro behaviors on infrastructure investment at the state and national levels. Results of the simulation model are used in a classification and regression tree meta-model to (1) simulate the landscape of infrastructure financing policies and (2) identify the most significant factors affecting the level of investment in transportation infrastructure. The reliability of the conceptual model, the computer simulation, and the data were verified and validated by subject matter experts from organizations heavily involved in infrastructure financing. The model is further validated through sensitivity analysis and uncertainty propagation analysis. The results of the model include the creation of landscape of policies and the identification significant factors affecting transportation infrastructure financing in the U.S. A scenario analysis is implemented and recommendations, including potential policy paths to close the financing gap, are provided based on the simulation results and the policy landscape.

INTRODUCTION

According to the American Society of Civil Engineers (ASCE), $2.2 trillion is required to improve the near-failing condition of infrastructure in the U.S. (ASCE 2009). Thus, there is a significant need for financial innovations to address the current need. The key to successful expansion of financing innovations is sustainable policymaking based on assessment of the dynamics of infrastructure systems (Mostafavi et al. 2011 a). The objective of this paper is to present a model created for simulating the micro-dynamics of investment in transportation infrastructure. The model was created using a hybrid agent-based (AB)/system dynamics (SD) approach. The results obtained from the simulation model based on Monte Carlo

experimentation were used to simulate the policy landscape of the transportation infrastructure investment. The simulated policy landscape was used to identify the significant factors for increased infrastructure financing and scenarios which lead to eliminating the existing financing gap.

RESEARCH BACKGROUND

There are many factors (e.g., economic conditions, public attitudes, political priorities, and business and market dynamics) that affect investment in infrastructure. While formulating policies related to infrastructure financing, policymakers often overestimate some factors and underestimate others (Mostafavi et al. 2012). Many researchers have recognized the limitations of the traditional ex-post methods (e.g., statistical approaches) in capturing the complexity of public policy analysis and management. Such models do not capture the complexity of policy problems, competing values, emergent behaviors, interdependencies, and uncertainties (Pfeffer and Salancik 2003). These issues can be addressed using complex systems simulation models which facilitate understanding the probable macro patterns of a system based on the micro behaviors of its adaptive components. Such models (so-called ex-ante analysis) facilitate considering various probabilities and possibilities to provide a set of "robust" solutions across different parameter values, scenarios, and model representations (Bankes 2002). Expansion of innovative financing for infrastructure is affected by the activities of and interactions between various players in the process, such as the federal government, local agencies, private organizations, and the general public (Mostafavi et al. 2011 b). These players are managerially and operationally independent and adapt new behaviors as they learn from their environment over time. Thus, assessment of the activities and interactions of the players in policy analysis requires complex systems simulation (ex-ante analysis).

SIMULATION MODEL AND DATA

An Innovation System-of-System (I-SoS) framework (Mostafavi et al. 2011c) was used to guide the creation of a model for micro-simulation of the dynamics of investment in infrastructure. The *context* of the analysis focuses on the transportation sector in the U.S. The *levels* of analysis include sub-national (local) and national, which means that the players, interactions, and factors within and across the local and national levels were considered. The *categories* of innovative financing policy considered in this paper include those policies which expand private investment, debt financing, and pay-as-you-go financing in infrastructure. Two sets of data were used to abstract the components of the system. Set 1 includes identification of the activities and institutions of the different players in infrastructure financing, which was extracted from interviews with 15 subject matter experts (SMEs) in the area of infrastructure financing. These experts included personnel from state Departments of Transportation (DOTs), the Federal Highway Administration (FHWA), private institutional investors, and private infrastructure operators and owners. Set 2 includes data regarding the current financing needs, the level of public and private investment, and the level of funding available for investment in highways and bridges. The data include the current debt level of the state DOTs; the level of funding available for

debt repayment by Departments of Transportation; the level of need for highways, roads, and bridges in the states; and the existence and background of implementing public-private partnerships (PPP or P3) in various states. The second set of data was obtained from the U.S. Department of Transportation (USDOT), FHWA, and the American Association for State Highway and Transportation Officials (AASHTO).

A hybrid AB/SD model was created to explore and visualize the effects of different factors such as the probability of successful investment, the financing capacity of public agencies, and the effectiveness of public support, on the level of investment in transportation infrastructure. The model captures the complex micro-dynamics of U.S. transportation infrastructure (i.e., highways and bridges) investment by simulating the micro behaviors of state Departments of Transportation (DOT), private institutional investors, and the general public.

Object-oriented programming and ANYLOGIC 6.6.0 were used to create the computational model. The classes of agents in the model include *Private Investors, State Departments of Transportation,* and *General Public*, each of which is simulated in the model as an object. *Private Investors, State Departments of Transportation,* and *General Public* classes of objects were defined to represent the properties of the agents. The model also includes another active object class called *Infrastructure,* which is not an agent, but which has a SD model related to each state. The purpose for considering an *Infrastructure* object class is to facilitate the aggregation of the outcomes of other object classes at the state and national levels. Fifty objects of the *Infrastructure* class (one for each state in the U.S.) were modeled to aggregate the dynamics of transportation infrastructure financing at the state level, and one object of the *Infrastructure* class was defined to aggregate the dynamics of transportation infrastructure financing at the national level. Figure 1 demonstrates the connection of the data and the variables related to different classes of objects aggregated using the *Infrastructure* object class. Table 1 summarizes the properties of different classes of objects in the model.

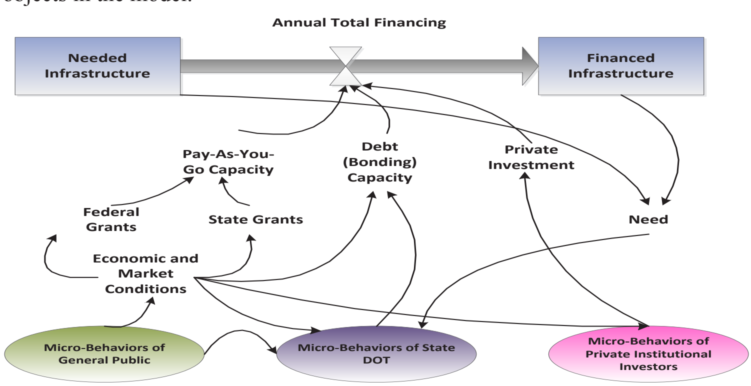


Figure 1. Dynamics of investment in infrastructure systems

$$\textit{Annual amount of investment in infrastructure at year t (\$)} = \frac{d(FinancedInfrastructure)}{dt} = (\textit{pay-as-you-go financing})_t + (\textit{debt financing})_t + (\textit{private investment})_t \quad (1)$$

$$\textit{Annual need for investment in infrastructure at year t (\$)} = \frac{d(NeededInfrastructure)}{dt} \quad (2)$$

$$\textit{Total Needed Infrastructure over the policy horizon (\$)} = \textit{initial value} + \int \frac{d(NeededInfrastructure)}{dt}\, dt \quad (3)$$

$$\textit{Total Financed Infrastructure over the policy horizon (\$)} = \int \frac{d(FinancedInfrastructure)}{dt}\, dt \quad (4)$$

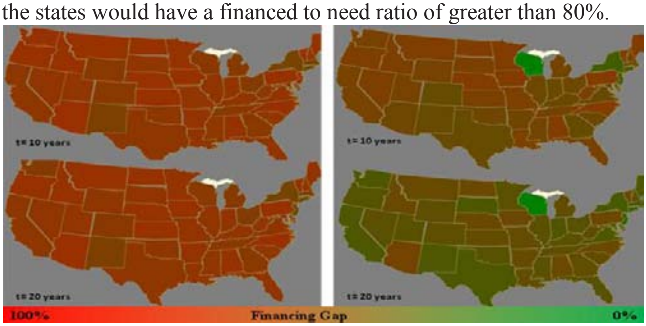
$$\textit{Investment Gap (\$)} = \textit{Total Needed Infrastructure} - \textit{Total Financed Infrastructure} \quad (5)$$

$$\textit{Financed to Need Ratio (\%)} = \frac{\textit{Annual amount of investment in infrastructure at year t}}{\textit{Annual need for investment in infrastructure at year t}} \quad (6)$$

Table 1. Summary of the properties of different classes of objects in the model

Object Class	Type (Number of objects)	Function	Parameters and variables	Examples of decision rules and formulas
Private Investors	Agent (100)	Simulation of the micro behaviors of private institutional investors	●Infrastructure need ●Public support ●Economic conditions ●Probability of successful investment ●Expected return on investment ●Existence of P3 program in a state	●Successful investment increases the probability of a new investment ●Unsuccessful investment reduces the probability of investment ●Signals from other investors affect the probability of investment ●History of PPP projects in a state affect the probability of investment
State DOT	Agent (50)	Simulation of the micro behaviors of state Departments of Transportation	●Current level debt in state DOT ●Level of funding for debt repayment ●Maximum debt capacity ●Debt ratio ●Investment need ●Economic condition	●Issue new debt when pay-as-you-go financing is limited ●The total amount of debt cannot exceed a certain limit ●The debt limit depends on the available funding sources for repayment of debts and debt interest rate
Public	Agent (1)	Simulation of the micro behaviors of the public	●Infrastructure need ●Investment support effectiveness	●Support infrastructure investment if the need is significant; oppose otherwise ●Public support increases the probability of successful investment
State Infrastructure	SD (50)	Simulation and aggregation of the dynamics of infrastructure investment in each state	●Level of pay-as-you-go financing in the state ●Amount of new debt issued ●Amount of private investment	See Equation 1 - 6
National Infrastructure	SD (1)	Simulation and aggregation of infrastructure investment at the national level	●Level of pay-as-you-go financing in the state ●Amount of new debt issued ●Amount of private investment	See Equation 1 - 6

The simulation model provides a tool for visualizing the effects of different financing policies. For example, Figure 2 demonstrates the simulated outcomes of two different financing policies. Figure 2a demonstrates the outcome of a policy that includes no growth in pay-as-you-go financing capacity and a reduction in the size of the U.S. transportation P3 market (15 projects per year – average size of P3 projects = \$200 million) over a 20-year policy horizon in each state. This policy could widen the financing gap; and at the end of the policy horizon, most of the states would have a financed to need ratio of less than 40%. While Figure 2b shows the outcome of a policy that includes a 3% annual increase in pay-as-you-go financing capacity and an expansion in the size of the U.S. transportation P3 market (25 projects per year – average size of P3 projects = \$500 million) over a 20-year policy horizon in each state. This policy could reduce the financing gap; and at the end of the policy horizon, most of the states would have a financed to need ratio of greater than 80%.



(a) (b)

Figure 2. Visualization and comparison of policy outcomes

Sensitivity analysis was implemented to evaluate the changes in the model output (i.e. financed to need ratio at the national level) with variations in the policy input parameters. The volatility of pay-as-you-go financing was the most significant parameter to which the level of financing was sensitive. The variation of the level of investment with respect to changes in the volatility of pay-as-you-go financing is shown in Figure 3.

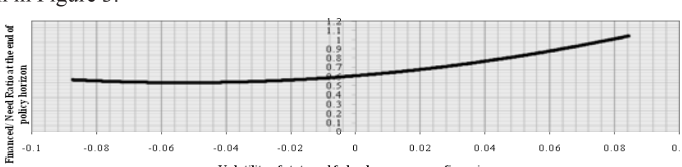


Figure 3. Sensitivity of model output to the volatility of pay as you go financing

ANALYSIS OF RESULTS

Using Monte-Carlo simulation, 2,000 replications of the simulation model were implemented. The simulated data were used for meta-modeling using classification and regression tree (CART) analysis (Breiman et al. 1984). The

simulated policy landscape was investigated to explore the scenarios which lead to a high level of investment. Table 2 demonstrates the identified scenarios which lead to a high level of investment (i.e., financed to need ratio > 1). According to the simulated policy landscape, there are seven scenarios that could be pursued to obtain a high-level of investment in transportation infrastructure (Table 2).

Table 2.Simulated policy scenarios that lead to a high level of financing in infrastructure

Scenarios	Values of Policy Target Parameters				
Scenario I	0% <PAYG financing growth< 3%	U.S. P3 market size < 20 projects per year	Funding for debt repayment growth > 4.8%	Successful P3 investment probability > 65%	
Scenario II	3% <PAYG financing growth<6%	U.S. P3 market size < 20 projects per year	Successful P3 investment probability > 95%		
Scenario III	6% <PAYG financing growth<10%		U.S. P3 market size > 20 projects per year		
Scenario IV	6% <PAYG financing growth<10%	U.S. P3 market size < 20 projects per year	Funding for debt repayment growth > 9%		
Scenario V	10% <PAYG financing growth		U.S. P3 market size < 20 projects per year		
Scenario VI	3% <PAYG financing growth<6%	U.S. P3 market size > 20 projects per year	Average P3 project value > $317 million	Successful P3 investment probability > 98%	Funding for debt repayment growth <10%
Scenario VII	3% <PAYG financing growth<6%	U.S. P3 market size > 20 projects per year	Average P3 project value > $317 million	Funding for debt repayment growth > 10%	

One of the challenges facing infrastructure financing is the reduction of pay-as-you-go financing capacity of the state and federal agencies. The model results would help seeking the scenario that could lead to a high level of financing while pay-as-you-go capacity is limited. Among the identified scenarios that lead to a high level of financing (i.e., financed to need ratio > 1), only *Scenario I* is achievable if the growth in the pay-as-you-go capacity of federal agencies is less than 3% annually. Thus, to obtain a high level of financing in the presence of limited pay-as-you-go capacity, the funding available for debt repayment should be greater than 4.8%, the size of the P3 market should be greater than 20 projects per year, and the probability of successful P3 delivery should be greater than 65%. Similarly, other paths to a high level of investment in infrastructure could be identified using the simulated policy landscape as listed in Table 2.

Using the simulated policy landscape, the significant factors affecting the level of investment could be identified as well. These factors are located in higher branches of the classification tree (i.e., policy landscape). As shown in Table 3, the volatility of state and federal grants is the most significant factor affecting the total level of investment. The size of the P3 market, the volatility of funding for debt repayment, and the probability of successful implementation of P3 projects are the next set of significant factors affecting the total level of investment. In addition, the volatility of state and federal grants is two and a half times more significant than the size of the P3 market for closing the existing financing gap. This result confirms that P3 financing is

not a panacea for the challenges facing U.S. infrastructure investment. Unless the level of federal and state grants is increased, achieving a high level of investment will not be very likely.

Table 3. Significant factors affecting the level of investment in infrastructure

Significant Factors	Score
Growth of federal and state pay-as-you-go capacity	100
U.S. public private partnership (P3) market size (number of project per year)	39.79
Volatility of funding available for debt repayment	21.09
Probability of successful implementation of P3 projects	19.87
Debt ratio (maximum acceptable level of debt in the DOT/level of funding for debt repayment)	17.79
Average value of P3 projects	11.40

VERIFICATION AND VALIDATION

To ensure the reliability of the model, a comprehensive verification and validation process was implemented. The validation process included steps suggested by Sargent (1998) and Pace (2000).

Table 4. Validation scores of the model

V&V Characteristics	Model Features	Average Score*
Conceptual Model Validity	The components of the model represent the most important features of the system	4.2
	The abstraction of the components and interactions in the model is complete	4.2
	The model explains the dynamics of the system	4.6
Simulation Model Validity	The behavior of the components of the model is reasonable	4.6
	The theories and assumptions underlying the model are correct	4
	The model's representation of the system and the model's structure, logic, and mathematical and causal relationships are reasonable.	4.6
Data Validity	The assumptions regarding model's parameters, variables, interactions and decision rules are reasonable.	4.6
	The level of detail and the relationships used for the model are appropriate for the intended purpose	4.6
Operational Validity	The output of the simulation model has the accuracy required for the model's intended purpose.	4.2
	The graphical/animation output of the model is appropriate for the intended audiences	5
	The simulated behavior of the model is reasonable	4.6
	The model could be helpful in the domain of its applicability	4.6

*1: Poor - 2: Needs significant improvement - 3: Needs modifications to be useful - 4: Good enough - 5: Excellent

The reliability of the collected data, the conceptual model, and the computer model were verified and validated by five experienced SMEs from different organizations involved in infrastructure financing (e.g., FHWA, AASHTO, the World Bank, and the Inter-American Development Bank (IADB)). The average length of experience of the SMEs was 18 years. Each validation meeting was face-to-face and two to three hours long. The SMEs assessed whether the simulation results were reasonable and consistent with the expected outcomes. The results of the model validation are summarized in Table 4.

CONCLUSIONS

This paper investigated a new approach for financing policy analysis in infrastructure. A hybrid agent-based/system dynamics model was created to simulate the dynamics of infrastructure financing for policy analysis purposes. Data related to the level of infrastructure investment at the state and national levels were simulated using a Monte Carlo experiment. Meta-modeling was performed on the simulated data to identify the significant factors affecting the total level of infrastructure investment. Growth of the *pay-as-you-go capacity*, the *size of the P3 market*, and the growth of the *funding capacity for debt repayment* were identified as the most significant factors affecting investment in U.S. transportation infrastructure. Policies which enhance these factors could be effective in enhancing the total value of the financed infrastructure. For expanding the bonding capacity of state agencies, innovative sub-sovereign credit-enhancing tools could be used. To expand the size of the P3 market, for example, innovative risk mitigation and contract tools might be considered by policymakers and public agencies. Then, using the simulated policy landscape, the likelihood of pursuing desirable scenarios could be determined.

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Building an Emergent Learning Environment for Construction Health and Safety by Merging Serious Games and 4D Planning

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ABSTRACT

Serious games provide an avenue for people to experience what occurs on a construction site and develop beneficial skills before they enter a live construction site. These tools have traditionally been designed around the assumption of users engaging with preset construction scenarios with the goal of learning specific skills or behaviours that are important when interacting with the site for real.

The construction industry has other tools it can exploit to increase the training value of serious games. 4D and 5D planning and visualisation tools and techniques can help expand the horizons of these types of training games. In particular, by merging virtual training environments with a 4D design ethos, the range of potential knowledge the game can impart would be significantly increased. This research paper is exploring how a cross-pollinisation of these two techniques can yield a richer environment for transferring skills and knowledge. This paper explores the creation of a multi-user virtual environment capable of providing health and safety training and orientation to groups of trainees before they step foot on site.

INTRODUCTION

This paper is proposing the development of a virtual training environment to provide construction managers and trainees with a means to experience Health & Safety issues as they exist on a live construction site. This will be achieved through provide new training tools that are aiming at integrating 4D (3D plus time) modelling technologies with H&S issues that have significant influence on the workers wellbeing and site progress.

The focus of this research is to explore 'serious games' as a solution to improve construction managers and site workers' understanding of construction processes. Serious games or serious gaming refers to the use of computer games technology being used to generate useful tools to solve real world problems. Serous games can provide virtual training involves using computer based tools to create an interactive simulation that can impart knowledge and skills to the user. Commonly training courses are currently focusing on scenario or exercise based learning exercises. In transitioning to a virtual environment new possibilities have opened up in the way health and safety and site training can be conducted that have been insufficiently explored to date.

Many construction companies have the capability to produce their building plans in the format of 3D models, both for site design and use with project management tools like 4D or 5D planning packages. This research was driven by how those existing techniques/tools could be integrated with virtual training environments. The approach that this research is striving to provide is one that is as similar to the construction site experience. Other virtual environments seek to replicate this through optical tricks to increase immersion. The goal here is to achieve that effect through a robust environment that is identical to an actual construction site. Other virtual tools aim for visual immersion, this environment is aiming for spatial immersion.

The key focus of this research is on the application of a common virtual game design framework as part of a health and safety training tool for the construction industry. Previous experts concluded that

there is a distinct lack of examination of game-play elements in the field of serious games (Portnow, Floyd and Theus 2010). This research will explore this further and how it would impact on the design and the pedagogy of serious games through the use of a ‘sandbox’ gaming environment. A sandbox environment is defined in this research as an interactive virtual area where users can engage in activities that are part of the core learning experience and in side-activities that have no direct connection to the core learning experience and serve to enhance the verisimilitude of the virtual environment from the user’s perspective.

With an evolving 3D model the environment can react to site changes to give an accurate view of the site at any moment. With a traditionally designed environment changing the model to react to site changes requires a substantial amount of work remodelling the changed sections of the site. Incorporating this into the design of the virtual environment itself should decrease the work load of implementing schedule based site changes. This can be done by linking the environment to an in-world schedule that will update the construction site to a given date when interacted with. Virtual worlds already contain some of the required infrastructure to perform this function. It is possible to create environments that user can change at the touch of a button. This will limit the 4D applications given that it still requires manual input to update the site and is one of the areas that is being explored for possible improvement. By linking this to a project schedule a planner or user should be able to keep this environment current with the physical location.

OBJECTIVES OF THE RESEARCH WORK

The aims of this research are to explore the use of trainee led scenarios in virtual training environments and how emergent learning and human centric design can improve user immersion and awareness of health and safety. To test the effectiveness of the research hypothesis, it will involve the development of an interactive multi-user virtual environment that can be used to generate and implement an H&S training experience for planners and site managers. This includes the identification and integration of beneficial learning technologies that have been developed in other industries or fields of research.

The objectives are:

- To develop a methodology for implementing a 4D construction site within a virtual world.
- To develop a structure and protocol to implement emergent learning behaviour as part of the virtual learning environment using serious game engine.
- To produce a framework or methodology that could be used to implement the knowledge created by this research into other construction sites using these tools.

STATE OF THE ART IN THE CONSTRUCTION INDUSTRY

The construction industry has problems with implementing and complying with health and safety approaches and procedures (Paton 2009). This area has seen a number of papers analysing how it can effect production and how health and safety can be improved within the industry (Goldenhar, Williams and Swanson 2003, McDonald et. al. 2009, Hasle, Kines and Andersen 2009 and Sacks, Rosenfeld and Rozenfeld 2009). Wong (Wong et. al. 2010) has conducted some analysis work on studying trends of construction employment as a means to predict future training needs. Their work highlights that in a rapidly changing market place the construction industry needs to be able to provide skilled workers to required areas of work. This means that ensuring these employees have suitable training on a short timescale is the key to this management of manpower.

The use of virtual reality in the construction industry has been the subject of interest for a number of researchers (Whyte 2002, Rojas and Mukherjee 2003, Faraj and Alshawi 1999, Wang and Dunton 2007). As 3D visualisation software tools become more widespread the industry has been looking to use it in a more integrated fashion and with greater interest in web-based solutions (Jaafari, Manivong and Chaaya 2001, Scott, Cheong and Li 2003). As these technologies mature companies are looking to exploit the design team to produce data models that will be suitable for more widespread applications.

Part of the initial inspiration behind this project has been the development and widespread usage of virtual training environments used in the aeronautics industry (Heerkens 2001). Research has been conducted on the approach of computer assisted learning and how that can be used with regards to engineering (Rubin 1996). Rubin has looked at the uses of computer assisted instruction and how that can be used in engineering training. The technology involved in providing an interactive 3D world has continued to mature and more advanced virtual worlds have started to gain a prominent web presence (Noor 2009). As these tools evolve they provide more opportunities to expand virtual reality training into other areas.

The construction industry has seen some work done investigating various applications of emerging interactive 3D environments with respect to the training of employees. Some of these have been very simple demonstrations of concept (Assfalg, Del Bimbo and Vicario 2002). Other research projects have been very ambitions learning environments that push the boundaries between serious gaming and virtual learning environments. Derby University has developed a virtual quarry using the second life engine (Pearce 2009). The Universities of Salford and Coventry are also exploring the use of virtual environments and serious gaming (Pappa et. al. 2010, Panzoli et. al. 2010).

The key differences are the scope and customisation of the virtual worlds. The difference here is that this research is looking at exploring alternate methods of developing the content of a virtual training environment. Another difference is that this research wants to expand site creation assets to allow different users to recreate their own sites within the world space of the model and generate a more accurate site experience for their trainees than more traditional training tools.

SERIOUS GAMES AND H&S TRAINING

The integration of video games related tools and tactics in a more commercially minded environment is starting to become an attractive proposal for some people. Getchell et. al. have conducted research integrating gaming methodologies with multi-user virtual environments and interactive media (Getchell et. al. 2010). Virtual environments are also affecting how learning within organisations is developing and how it can be of benefit for employee training (Anon 2007). The research being undertaken here seeks to expand on these foundations to explore how games design technologies can be applied toward generating a workplace training environment.

The current work that has been done in this field has focused on providing a specific training solution to a problem. With this research we are looking at creating a more modular toolset. The application of a sandbox environment has yet to be rigorously applied in a serious gaming setting. By carefully setting out the way the user will interact with the game world the 3D environment will naturally direct them toward the desired learning objectives. This is becoming more common within the games entertainment industry and seems a natural fit for a construction industry training site. Chen and Sager have developed a framework for working within a virtual environment (Chen and Sager 2007). While they are not concerned with a purely pedagogical perspective it is felt that elements of the framework can be used to build up a procedure or methodology for implementing a successful training solution.

Learning models in engineering education can be improved by including IT support into existing learning frameworks (Li 1997). This research is attempting to combine the positive educational aspects of serious games with the site management potential of 4/5D modelling. By merging 4D principles with the design of virtual training scenarios it is hoped that a greater feeling of verisimilitude can be created in the minds of the users. Virtual prototyping of construction operations have been shown to be of beneficial use to construction operations (Li et. al. 2005). This type of virtual model tends to be a top down affair, focusing on management and planning. Could this be useful when oriented from a bottom up perspective? By taking the site down to a personal scale and using it for different levels of employees' training, they can proactively experience the site and become aware of some of the potential problems and pitfalls they face on site in a safe environment. In this research, the inclusion of game-play frameworks specifically that of open world gaming, are being explored to determine if they can also bring similar benefits to engineering training

The inherent nature of a multi-user virtual training environment bears some similarity to work done by Dugdale in developing a group based training tool for fire fighting scenarios (Dugdale et. al. 2004).

While the needs of a training environment differ in terms of the desired learning experiences between fire fighting and construction training the methods used to interact with the environment are somewhat similar. Dugdale's tools had users interacting with an environment through a PC based interface with multiple users active within the same virtual world.

By constructing a dedicated scenario for the training or education of users the work becomes that much more focused. It gives a greater ability to structure the learning outcomes to the specific lessons that the program wants to impart. It resembles early game design in structure. The immediacy of this design structure makes it popular for constructing directed tasks such as learning activities. This approach allows for scenarios to be created efficiently and has been the focus of a significant amount of research into the application of serious games as a teaching tool. The structured nature of this type of virtual learning is also similar to classroom exercises or workshops, which provides a certain transferability of design experience.

Non-linear game-play scenarios are starting to be explored for training within a construction context. Even so current efforts are still rooted in scenario based design (Lin, Wook Son and Rojas 2011). This suggests that a sandbox approach is something that could benefit the industry, if the open world nature provides valuable learning outcomes that can compete with a more focused scenario based game.

SANDBOX ENVIRONMENTS AND MISSION HUBS

The primary inspiration behind the creation of an emergent virtual learning environment is that of popular sandbox style video games like the Grand Theft Auto series. These types of games are usually structured around a mission hub where the game designers place content that they believe will entertain their audience. This hub is then designed to evoke a feeling of verisimilitude within environment by allowing players to explore the wider environment while still providing progress through the game by directing them toward the individual missions and letting the player choose when to trigger that progression. This is achieved in the GTA series in the form of a sprawling urban city with a simulated populous. The mission hub also includes a number of mini games or side quests that players can engage with or not, at their discretion. The goal with these additional game play elements is to provide more compact content than a full mission and to encourage players to interact with the mission hub as an actual environment and not as a barrier to progress.

From a pedagogical perspective a scenario based design provides a more immediate gateway to learning. The environment can be set out so that when users enter they can encounter learning challenges to engage them in the activity. Further the layout of the environment allows users to gradually explore the virtual world and experience tiered challenges that build upon knowledge previously gained from the scenario. With a sandbox style emergent learning environment there are different pedagogical challenges to face. The environment has a different structure and flow due to its open plan nature. When users are interacting with the environment it should allow for an element of free roaming exploration as part of the learning experience. The environment should be approachable through different directions; the learning challenges within the virtual world should not be on a linear scale of difficulty.

The very fact of trying to provide educational content in a 3D immersive space faces some new pedagogical challenges (de Freitas and Neumann 2009). The learning community that has developed around the area of serious games has a number of limitations. The common pedagogical base for developing these types of games is usually rooted in classroom thinking. This leads to game development being constrained to the types of activities already in use in classroom environments, typically that of simple role-play activities or that of highly focused demonstrations. The way people approach interactive media means this pedagogy has stumbling blocks that a more game-based approach can be avoided by keeping the engaging elements of the medium and then providing educational content as part of the game-play (Savin-Baden 2007).

Educational tools based around site management and health and safety issues in the construction industry are also having benefits divorced from an educational context (Goedert et. al. 2011). The very nature of the industry means that any sufficiently expansive training tool can also have benefits for the planning and management from a design or planning perspective. If a training tool allows users to

experience health and safety risks on an accurate replica of a site then the planner or designer can use the same tool to explore the site. In this manner they can examine their building for any problems with site layout or access that are less obvious from even a 3D or 4/5D model.

RESEARCH METHODOLOGY

The research is intending to explore the potential for using interactive 4D environments as a training tool for the construction industry. This will involve the generation of a test environment to provide feedback on the effectiveness of the environment and supporting design theory. This research is following a qualitative method toward the analysis of the generated data.

The research problem revolves around the potential benefits toward adopting an IT centric training style to provide training to the construction industry. Solving this will involve the development of a pedagogical model suitable to the needs of this industry. To build up this model this research is progressing on the assumption that a virtual construction site processes replica will provide a greater immersive experience than more targeted serious gaming scenarios.

This research intends to examine the areas of health and safety in construction, human centric design, virtual learning environments, web-based tools, emergent learning and 4D planning as part of a means to building up a sandbox virtual environment that will reflect a building site over its working life. The pedagogy of development for the virtual environment is focused on allowing the virtual environment to provide some of the learning outcomes as opposed to purely scenario driven learning outcomes.

DESIGN OF THE VIRTUAL ENVIRONMENT

This research is built around the assumption that an expansive and fully realised virtual training site provides a greater educational benefit than an intentionally constrained virtual training scenario. In order to achieve this, it is necessary to be able to create a full scale site within the virtual environment. In this instance the decision was made to make a true to life replica to ensure that the virtual model is a truly open world environment. To do this a construction company, Morgan Ashurst, agreed to be part of a case study and a complete set of site plans was acquired as well as a project schedule. In addition to these a fire evacuation diagram was also obtained. This is an important piece of information for generating a replica site because of the fact that it includes temporary structures in the site layout. These temporary structures are important to provide the feeling of a living construction site but aren't included in normal design schematics.

To recreate this virtual site 'OpenSim' environment was used. Primarily this was selected because of inbuilt functionality that supports multiple users interacting with both the environment and each other. The building schedules and 3D models were manually imported into the environment. The model was then built up in a series of sections that reflected construction processes, as would be the case in a more traditional 4D modelling tool. These sections have then been grouped by task, using their textures and spatial position to visually identify which structures belong in which task. By building the environment in this fashion it allows the site to be linked with the timing of the schedule. This will be exploited through the use of 'Holodeck' technology. This is a process whereby the environment within OpenSim can be changed from one world to another through a simple command. This is being used to replicate the effect of the time axis that would be present in a traditional 4D model. By linking the individual models to the start and finish dates of each task this technology can be used to display how the site appears according to wherever on the timescale the simulation or scenario requires.

To add H&S training to the environment, a number of linked training scenarios have been developed. These scenarios serve to illustrate the potential usage of this tool by allowing trainees to interact virtually in similar fashions as they would on-site. By using predefined scenarios the effectiveness of the learning experiences being generated can be examined. Rather than a specific learning scenario, the test scenarios are being designed to reflect true to life experiences. In order to achieve this, the tasks set to the users in these scenarios will be along the lines of a traditional job role in such an environment. By placing the requirements of the job role front and centre it will encourage the users to engage with the environment in ways which allow them to complete their assigned job and not to maximise their 'learning experience'. This is important because the goal is to allow them to interact

with the environment in a realistic or lifelike fashion. Presenting them with a list of learning objectives would encourage them to seek out these lessons but would cause the environment to seem artificial as a real construction site is not experienced in this fashion.

These scenarios are envisioned as small group exercises with an instructor present to evaluate trainee performance. In addition, the users will be given a feedback sheet where they can record their experiences. This will allow a measurement of both their comparative performance and their personal reactions to the training style. The drawback of this style of open learning environment is that not all trainees will experience all of the learning points available in the virtual world. It is hoped that by structuring the training as a group activity the communication between the trainee group will cause them to compare each other's performance and make them consider why different people encountered different safety risks.

With regard to the training element of the project there will be a number of testing workshops to evaluate the test environments. This will involve multiple users being active in the program concurrently. In order to test the capability of the environment to impart knowledge to its users there will be both a directed session and a free session. The directed session will deal with interacting with the environment and dealing with interface issues and include the use of existing H&S training tools such as orientation videos and toolbox talks. The learning experience will be directed by in world by a user portraying the site foreman. This will allow data to be gathered on how intuitive to manipulate the environment is. The free session will consist of users being given job roles to perform and left to interact with the environment without explicit direction. This will be where the primary feedback from the effectiveness of the learning environment will be gathered.

Very few evaluation frameworks exist in the area of immersive virtual worlds (de Freitas and Oliver 2006). The areas of evaluating immersive learning has received some attention by previous researchers and provide some interesting ideas for developing evaluation criteria in an under researched field (de Freitas et. al. 2009). de Freitas' research is a useful starting point for the development of feedback and evaluation frameworks that need to be developed for the testing phase of the research reported in this paper.

As part of the feedback, this research hopes to adopt some of the methods put forward by Augustin for individual skill assessments where it is practical (Augustin et. al. 2010). By giving the users a longer leash to immerse themselves in the environment their behaviour should provide data on how people will choose to interact with the software. This data will allow the refinement of the emergent learning techniques that are deployed in the environment. Both tests will be performed on the two test environments. The data from the first feeding back into the design of the second and the final testing allowing a comparison between what was aimed for and what has been accomplished.

CONCLUSION

The research reported in this paper is adapting the concept of serious games environments and exploring how to improve its potential as a training tool for H&S in construction. This works has been sponsored by Dynamic Distance Learning; a company involved in the creation of training tools for the construction industry and is part of an EPSRC Case Studentship.

Aspects of 4D planning, emergent play and sandbox training scenarios are the current focus of the work. By providing an environment that is easier to understand and interact with there should be an increase in the training that can be imparted to any given user.

In addition to the consideration of emergent training opportunities the way the user interacts with the technology itself is also a potential benefit. Out of contemporary training methods practical exercises provide the most transferable skills back to the trainee. For designing a virtual training environment matching the interface to the activities performed maximises the transferability of the skills learned. This research hopes to apply these principles to design and use of user interfaces in current virtual environment tools and provide suggestions for improvement.

By designing the interface and environment in this way the lessons and experience gained using this technology will face fewer barriers in transferring into real world skills. To accomplish this there was

a focus on avatar directed activities and a movement away from menu driven commands. Another aspect that has been informed by this is scenario design itself. By integrated elements of scenario design into the world design it will lessen the need for specific scenarios and allow it to function as a more realistic construction site.

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A Serious Game for Learning Sustainable Design and LEED Concepts

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ABSTRACT

With the growth of the population worldwide and the increased demand on resources, there has been a growing emphasis on sustainability and awareness of green and responsible use of resources. In response to the need for a sustainable built environment, the United States Green Building Council (USGBC) has established the Leadership in Energy and Environmental Design (LEED) rating system, which includes a set of metrics for defining and measuring "green buildings". Construction professionals and designers are recognized as LEED AP (Accredited Professionals) if they can demonstrate, via the LEED exam, knowledge and understanding of the LEED rating system. In this paper we describe a serious game for learning Green Building design principles and LEED concepts. The game is aimed at undergraduate students enrolled in Civil Engineering, Architecture and Building Construction Management programs, and professionals who are interested in becoming familiar with the LEED system. The game includes five levels that focus on the environmental categories of the LEED rating system for 'New Construction and Major Renovations' 2009 version.

INTRODUCTION

There is a worldwide push for the implementation of "Green Building" through increasing efficient use of resources such as energy, water, and materials during a building life cycle. This effort is encouraged in the U.S by the Leadership in Energy and Environmental Design (LEED) Green Building Rating System™. Another important effort is the LEED Professional Accreditation that distinguishes building professionals with the knowledge and skills to successfully steward the LEED certification process. Currently, there are about 170,000 people in the US that have earned the credential by passing the LEED Professional Accreditation exam (USGBC 2010). This number is not sufficient to successfully accomplish the worldwide push for green building to its fullest.

The objective of the project reported in the paper is to develop a serious game for teaching Green Building design principles and the LEED system. The serious game is aimed at undergraduate students enrolled in Civil Engineering, Architecture

and Building Construction Management programs, and professionals who are pursuing the LEED certification. The long term goal of our research is to assess the effectiveness of using a game approach to integrate sustainable design in the undergraduate curriculum.

BACKGROUND

Green buildings and LEED. Green buildings, also referred to as sustainable buildings, are new structures designed with the intent to be environmentally responsible. The U.S. Environmental Protection Agency (EPA) identifies Green buildings as structures that use environmentally responsible and resource-efficient processes throughout their life cycle, in addition to the classical building design concerns of economy, utility, durability, and comfort.

LEED is an initiative to redefine the way owners, designers, construction, operation and maintenance practitioners think about the built environment. The United States Green Building Council (USGBC) a non profit organization committed to the prosperous and sustainable future through cost efficiency and energy saving green building, identifies that buildings are responsible for 39% of CO_2 emissions, 40% of energy consumption and 13% of water consumption per year.

The LEED accreditation/certification process requires professionals to continue to learn through webinars, online classes, courses and supporting resources that go beyond the initial exam. The USGBC website offers an insightful four-step process on preparing and passing the LEED AP exam. The main objective of this work is to enhance existing instruction methods with a unique approach: an engaging, fun serious game that supports learning of sustainable design and LEED concepts. The proposed game is not meant to completely replace current educational practices and materials; rather, it will be integrated in green building and sustainable design courses as an additional educational tool. It will also be available to those who are pursuing the LEED accreditation as another training strategy.

Serious Games. In Mike Zyda's definition, a game is *"a physical or mental contest, played according to specific rules, with the goal of amusing or rewarding the participant",* while a serious game is *"a mental contest, played with a computer in accordance with specific rules that uses entertainment to further government or corporate training, education, health, public policy, and strategic communication objectives"* (Zyda 2005). Serious gaming repurposes the concepts of videogames and videogame technologies that have been used for commercial entertainment, and uses the gaming approach for training, education, advertising, national defense, general productivity, and more.

The founders of the Education Arcade at MIT stated that there are many intrinsic motivations for learning associated with games. *"The threat of failure is lowered. Games allow players to try, make mistakes or fail, and then try again without losing face. Discovery and application of learned skills in new contexts encourages exploration and experimentation. A sense of engagement continues during gaming. Computer games allow players to be stakeholders in the events that occur on the screen"* (Klopfer et al. 2010).

Some research has taken place on serious games from a "new media" perspective (Dovey & Kennedy 2006) from psychological perspectives (Reese 2007) (Greitzer et al. 2007) as well as from sociological perspectives (Schuurman et al. 2008). Blunt (2009) demonstrated that students taking specially designed business, economics, and management courses that had an additional serious game component performed better than students that took the course without the serious game component. Wong (Wong et al. 2007) found in an NSF study that non-science major students taught physiology using a serious game methodology performed better than those taught using traditional static text and images. Coller et al. (Coller & Scott 2009) (Coller & Shernoff 2009) taught a numerical methods course centered completely on a serious game in which students wrote programs that would race a virtual car around a track. They discovered that students in this course spent more time out of class working on the material, demonstrated deeper learning, greater intellectual intensity, more intrinsic motivation, and increased engagement as compared to traditional approaches. Further, these students reported greater levels of challenge and concentration as well as greater interest and enjoyment in the subject matter.

A variety of serious games focused on sustainability, energy efficiency and renewable energy have been developed. Examples are EnerCities (Knol & DeVries 2011), ElectroCity (2007), EfficienCity (2001), EnergyVille (2011), Clim' Way (2010), BBC Climate Challenge (2010), CityOne (2011). Several serious games have been developed to teach architectural design and visualization.

To our knowledge, no serious games specifically designed to teach sustainable design and LEED concepts exist. The 'BIM game' (Yang 2009) is a serious game that aims to teach some sustainable design principles. Its goal is to educate non-experts about energy related design and living. The specific objective of the game is to use a variety of strategies to reduce the Carbon Footprint while designing a new home. The game focuses primarily on one aspect of green building design and does not cover the LEED concepts and rating system.

Knol and DeVries (2011) argues that the majority of serious games in the field of sustainability and design "*have put fun and enjoyment less central in the game concept. Ideally, they should be in the first place games for enjoyment with implicit educational content, rather than learning content translated into a game format*". Our work has three main objectives. First, in an effort to improve on the current state-of-the-art in serious gaming, we plan to bridge the gap between tools for learning, such as educational software, and tools for fun, such as computer games, by creating an application that is not just a game, yet remains engaging, is not a lesson, yet promotes learning. Second, although some studies suggest that serious games can improve learning, there is still limited scientific evidence; thus, there is a need to investigate the role and benefits of serious games in the classroom. An important goal of our work is to advance the knowledge in the field by evaluating the effectiveness of serious games for teaching green building design concepts to undergraduate students. Third, a main objective of this work is to enhance traditional instruction methods with a unique approach: an engaging, fun serious game that supports learning of sustainable design and LEED concepts. The proposed game is not meant to completely replace existing educational practices and materials; rather, it will be

integrated in green building and sustainable design courses as a preparation, revision and assessment tool. Furthermore, it can be used as another training strategy for those who are pursuing LEED accreditation.

THE GAME

The goal of the game is for college students and professionals to learn sustainable design and develop a solid understanding of LEED concepts, while having an enjoyable experience. The 'LEED-ers' game is a role-playing serious game (RPG) in which the student plays as the main protagonist. Figure 1 (left) shows a concept sketch of one of the protagonists; the player can choose to play as one of four different characters (2 males and 2 females). The protagonist travels through 5 environments (game levels) and in each environment he/she acquires in depth information about sustainable design and the LEED rating categories.

In order to maximize the effectiveness of the game, we have researched the elements of video game design that promote engagement and motivation for continued play. Based on literature findings, as well as our own experience, we have defined a set of game design features that are likely to promote user's interest and enjoyment, and, therefore, learning. These elements include: a shared story context that establishes and support the activities (Lepper 1988; Barab et al. 2005); an overarching goal (Malone 1980; Lepper 1988; Shelley 2006); a gentle on-ramp (Malone 1980; Lepper 1988); multiple levels with variable difficulty (Malone 1980; Clanton 1998); a well defined advancement system and rewards associated with advancement (Shneiderman 1983); opportunities to build new content (Roussou 2004; Barab et al. 2005); ability to progress at the user's own rate (Shelley 2006); hints not answers (Shelley 2006). We have integrated these features with the three elements of intrinsic motivation (challenge, curiosity, and fantasy) identified by Malone (1980) and Lepper (1988).

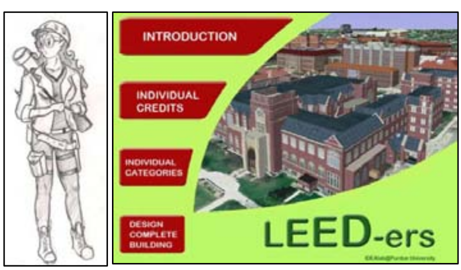

Figure 1. Concept Sketch of One of the Main Characters, Miss Verde, the Architect (left); Game Opening Screen

Gameplay and educational content. The game includes five levels; each level is an engaging environment in which the player is exposed to various LEED concepts. In each level the player is given a task to accomplish; upon completion of the task he/she can move to the next environment. The first level of the game is dedicated to the exploration of the credit system and the goal is to provide the student with a good

understanding of the intent of each category. The student can select a category from the rating system (i.e. Site Selection) and focus on one category at a time. Figure 2 shows two screenshots of the first level of the game, specifically the site selection category. The second level of the game introduces the student to the LEED credits and point systems. In the third level the student is challenged with a series of tasks whose goal is to maximize the points in each category. Based on a predefined set of constraints such as, for instance, location of public transportation, brown fields, gas station, parking garages, etc., the student is required to analyse multiple case scenarios and explore multiple options in order to maximize the points. Level four of the game focuses on the documentation aspects and the requirements for gaining recognition for the choices, and collecting the LEED points for the certification process. The student is presented with a case scenario similar to the ones in previous levels, however, at this time the student is required to concentrate on the paperwork and submittals needed to collect the LEED points for the certification, and on the use of Information technology and BIM methodology in order to track the documentation. Level five of the game requires the student to integrate and apply all the skills acquired in the previous levels. The student is given a building project and is challenged with the task of developing an effective strategy for maximizing the LEED points.

The ultimate project goal is to expose students to fundamental LEED concepts in a visual fashion that is entertaining and compelling. It is expected that, through sheer exposure, the concepts will insinuate themselves in the user's mind thus making her or him more receptive and willing to learn.

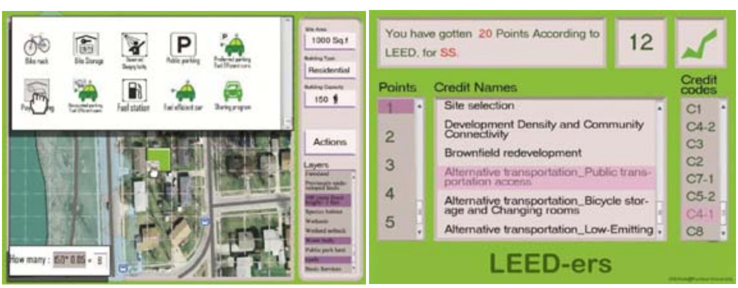

Figure 2. Two Screenshots of the First Level of the Game.

Technical implementation. The platform for the game is based on Autodesk Revit, Maya and Unity3D. We use Revit and Maya software to model and texture the buildings, virtual environments and characters and to animate their functionality. Interactivity with the 3D components is programmed in C# using the Unity game development platform. The choice of the Unity platform was based on the following considerations:

• Unity has an optimized graphics pipeline that supports interactive rendering of complex animated 3D meshes and advanced lighting and textures even on computers with limited graphics capabilities.

• Unity interfaces seamlessly with major 3D tools (i.e. Autodesk Maya, Revit and 3D Studio Max) and file formats, and allows for instantaneous import and update of asset files and animations.
• Unity supports a wide range of publishing platforms, including: standalone builds for Mac OS and Windows; web delivery through the Unity Web Player Plug-in (3 MB); Wii and iPhone publishing.

The game is deliverable via web or as an exe or app file, and is being designed to run on hardware and software infrastructure that is already widely deployed in universities. Students will be able to use the game on low-end personal computers (PC/MAC) with low-end graphics cards. Different strategies are being used in order to optimize the game performance. Geometric complexity of the 3D models is kept at a minimum, while retaining visual quality, to ensure client hardware can run the application at interactive rates. Normal maps, a technique for simulating complex geometric detail, is used to add fine detail to objects without adding extra geometry. Level of detail is also employed to find an accurate balance between performance and visual quality on the client machine. Furthermore, light maps are implemented to provide high quality lighting for static geometry without impacting performance.

CONCLUSION AND FUTURE WORK

In this paper we have described the initial design and development of a serious game whose goal is to augment the teaching of sustainable design and LEED practices and principles to undergraduate students and professionals. The overall goal of the project is to provide a demonstration that LEED concepts and sustainable design fundamentals can be taught as or more effectively using serious games than by traditional methods. Future work will include iterative development and completion of the five game levels, and assessment of learning outcomes. Based on student feedback, future consideration might be given to developing a multi-player version of the game. The game is being created using an iterative approach that includes 2 forms of evaluation: formative user-centered and summative evaluation. Formative evaluation focuses on the design features of the game, i.e., usability, fun and engagement, and quality of the graphics. Since game development relies heavily on formative feedback from users early and continually, we are conducting formative assessments throughout the design and development phases of each level. Summative evaluation will be conducted once the game is completed to: (1) assess the overall worth and effectiveness of the game; (2) draw out key lessons learned from the project; and (3) determine the sustainability, transferability, scalability, and relative importance of the initiative in enhancing students' understanding of LEED and sustainable design concepts. Results of the formative and summative evaluations will be reported in future publications.

Provided that our work is successful, (e.g. students' learning outcomes are equal or higher than with current teaching approaches) expanding the serious game approach to other engineering/architectural concepts as well as other subject domains seems to be a logical step in which to proceed. Future iterations could also be expanded to provide a mechanism to assess LEED and sustainable design knowledge beyond the specific examples within the game to a more general sense of the domain.

If we are able to show a correlation between this serious game playing and student attitudes and performance in the classes in which it is used, we expect to expand the tasks to other courses, as well as broadening usage in the target courses.

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An Autonomous Landslide Monitoring System based on Wireless Sensor Networks

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ABSTRACT

Landslides cause significant damages to civil infrastructure. Over the years, methods and technologies have been proposed to determine the risk of landslides and to detect hazardous slope movements. There have been increasing interests in developing and landslide monitoring systems to observe movements using sensors installed on the slope. Although providing accurate data, many landslide monitoring systems are not operating in an automated fashion and lack the ability to analyze the collected data in a timely manner. This paper presents an autonomous landslide monitoring system based on wireless sensor networks. Self-contained, autonomous software programs ("software agents") are embedded into the wireless sensor nodes. In cooperation with each other, the software agents are continuously collecting and analyzing sensor data, such as recorded ground acceleration and the orientations of the sensor nodes along the slope. If movements are observed, the collected data sets are automatically transmitted to a connected server system for further diagnoses. The landslide monitoring system presented in this paper is remotely accessible via Internet and provides real-time information about the current state of the monitored slope. Laboratory tests have been conducted to validate the reliability and the performance of the monitoring system.

INTRODUCTION

Landslides are gravitational movements of soil or rock down slopes that can cause severe damage to civil infrastructure. Numerous fatalities and structural failure caused by landslides have been reported over the years (Guha-Sapir et al., 2011). Therefore, efforts to measure and to monitor potential landslides are essential to ensure human safety and to protect civil infrastructure. To observe the behavior of slopes, monitoring systems have been installed or manual inspections by human experts have been conducted.

Several measurement techniques have been proposed to identify slope instability and to estimate the risk of landslides (Lynn and Bobrowsky, 2008). For example, map analyses and aerial reconnaissance are used to assess the risk of landslides based on the interpretation of terrain and geological information. These methods, however, are known to be costly and labor-intensive as well as highly subjective because the results depend on the experience and judgment of the

human experts. Furthermore, landslide-indicating features in certain terrains (e.g. forests) cannot be identified by these techniques.

Another approach towards landslide monitoring is based on geotechnical instrumentations using, for examples, inclinometers, extensometers, or piezometers. The instruments are usually installed on the slope and wired to computer systems hosting data analysis software. Several cable-based landslide monitoring systems have been reported (Singer and Thuro, 2006). However, cable-based monitoring systems are costly, require continuous maintenance, and are limited in their communication flexibility. To overcome these limitations, wireless sensor networks are a viable alternative technology. State-of-the-art wireless landslide monitoring systems collect environmental data from the slope and forward it to connected computer systems for persistent storage. The collected data sets are not processed and analyzed automatically (Garcia et al., 2010). Thus, hazardous slope movements are not usually detected in real-time (Zhou et al., 2005; Bertacchini et al., 2009).

This paper presents a preliminary research effort towards the development of an autonomous landslide monitoring system based on wireless sensor networks that is capable to collect and process data autonomously. The prototype system is designed to automatically detect pre-failure slope deformations based on real-time data analyses. The prototype implementation using an agent-based approach is presented in detail. In addition, laboratory tests validating the prototype monitoring system are shown.

SLOPE FAILURE FORECASTING

Several methods for slope failure forecasting have been developed (Busslinger, 2009). In this paper a method based on the inverse velocity of the surface movement is employed. The concept of inverse velocity for predicting slope failure time was developed by Fukuzono (1985), who has conducted large-scale laboratory tests to simulate rain-induced landslides. The conditions in the laboratory were considered to be characteristic of accelerating creep conditions under gravity loading. The assessment of the laboratory data unveiled that the acceleration of surface displacement and the velocity of surface displacement where related, which can be expressed as:

$$\frac{d^2x}{dt^2} = A\left(\frac{dx}{dt}\right)^{\alpha}. \tag{1}$$

In the above equation, x is downward surface displacement, d^2x/dt^2 is the acceleration, dx/dt is the velocity, and A and α are constants depending on the slope characteristics (Fukuzono, 1987). The laboratory tests also led to the recognition that, when plotting the inverse velocity versus time, the values of inverse velocity approach zero, as the velocity of surface displacement increases towards final slope failure (Fig. 1). Plotted graphically, the slope failure time can be predicted at the point at which the trend line through values of inverse velocity crosses the abscissa axis. This relationship between velocity and failure time, as proposed by Fukuzono (1985), can be described by the empirical equation

$$V^{-1} = \{A(\alpha-1)\}^{\frac{1}{\alpha-1}} \cdot \left(t_f - t\right)^{\frac{1}{\alpha-1}}, \tag{2}$$

where V^{-1} is the inverse velocity of surface displacement and t_f is the failure time. Depending on the values of α, the curve of inverse velocity is linear ($\alpha = 2$), concave ($\alpha < 2$) or convex ($\alpha > 2$), as shown on Figure 1.

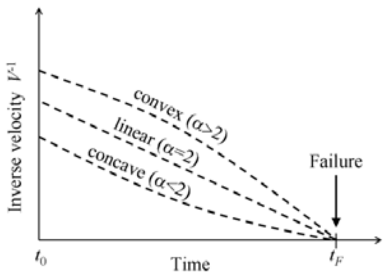

Figure 1. Inverse velocity over time (Fukuzono, 1985).

AUTONOMOUS LANDSLIDE MONITORING SYSTEM

The purpose of the landslide monitoring system is to enable early detection of hazardous slope movements. If having identified pre-failure slope deformations, the system automatically informs human individuals about potential landslides. Relevant measurements taken from the observed slope are continuously stored and available for detailed diagnoses of the slope movements. The landslide monitoring system automatically calculates the inverse velocity, and determines whether and when landslides can be expected. The architecture of the implemented prototype system is shown in Figure 2. The system is composed of two subsystems, a wireless sensor network and a server system.

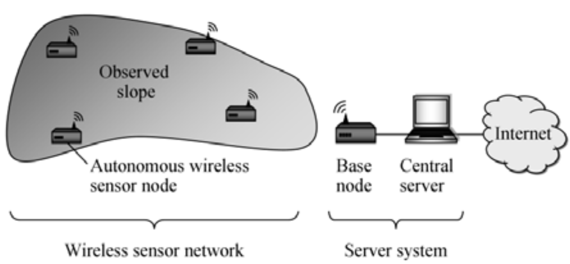

Figure 2. Architecture of the autonomous landslide monitoring system.

Wireless sensor network. A wireless sensor network is comprised of sensor nodes, each has a processor board and a three-axis accelerometer. Mobile software agents are embedded into the wireless sensor nodes to collect acceleration data and to conduct in-situ analyses of the observed slope. A software agent is an autonomous, flexible software program able to complete a specific task without direct human intervention (Wooldridge, 2002). Software agents interact with their environment and respond to environmental changes. Software agents can cooperate with each other to solve comlex problems. Time-consuming data analysis and computation tasks can be performed concurrently by several agents to enhance system performance, which is crucial for real-time monitoring systems.

For modular design of the monitoring system, three classes of software agents are defined and embedded into each wireless sensor node: *ManagerAgent*, *SensorSamplerAgent* and *AnalysisAgent*. The *ManagerAgent* enables the

communication between the agents embedded in different sensor nodes, as well as between the agents and the server system. The *SensorSamplerAgent* collects the acceleration data from the slope at a certain sampling frequency and sends the data to the *AnalysisAgent*. Moreover, the *SensorSamplerAgent* determines the sensor orientation and reports tilt changes, if identified. The *AnalysisAgent* determines the motion of the node, thus reflecting deformation in the environment in which the node is installed.

For the communication between the sensor nodes and between sensor nodes and the sever system, radio connections are necessary. Because radio communications consume a lot of battery power, the number of data messages should be kept to minimum. By first sending data to the *ManagerAgent*, which then forwards it to the recipients of other sensor nodes, the *SensorSamplerAgent* and the *AnalysisAgent*, through the *ManagerAgent*, communicate with agents situated on other sensor nodes using just one single radio connection (managed by the *ManagerAgent*) instead of establishing multiple connections.

If a sensor node is in motion, the *AnalysisAgent* sends a command to the *ManagerAgent* to inform all other nodes and the server system. As a direct consequence of a detected motion, all nodes increase the sampling frequency and the server system starts analyzing the global situation of the slope. Furthermore, the *AnalysisAgent* computes the inverse velocity of the sensor node according to the previously described method using the collected acceleration data. The *ManagerAgent* sends the result of the inverse velocity analysis to the server system. A typical monitoring sequence is shown in Figure 3. Due to the multi-agent architecture, the functionality of the wireless sensor network can easily be extended by adding new analysis agents.

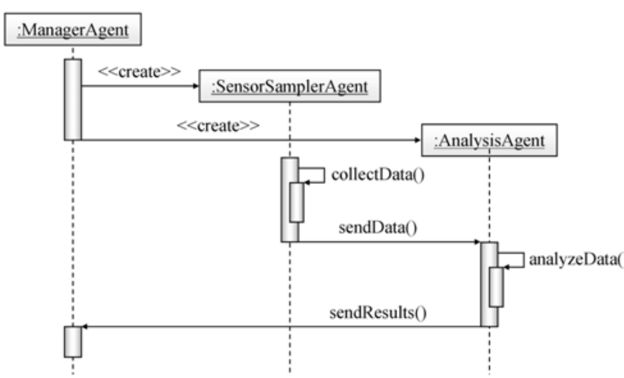

Figure 3. Monitoring sequence executed at system start-up.

Server system. The server system allows human individuals to communicate with the wireless sensor network. The server system is responsible for storing the data and conducting detailed data analyses. In addition, if the server system does not receive the results of the inverse velocity analysis from each sensor node, an attempt to establish a connection to the sensor node is made. If it is not successful, the human experts are informed via email about possible sensor malfunctions. All measured data as well as the results of data analyses can be accessed through a Java application running on the server. Figure 4 highlights the main view of the

application showing the functionalities to add or to remove sensor nodes. Data requests can be sent to the wireless nodes to visualize current field data. In addition, the application allows saving data plots in the form of PDF files. In Figure 4, acceleration data is exemplarily shown, collected by two wireless sensor nodes, S_1 and S_2, during laboratory tests.

LABORATORY TESTS

Laboratory tests are conducted to validate the performance of the prototype landslide monitoring system. Specifically, the functionalities of the software agents are analyzed to determine the accuracy of the inverse velocity method applied. To prove the concept, a sand slope is exposed to flooding, which results in soil movement (i.e. landsliding).

Laboratory test setup. A container is filled with sand as illustrated in Figure 5a. The depth of the container is 42 cm. A sand slope with an inclination of 45 degrees is built with a bulk density of the sand (i.e. the ratio of the mass of the sand particles to the total sand volume) of 1.56 g/cm^3 and a void ratio of 0.7; the void ratio describes how sand particles are packed. A void ratio of 0.7 indicates that the sand is of middle-graded density. The wireless sensor nodes, S_1 and S_2, are installed on the top and at the toe of the slope surface. Every sensor node hosts the embedded agents.

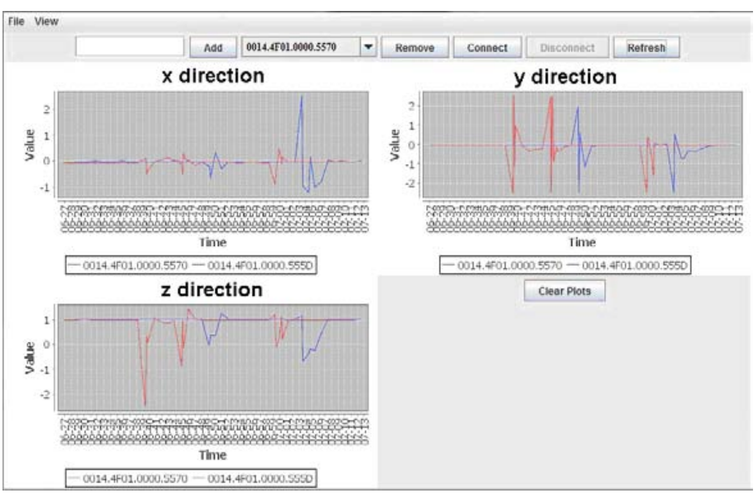

Figure 4. Prototype control and analysis web application.

To determine the initial slope condition, the embedded agents continuously measure the acceleration and the orientation of a node at a relatively low sampling rate of 0.001 Hz; they analyze the data with respect to changes, condense it, and send it to the server system. To simulate heavy rainfall, water is poured slowly at the top of the slope. After pouring 10 liters of water, the soil is saturated and a slow movement starting at the toe of the slope is observed by the

monitoring system. Tension cracks also occur because of the weak foundation material. The movement results in changes in the acceleration data, which are identified by the agents. The sampling rate is automatically increased to 0.01 Hz. Based on the acceleration data, inverse velocity values are calculated and sent to the server system for further analysis and visualization. After a total of 14 liters of poured water, cracks occur at the top of the slope as shown in Figure 5b, leading to another movement at the top of the slope and to a total slope failure.

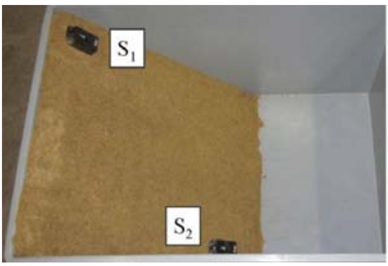

Figure 5a. Sand slope instrumented with sensor nodes before flooding.

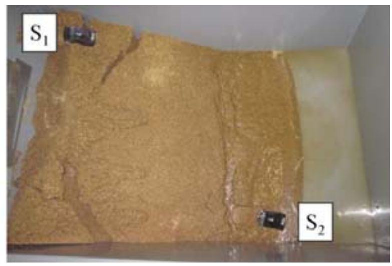

Figure 5b. Sand slope after flooding and landsliding.

Results of the laboratory tests. Slope movements have been detected and, based on the inverse velocity method, the failure time has been calculated by the prototype monitoring system. Relevant information has been forwarded from the wireless sensor nodes to the server system. Figure 6 illustrates the inverse velocity calculated by S_2 before failure. As can be seen, the inverse velocity decreases as failure time approaches. In summary, the laboratory tests have proven that the landslide monitoring system is capable of autonomously identifying anomalies and pre-failure deformations.

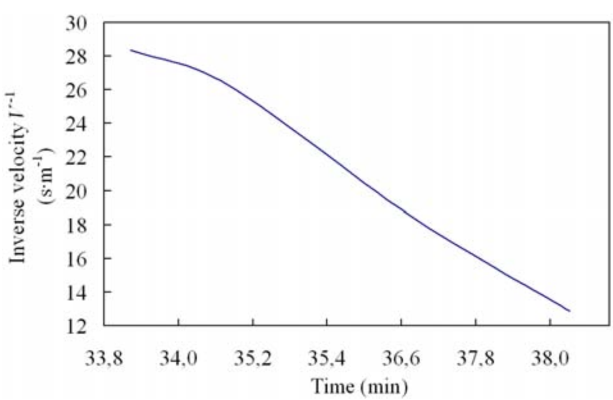

Figure 5. Inverse velocity time history records calculated by sensor node S_2.

CONCLUSIONS

In this paper, the prototype development and implementation of an autonomous landslide monitoring system based on wireless sensor nodes has been

presented using a wireless sensor network. Software agents have been embedded into the wireless sensor nodes to continuously collect and analyze ground acceleration data and orientations of the nodes. Within the laboratory experiments, it has been demonstrated that the software agents react appropriately on environmental changes, e.g. by increasing the measuring frequency if anomalies are identified. The collected data can be sent from the wireless sensor nodes to a server system for further analyses and automated email alerts. A distinct advantage, compared to conventional landslide monitoring systems, is that the presented system observes slopes without permanent human interaction. Furthermore, costs for cable-installation and maintenance are avoided because of the utilization of wireless sensor nodes. Due to the flexibility and adaptability of the software agents embedded into the wireless senor nodes, a resource-efficient reduction of measured data is achieved. Future improvements can be made, for example, by incorporating soil moisture sensors into the system. Also, the implementation of additional agent functionalities could further enhance the autonomous monitoring.

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Colored Petri-Net and Multi-Agents: A Combination for A Time-Efficient Evaluation of A Simulation Study in Construction Management

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ABSTRACT

The estimation of the impacts an uncertainty might have on a construction project is particularly challenging. The major reason is that construction projects are considered as unique facilities. Therefore, a successful estimation requires from the project manager an evaluation of the different simulation scenarios and alternatives and this apparently demands time and efforts. This paper discusses the huge number of simulation runs that are needed for the evaluation of a simulation study in construction projects, and efficiently reduces the overall simulation time without increasing the required processing needs. Concerning this goal, the combination of a deterministic colored petri-net model with a multi-agents model to build a simulation model is suggested. Furthermore, a simulation framework named MOSAICA is developed in order to properly execute these models. And thus, the results of applying MOSAICA on a real project are encouraging. As a conclusion, the proposed approach made it possible to concurrently run large number of simulation models alternatives of a real building construction project within milliseconds.

INTRODUCTION AND BACKGROUND

The building construction sector is suffering from uncertainty, which is manifested in unexpected delays in resource delivery, sudden changes in the use of construction methods, variable production rates, technical breakdowns of equipment, effect of weather, etc. The main reasons behind this uncertainty are the unique characteristics of each new building facility, and the different surrounding construction conditions (Franz 2011), such as the building location and the involved organizations and individuals. If a good decision is not taken during the execution phase, uncertainty will definitely have a direct impact on the project's economic factors. In this context, simulation plays an essential role as a project management tool for quantifying and assessing the impact this uncertainty may have on the whole project (Bennett et al. 1984). Some practitioners criticize simulation in that the construction project is being forced to be carried out within a predetermined fixed budget and duration. Nevertheless, the use of simulation is still intuitive to acquire more and better information on which to base a decision and increase the possibility of its accuracy (Bennett et al. 1984). This fact was proved in AbouRizk's experience with simulation in construction industry (AbouRizk 2010) which shows that simulation is most effective when problems are characterized by uncertainty.

Any simulation study (VDI 3633, part 1 2010) would be consisted of three phases: simulation preparation, execution and evaluation. The same procedure and scope are divided into 4 phases (AbouRizk 2010): product abstraction, process abstraction and modeling, experimentation, and decision making. During the simulation evaluation (or decision making) phase the simulation results are analyzed and the model is manually adjusted in an attempt to satisfy different economic objectives, and to investigate the impact of uncertainty on these objectives. But to what extent can we consider this manual procedure applicable? Especially when taking into considerations that this procedure requires the investigation of various construction plans describing different production activities and interdependencies. And then comes the phase of making distinctive estimations regarding the required production resources for each construction plan. At last, the need to examine different resource allocation strategies for the developed scenarios arises. These considerations simply lead to the need of investigating over 500 different simulation models, which is truly exhaustive in regards to both time and effort. A satisfactory approach would be automating the evaluation phase in order to automatically and efficiently run all possible simulation model's alternatives within a simulation study.

An appropriate simulation model and tool are needed in order to automate the evaluation phase. There are a lot of approaches for simulation models and tools for the construction industry, started by CYCLONE method in the 1977. An extensive literature on simulation tools and models is described in (AbouRizk et al. 1998 and AbouRizk 2010). These approaches are classified into general purpose and special purpose (or domain specific) models and tools. In addition, some of the approaches from the local German research field on simulation in construction follow next. First, the use of a multi-agents model (Kugler et al. 2011) for simulating construction processes. The model consists of a process model that is linked to a product model, and is integrated into a CAD/BIM environment. The simulation model is then executed within the general purpose simulation environment "SeSAm". Second, the development of a library of reusable components specified for the domain of building processes (Scherer et al. 2011). Process templates are one kind of these components, and represent a simple work flow of a construction work (like Steel work or Install formwork). Similarly, the process templates are modeled using BPMN and are executed within the discrete event simulation environment "Plant Simulation". Last but not least is the use of a constraints based model (Marx et al. 2011) to simulate construction processes. The constraints are defined or generated from former projects, and represent precedence sequences or spatial constraints among the different construction methods.

In fact, general purpose simulation models suffer from the complexity of modeling and achieving a stable model during the evaluation phase. And here we discuss our own experience regarding "SeSAm" environment. It was not easy to integrate any kind of intelligence in the agents' model in order to reflect economic objectives. Still, the multi-agents model is very prominent, in that it is a real-world modeling. Moreover, a multi-agents model is a coarse-grained model, this means having the ability to model a project manager agent who has control over the execution process of the whole project. This agent has the ability to direct the execution process in order to achieve the predefined objective. On the other hand, developing a simulation model using reusable domain's specific components is very intuitive. However, the use of the domain specific models previously

mentioned results in fine-grained models. This means that the model is built from a set of isolated separated components (for example, constraints) that do not and could not share a global goal or objective.

The purpose of this in-progress research project is to automate the evaluation phase and to present wide expressive scenarios' analysis, such as costs, durations and resources' utilization analysis, which supports the manager with all information he/she might need to be aware of the impact of uncertainty on his/her project. This paper will be focusing on explaining the developed approach by introducing the following:

- A multi-objective hybrid simulation model specialized for building construction projects. This step will be explained in section simulation model.
- A corresponding special purpose simulation framework where the complete simulation study is carried out and the results are generated. Also an overview of the architecture will be presented in section simulation framework.

After proposing the new approach, it will be applied on a real building project, and the results will be shown and compared to another approach, then some performance characteristics are discussed in section: "tests and results". This paper ends up with a short conclusion and a list of challenges as a further work in section: "conclusion and further work".

SIMULATION MODEL

The proposed simulation model is a hybrid model built from a combination of a deterministic colored petri-net model and a multi-agents model. The well-defined execution semantics of a petri-net model is behind the decision to use it. The adoption of CiSmo process model and its linkage to a product model makes the simulation model obviously specialized for building construction projects. The behavior of each agent is objective driven that makes the proposed model a multi-objective model.

CiSmo process model. It is specialized for building construction projects (Kugler et al. 2011). Its formal model consists of construction methods that are linked directly to component types instead of components. Each construction method defines multiple construction activities, and each activity consists of different tasks. The construction activities implement the listener design pattern, in that each activity is an events listener, and at the same time an event producer. For example, the activity "*A3: build limestone wall_11.5*" consists of the tasks "*T1: build*" and "*T2: make openings*". It is been previously determined that the activity should start in the first working section and it listens to (or, waits for) the following events: "activity *A1: building limestone wall_17.5 is done at the same floor and all working sections*", and "*6 days passed after the end of activity A2: building RC wall_25.5 at the same floor and all working sections*". When the activity is finished, the event "*building limestone wall_11.5 at the floor and all working sections is done*" is fired.

Deterministic colored petri-net model. The model is defined by the tuple <P, T, W, M, C>, where P: is a set of places, T: is a finite set of production tasks from the process data, W: is a finite set of arcs representing precedence restrictions and organizational interdependencies among the tasks, M: is a set of tokens preserving the execution's state, and C: is a finite set of colors. Actually, the model is

deterministic in that $\forall p \in P : |{}^{\circ}p| = |p^{\circ}| = 1$. A transition $t \in T$ is enabled in M iff:
$\forall p \in P : M(p) \geq W(p,t)$ & $areResourcesAvailable(t)$ & satisfy$Objective(t)$, i.e. in addition to the available number of tokens for consumption, the needed production resources must be available and the transition must satisfy the assigned objective. An enabled transition consumes one token out of each place of its input places, and produces one token to each place of its output places. Besides, each token has an attached token color that can be recognized by the transitions. There are 4 different types of transitions: Transition, Split-transition, Synchronization and Interval. The following figure (see Figure 1) illustrates mapping between the process model and the petri-net model applied on the example mentioned in the previous section.

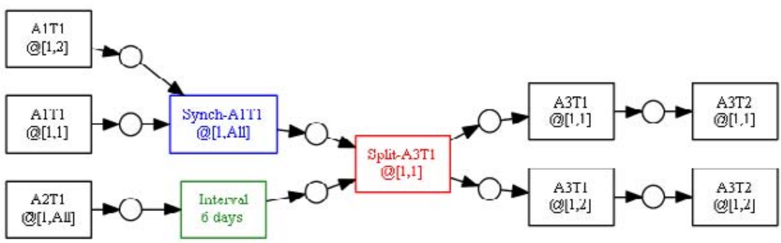

Figure 1. A sample petri-net built for a construction activity

Based on a set of formal mapping rules, a petri-net is automatically generated for the process data. This previously mentioned net represents a part of the project's execution plan in regards to tasks, workflow directions and the dependency relationships. Hence, changes on the process data, such as changing the construction method of a component type or assigning different production equipment for a task, results in a new petri-net that does not differ much from the original one. The simulation framework presented later will benefit from this fact in order to build one and only one global, but still a deterministic petri-net.

Objective driven multi-agents model. The model consists of 4 types of agents; a project manager that is assigned a specific color (ID), a resource allocation manager, a resource manager and a time distribution manager. The agents' relationships and methods of interaction (Macal et al. 2011) are defined. Their environment is the petri-net that represents the project execution plan. Moreover, default implementations of the agents' attributes and their individual behaviors are developed, however, it is still flexible enough to implement the behavior of a new agent and inject it into the model in order to integrate any new objective. This makes the system an open architecture system (Shen et al. 2006). The transition's guard expression is evaluated in the context of the project manager agent that is the central controller of the system. The project manager agent communicates with the available resource managers through the appropriate resource allocation manager in order to execute the project. Resource allocation managers are classified according to the resource type, name and ID. The following table (see

Table 1) shows the main communication methods and responsibilities of each agent type.

Each simulation model consists of a project manager that is assigned for a petri-net (project execution plan) and a color, different resource allocation managers, different resource managers, and a time distribution manager.

Table 1. Types of an Agent

Agent type	Communication methods	Responsibility
Project manager	Prioritizes enabled transitions, and update key performance indicators.	It is responsible for executing the project plan represented by the petri-net. It is asked to prioritize the enabled transitions according to its assigned objective (goal), and demands for allocating the corresponding resources.
Resource allocation manager	Distributes resources on the transitions.	It is responsible for checking the availability of resources for the transitions passed from the pm, and then allocating them.
Resource manager	Is available, lock and unlock.	It is responsible for the availability, locking and unlocking of its own resources.
Time-distribution manager	Determines the duration of a transition.	It is responsible for manipulating the production duration of the transitions. It can be deterministic, stochastic, or it may adapt the weather forecasts.

SIMULATION FRAMEWORK

Our goal is to develop a framework where more than one simulation model is being simultaneously carried out efficiently. Consequently, the results are going to be multiple project schedules in addition to comparisons among these alternatives according to costs, duration and resources utilizations. Figure 2 shows the main components of the developed framework.

Simulation engine. It is a discrete event simulation engine that deploys a dynamic time step (clock manager) in order to accelerate the simulation run. The executor is responsible of fetching the tokens from the net that correspond to the agent's color. Accordingly, it coordinates the communication among the participant agents in order to consume any finished tokens and produce new tokens. The execution is represented by the tokens that are saved within the data store. Each token holds the necessary information such as: related task, production date, finish date, assigned resources, trace of decisions taken.

Agents' pool and IoC controller. The pool component is where agents are saved and from where they are called while the execution. Calling agents is done through an IoC controller (inversion of control pattern). The essential role of the IoC controller is to ensure soft dependencies among the agents, and therefore making the system dynamic. Agents are registered according to its context in the IoC.

Global petri-net. This net is the union of all other petri-nets (all the project execution plans) within the simulation study. After this union process, some places might have more than one transition in its preset or post set, yet it is still

deterministic in that: $\forall p \in P : |^{\circ}p(planID)| = |p^{\circ}(planID)| = 1$, where the planID is the ID of the agent's project execution plan.

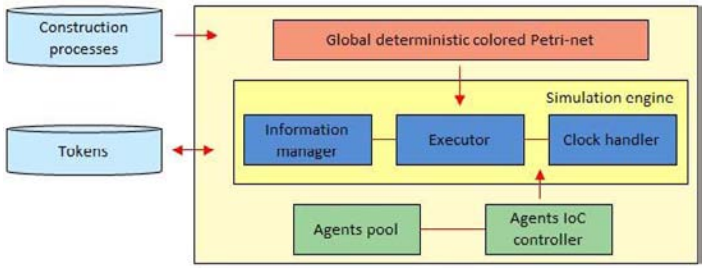

Figure 2. Architecture of the Simulation Framework

TESTS AND RESULTS

The implemented approach is named MOSAICA (**M**odeling **O**bjects and **S**imulation **A**gents with **I**mpact on **C**onstruction M**a**nagement). MOSAICA is applied in-house on a real building construction project. The building is a four floor nursing home that was built in Thueringen, Germany. Namely, the test case conditions are the following: All types of the production equipment are made available, and all types of the production materials are made available. For each type of working labors, 2 groups that each consists of 5 workers are made available. The agent's objective is to prioritize the tasks on the critical path. Table 2 shows the results after running the simulation model using both CiSmo in SeSAm (column 3) and MOSAICA (column 4). Also all durations considered are in minutes. The results are classified according to the component type, i.e. it indicates how long it took to build all the components of a corresponding component type during the whole project.

Table 2. Sample From the Simulation Results Compared to Real Durations

Component type	**Real duration**	CiSmo duration	MOSAICA duration	Difference % col_2 from col_1	Difference % col_3 from col_1
Wall 36,5	134390	134892	134351	0,0037	0,0003
Continues footing	67215	67306	67202	0,0013	0,0002
Column 30x30	9887	10063	9895	0,0178	0,0008
Stairs	10494	10626	10494	0,0125	0,0000

This table is considered as a validation for both CiSmo in SeSAm and MOSAICA. The main reason behind the differences shown in column 5 is the delay of the agents' movement on the virtual site. In column 6 there's a difference from the real duration as well. In order to clarify this difference, the following table (see Table 3) is established. In fact, this table shows the same previously shown simulation results but this time compared to the durations that were calculated directly from the performance keys.

Table 3. Sample From the Simulation Results Compared to Calculated Durations

Component type	**Calculated duration**	CiSmo duration	MOSAICA duration	Difference % col_2 from col_1	Difference % col_3 from col_1
Wall 36,5	134351	134892	134351	0,0040	0,0000
Continues footing	67200	67306	67202	0,0016	0,0000
Column 30x30	9895	10063	9895	0,0169	0,0000
Stairs	10494	10626	10494	0,0125	0,0000

Analyzing these values will allow us to easily come to the fact that the values' precisions of the performance keys play an essential role during this kind of simulation. Further, there is a remarkable difference in the simulation run time. The same configuration is carried out in SeSAm and MOSAICA, and the following table (see Table 4) shows the recorded results.

Table 4. Comparison of the Execution Time Between 2 Different Simulation Tools

Simulation environment	Simulation time for 1 simulation model	Simulation time for 100 simulation models
SeSAm	12 minutes	-
MOSAICA	204 milliseconds	2693 milliseconds

As for the performance characteristics of MOSAICA, the fact that a petri-net preserves the execution state by means of tokens keeps the execution complexity very applicable. In other words, instead of scanning all the net's places (~300 places for this test case) to fetch all enabled transitions, only pending tokens (~20 tokens, this number is concluded from the test experiment) that are residing in places are checked in each clock tick.

Furthermore, the global petri-net, which is the union of all the nets, actually saves execution memory. To explain more, it builds only one net with extensions (<400, 400> enrolled from the test case) rather than holding multiple almost identical nets in the memory (regarding this test case: 100 * <300, 300>), likewise the model can distinguish the different execution plans.

Besides, the dynamic time step reduces the number of the needed execution loops and checks. Regarding this test case, the average step size was 40 minutes instead of 1 minute when running one agent, i.e. 40 times faster. Running 100 agents concurrently reduced the step size to16 minutes, i.e. 16 times faster, considering the fact that it took one of the agents about 450,000 minutes to execute the project.

CONCLUSION AND FURTHER WORK

This paper presented work in progress in achieving an automated evaluation phase of a simulation study. That was done in an attempt to support a project manager by a management tool to cope with the impact of uncertainty on his/her project. The proposed multi-objective hybrid simulation model made it possible to create different objective-oriented scenarios. As for the developed simulation framework, MOSAICA established the possibility of running a large

number of model's alternatives simultaneously within milliseconds. Some of the urgent further work is listed in the following two challenges:

- The definition of objectives, and developing economic criteria. For example: prioritizing tasks along the critical path, increasing the utilization of special key resources, sticking to the contracts dates, and taking into account weather conditions.
- The automatic preparation and generation of possible simulation model's alternatives within a simulation study. It's suggested that the process data can be modified based on the experience of the previous finished construction projects and thus, different simulation's experiments can be generated. Furthermore, the number of the available resources in each experiment will be changed according to the value ranges, which are defined in the process model, and different new simulation's situations are generated accordingly. Besides, different objectives will be assigned to the agents.

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Organization-Centered Multi-Agent Systems for Dynamic Highway Maintenance Planning

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ABSTRACT

Maintaining the infrastructure involves managing structural elements requiring different maintenance strategies. Some elements have to be maintained at regular intervals based on a pre-programmed routine. Other elements are inspected at regular intervals and the specific the requirements for maintenance remain unknown until after the inspection. The latter complicates job scheduling as it disrupts existing programs for routine maintenance. Conventional maintenance planning systems lack dynamism and/ or fail to acknowledge all relations between actors, activities and resources. This paper discusses the potential of addressing these challenges using an organization-centered agent-modeling approach where different scenarios are encapsulated in agent models which captures: 1) global organization strategy and goals, and 2) the objectives and requirements of different stakeholders. Specific challenges of maintenance planning that cannot be fully addressed using conventional tools have been identified. The paper describes implemented of proof-of-concept organization-centered agent models that capture the requirements of maintenance planning.

INTRODUCTION

Despite the significant advances that have been in construction informatics, there are still key outstanding issues that impede the seamless flow of information and knowledge across distributed applications (Sierhuis et al. 2009; Preitula 1998). Significant factors include the explosion in the sheer volume of real-time data generated through the use of robotics, the emerging smart grid and other advances intelligent infrastructure systems. The resulting knowledge and information integration challenge is further compounded by the growing number of business operations being executed in a global context by multinational corporations; a trend that has altered organizational time scales and also given rise to new organizational forms, complexity and environment. Some issues have been addressed through the evolution of sophisticated building information models. However, some challenges still remain unresolved. Many of these can be attributed to the interfaces with a

number of discipline-specific applications. The complexities inherent in generating explicit and independent representations of knowledge structures within such distributed applications remain largely unresolved. To fully address the information and knowledge flow needs, there is a need for dynamic organizational models that capture the critical aspects of an open, heterogeneous environment – see Table 1 (Clancey et al. 2002 & 2005; Klein et al. 2005; Sierhuis et al. 2009).

Table 1. Modeling an open, heterogeneous environment

Critical Aspects	Examples
Organizational structures	Dynamic entry and exit of actors
Behavioral complexities	Flexible roles, goals and tasks
Collaboration complexities	Formal and informal interactions, multiple teams or adhocracies through which actors perform individual or joint activities.
Regulatory components	Flexible representation of organizational norms, policies, laws and culture
Common understanding	Seamless flow of knowledge among actors through shared understanding of positions and arguments
Context awareness	Using, reasoning and communicate about the physical and virtual environment

The authors identified several examples of specific challenges in systems being used for highway maintenance planning. The information was gathered through a case study review of ABC Limited, a large company contracted to perform highway maintenance for UK's High Agency (HA). In 2001, the HA adopted a new type of maintenance contract - Management Agent Contracting (MAC). The types of maintenance activities undertaken by company ABC under the MAC agreement include: 1) Planned maintenance that are generally speaking activities undertaken to address normal "wear and tear" of the physical asset that can be expected over time (e.g. road resurfacing, strengthening or replacement of structures such as tunnels and bridges); 2) Routine maintenance (e.g. pothole repairs or street light outages, response and repairs following collisions or spillages, cyclical tasks such as cutting grass verges, periodic inspections of the condition of road surfaces and structures, as well as identifying the need for maintenance); 3) Winter maintenance (e.g. gritting of roads, snow clearance and maintenance of the equipment used for those tasks), and; 4) Technology maintenance (emergency phone systems, road sensors, CCTV and communications systems for regional control centers).

The National Audit Office (2009) observed that there were some improvements to service delivery that could be attributed to the use of the MAC model. However, there were also some rises in costs, with routine maintenance costs increasing by 11 per cent above inflation since 2002-03 and expenditure on planned maintenance rising overall by 5.5 per cent above inflation. A significant proportion of these additional costs can attributed to the use of static and closed knowledge systems. It is relatively easier to design intervention strategies, plan and schedule the use of resources for maintenance activities that are time-based, condition-based or preventive by nature than to plan for reactive maintenance. Reactive maintenance activities, being unpredictable, are generally disruptive to the existing plans and schedules. Depending on the severity of the incidence, the stipulated response can vary from 15 minutes (Category 1) to the action being designated as something to be

done as part of routine maintenance at a late date (Category 2 or 3). There are financial penalties associated with not acting within the required response time. In addition, as the contracts are renewable, none performance could result in losing the contract. Needless to say, responding to incidents is given high priority with the primary focus being completion within the stipulated time. From the authors' experience, conventional knowledge system (See Figure 1) for managing the work orders and allocating of tasks to different crews do not adapt easily to such disruptions.

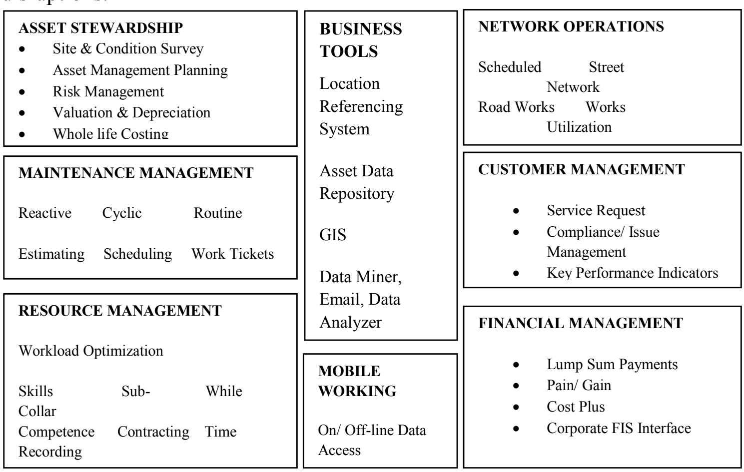

Figure 1. Features of Conventional Maintenance Management Knowledge SystemsAdapted from Pitney Bowes Business Insight (2009)

Maintenance service providers have Incident Response Units (ISU). When not responding to an incident, the ISU crews perform routine and preventive maintenance activities. Failing to make strategic decisions on how to adapt to changes triggered by disruptive reactive maintenance activities affects the projected schedule of payments from the client as some work items will take longer than planned. Some incurred costs that risk not being recovered in the payment period during which they were incurred include the engineering designs developed for the work items left pending as the ISUs respond to incidents. There are some other payment-related factors that make scenario modeling in this use case advantageous. Under the MAC model, the maintenance provider negotiates lump sum payments for some work items. The contractor is expected to absorb any additional costs that are incurred through the ISU crew being reassigned to an incident. Without having a strategy for managing adversely impacted scheduled routine maintenance work is the contractor can incur significant loses. Payment for some work items is governed by the "Pain/ Gain" agreement - the HA and the service provide commit to sharing any cost savings or losses. Both the provider and the HA benefit from work being performed under the budgeted costs. Some work items are governed by a "Cost Plus" agreement through

which the contractor can negotiate for payments to cover costs over and above the original budget. The decision on whether or not to award payments for additional costs is at the discretion of the HA and there is therefore no guarantees that the contractor will always receive the requested adjustments to the original budget.

From the foregoing, it is clear that decisions being made can be greatly enriched through using a dynamic and adaptive intelligent knowledge system that can model different scenarios giving the maintenance service provider a global perspective of the net impact of decisions being made when responding to incidents.

THE AGENT ORIENTED METHODOLOGY

There have been efforts invested in addressing the requirement for dynamic and adaptive using agent-based knowledge systems. Since the 1990s, researchers have demonstrated different ways through which agent-based approaches can address some of these challenges (Ferber, 1999). The benefits of using agent-based approaches in construction industry-specific knowledge systems is a subject that has previously been covered extensively elsewhere (see Anumba et al. 2005 and Obonyo and Anumba, 2011) and will not be duplicated here. Agents present a distributed approach to locating, retrieving and integrating information, and therefore resulting in applications that co-operate, co-ordinate and share their information with other applications. Interestingly, in many of the conventional agent-based systems, agent-to-agent communication is achieved through interaction protocols such as FIPA ACL. In these applications, agents can only communicate with one another within a closed system. Since agents generally exist in the context of multi-agent software systems with some defined global behavior being derived from the interaction of constituent agents, the deployment of ACMAS-based applications greatly undermines the potential benefits of using a community of autonomous problem solvers (Jennings and Wooldridge 2000; Zambonelli et al. 2001).

Existing construction industry-specific applications have been based on 'agent-centered multi-agent system' (ACMAS) models. This limits the extent to which intelligent knowledge systems can exploit the advantages of deploying a community of autonomous problem solvers. ACMAS models focus on the internal mental state of an agent, the relationship between these states and the agent's overall behavior (Ferber et al. 2003). In this approach, communications become speech acts whose meaning may be described in terms of the mental states of an agent as is evident in agent communication languages such as the KQML and FIPA ACL. Agents in these applications can only communicate with one another within a closed system. Since agents generally exist within the context of multi-agent software systems with some defined global behavior being derived from the interaction of constituent agents, the deployment of ACMAS-based applications greatly undermines the potential benefits of using a community of autonomous problem solvers (Jennings and Wooldridge 2000; Zambonelli et al. 2001).

Without this societal structure the patterns, the outcomes of the interactions are inherently unpredictable. Predicting the behavior of the overall system based on its constituent components is extremely difficult (sometimes impossible) because of the high likelihood of emergent (and unwanted) behavior (Jennings 2000). In agent-centered models, achieving interactions between agents from different designers

assumes that one has knowledge of the primitives of communications (the "performatives" of the language) and the architecture of agents (for example, assuming that agents are behaving purposively in a cognitive way, using some kind of BDI (Belief-Desire-Intention) architecture (Ferber et al. 2003). ACMAS-based agents do not have access to such constraints, which are often specified as ISO-like standards. They also lack the ability to either accept or refuse to follow these standards. For these agents to communicate, they must therefore be deployed using the same language and very similar architectures. There has been a growing interest among researchers to resolve this problem through modeling agent-based systems using organizational abstractions. The subsequent section discusses the potential for using an organization-centered multi-agent approach to address some of the complexities in highway maintenance planning.

PLANNING FOR HIGHWAY MAINTENANCE USING THE ORGANIZATION-CENTERED MULTI-AGENT APPROACH

The challenges inherent in the highway maintenance scenario described in a preceding section mirror the challenges for railway maintenance observed by Mensonides el al (2008). Their proposed solution was based on the use of OperA (Mensonides et al. 2008) organizational agent models. Since agent-based systems can be naturally viewed as computational organizations, organizational abstractions and the associated metaphors and concepts should play a key role in the analysis and design of MAS (Jennings 1999; Zambonelli et al. 2002). In this approach, issues such as open organization modeling, argumentation frameworks, teamwork, and culture are captured using macro-level concepts such as 'organizations', 'groups', 'communities', 'roles' (Ferber et al. 2003; Zambonelli and Parunak 2002, Sierhuis et al. 2009).

Despite the similarities in the use cases, the author favors the use of AGR (Agent-Group-Role) models over the approach adopted by Mensonides el al's (2008) models. AGR models have been deployed within MADKIT (URL2) which is a stand-alone, java-based platform. The OperA approach was implemented as part of the EU-funded ALIVE project (Aldewereld et al. 2010). The ALIVE was a project directed at implementing a suite of adaptable, organization-aware, service-oriented computing applications. It is difficult to deploy standalone organizational-models based on the OperA approach.

The authors have used MADKIT (URL1) to deploy an organization-centered MAS construction e-business prototype for the procurement of concrete. As indicated in a preceding section, structural repair of the infrastructure is an integral part of maintenance activities. Suppose structural damage occurred through an incident and there will be a need to urgently identify the most optimal strategy for getting the required material (concrete, in this example). In the implemented proof-of-concept requests for bids, identification of suitable suppliers and the negotiation to close the transaction are all be done using MADKIT's macro-level concepts as shown in Figure 2. Because the agent-to-agent interaction in not based on the mental states of agents, an infinite number of options can be explored through agentifying existing targets using wrappers.

The authors have also modeled different scenarios for dynamically assigning work items to groups of maintenance crews (see Figures 3 & 4). Within this organization-centered MAS, new work items arising from incidents and disruptions to planned maintenance activities as incidents occur can be competitively assigned dynamically to a large team of distributed crews using negotiations governed by macro-level concepts such as 'organizations', 'groups', 'communities', 'roles.' The distributed units across all contracts being managed from dispersed locations are structured into communities. Agents representing the different units can join and leave the communities at will. The agents' interactions are based on the different units assuming one of the following roles: broker, client or provider. The successful negotiation that results in the dispatch of an ISU in response to an incident creates a demand for a crew to take on the activity that the ISU crew was previously performing. This becomes a request bid item for other crews. Through pre-specifying the preferred hierarchy of importance for the maintenance activities, pending work items can be dynamically re-negotiated multiple times to assess the global impact of different adjusted schedules and plans following disruption.

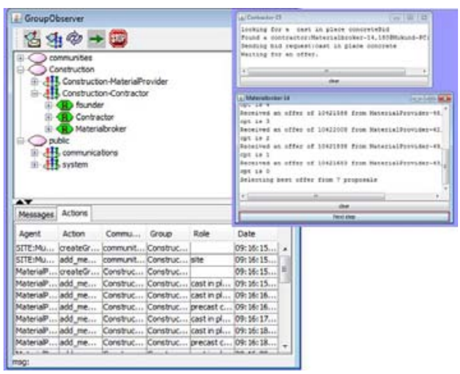

Figure 2. Organization-Centered Agent-based Concrete Procurement

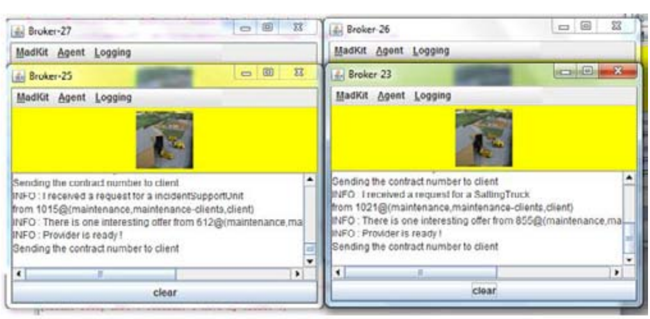

Figure 3. Work Assignment Based on Organization-Centered Models

DISCUSSION AND CONCLUSIONS

The discussion in the preceding sections has demonstrated the superiority of using organizational-centered models which allow flow of information across agents without using their internal mental states. In the implemented proof-of-concept communication was achieved though using the MADKIT platform, an implementation of Ferber et al.'s (2003) Agent-Group-Role approach in which MAS are designed using only organizational concepts such as roles (or function, or position), groups (or communities), tasks (or activities) and interaction protocols (or dialogue structure). This approach gives developers the ability to build organizations as frameworks where agents with different cognitive abilities can interact. The resulting organization-centered MAS applications reflect the dynamic and flexible characteristics of an open, distributed system. This approach can therefore address many of the challenges inherent in existing decision support knowledge systems for highway maintenance. Specific examples have been outlined in Table 2 (Mensonides el al, 2008).

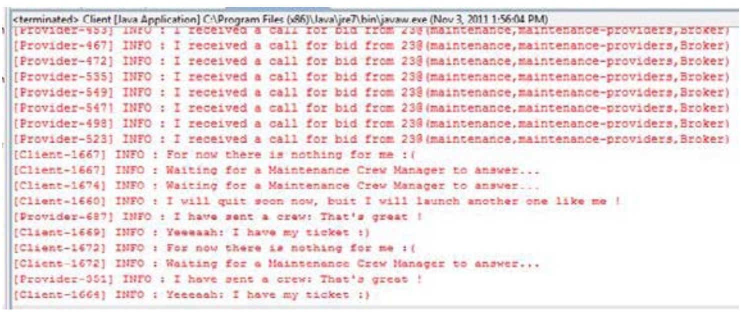

Figure 4. Extract of Agent-Group-Role-Based Work Assignment Negotiation

Table 2. Enhancing Existing Systems

Known Limitations	Required Change
Rigid operations driven by timetables	Dynamic scheduling of operational serviced and maintenance jobs triggered by events
Homogeneous processes for a single client	Heterogeneous processes to comply with a number of contracts
Top-down planning and scheduling	Negotiation between parties with conflicting interests
Rigid maintenance allocation based on head office planning	Dynamic negotiation based on the condition of the highway assets

The deployment of both OMACS and MASC into universally-applicable, organization-based models requires verification and validation in different use cases based on the requirements of a specific disciplinary domain. Construction Informatics researchers can make a contribution to their transition from experimental prototypes into more stable and robust organization-centered models through re-deploying the existing ACMAS-based systems such as the architectural and engineering agent-

based applications described Anumba et al. (2005). This would significantly advance the efforts directed at enabling the seamless flow of information and knowledge in open, intelligent, knowledge applications. In subsequent research, the authors enhance the proof-of-concept implement for highway maintenance through assessing the feasibility of using an agent-based wrapper to enrich these models with real-time data captured from sensors being used to monitor the structural health of the infrastructure.

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Recovering 3D Structure of Poorly Textured Infrastructure Scenes Using Point and Line Features

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ABSTRACT

Most of the existing automated machine vision-based techniques for as-built documentation of civil infrastructure utilize only point features to recover the 3D structure of a scene. However it is often the case in man-made structures that not enough point features can be reliably detected (e.g. buildings and roofs); this can potentially lead to the failure of these techniques. To address the problem, this paper utilizes the prominence of straight lines in infrastructure scenes. It presents a hybrid approach that benefits from both point and line features. A calibrated stereo set of video cameras is used to collect data. Point and line features are then detected and matched across video frames. Finally, the 3D structure of the scene is recovered by finding 3D coordinates of the matched features. The proposed approach has been tested on realistic outdoor environments and preliminary results indicate its capability to deal with a variety of scenes.

INTRODUCTION

According to NIST (2004), inaccurate or unavailable as-built information of the US capital facilities annually costs $1.5 billion in the Architecture, Engineering, and Construction (AEC) or Facilities Management (FM) industry. This indicates the need for new solutions that improve data acquisition and building information exchange in this industry. In terms of documenting 3D geometric information of infrastructure as the main scope of this paper, machine vision-based technologies have demonstrated promising capabilities as a cost-effective and easy-to-use alternative to the traditional methods (Gorlparvar-Fard et al., 2009; Fathi and Brilakis, 2011; Golparvar-Fard et al., 2011; Klein et al., 2012). These technologies provide an opportunity for extracting as-built semantic information and generating photo-realistic models; however, they may not be as accurate as laser-based sensing methods (Golparvar-Fard et al., 2011). Several factors could affect the accuracy of the output of these approaches including camera resolution, lens distortion, distance between the object of interest and the camera, texture of the scene, etc. (Fathi and Brilakis, 2011). Although most of these factors can be adjusted for a specific scene in order to enhance the output accuracy, the scene characteristics cannot be altered. From a practical perspective, this means that a machine vision-based method should be able to deal with a wide variety of scenes ranging from poorly to well-textured.

Most of the conventional machine vision-based methods have utilized corner like features in the 3D reconstruction process, especially camera motion estimation step; the reason is the distinguishability of these features which makes it easier to match them across different views of a scene (Tomono, 2009), the fundamental task in the Structure from Motion (SfM) process. However, corner points are not sufficiently available in non-textured environments such as smooth surfaces of a concrete wall or roof structures; this causes instability in these methods which can lead to failure of the process. Significant progress has been made in solving this problem by using different forms of visual features such as edge points or lines (Tomono, 2009; Chandraker et al., 2009; Pradeep and Lim, 2010). However, these methods mostly focus on the visual odometry aspect of the problem, which is finding the motion of the camera set in the environment, not the ability to generate accurate reconstruction of the scene.

This paper presents a video-based method which uses a combination of point and line correspondences across two stereo views of a scene. It allows maintaining the well-known benefits of point features while taking advantage of well-localized and reliably tracked line features. The contribution of this paper is twofold: (1) a novel algorithm that calculates two multi-dimensional descriptor vectors for each line feature which subsequently facilitates the line matching process; and (2) a new metric to calculate the reprojection error of line features. Preliminary results from applying the proposed method for reconstruction of a façade and a roof structure indicate: (1) 94% accuracy in line matching and (2) an average of 7mm improvement in the metric accuracy of 3D line segments.

BACKGROUND

A videogrammetric framework for 3D reconstruction of an environment is generally composed of several individual steps including data collection using a proper camera set up (e.g., monocular, binocular, or multi-camera rig), feature detection and matching/tracking (e.g., corner points or straight lines), camera motion estimation, global optimization, and visual triangulation. Since the contributions of this paper fall into the feature matching and camera motion estimation steps, this section only presents background information about these two processes.

Automatic feature matching has been widely studied in the past few years. Most of the successful approaches proposed for this purpose characterize the local neighborhood of a feature into multi-dimensional descriptor vectors (Lowe, 2004; Bay et al., 2008; Wang et al., 2009). The emergence of invariant local feature points and descriptors such as SIFT (Lowe, 2004) and SURF (Bay et al., 2008) has successfully addressed the matching problem for feature points. However compared to feature point matching, a significantly smaller number of studies have been carried out for line feature matching and therefore it is still a challenging task. Schmid and Zisserman (2000) proposed a method that uses: (1) the epipolar geometry constraints of line endpoints for short baseline matching; and (2) one parameter family of plane homographies for wide baseline matching. This method requires known geometrical relationships between images or video frames which are not always available. Bay et al. (2005) used color histograms to generate an initial set of line segment correspondences; then, a topological filter is used to increase the number of possible

matches. However, this method heavily relies on color histogram information of the local neighborhood of a line segment which is very sensitive to illumination, point and angle of view, and the distance between the camera and object of interest. Wang et al. (2009) proposed a line matching method that is motivated by the concept of local descriptors presented in Lowe (2004). It uses local image gradients to generate a descriptor vector for each line segment. This method provides poor matching results for line segments that are located in object boundaries when the background of the object changes in two views (Figure 1). The reason is that the descriptor vector is built for a rectangular pixel support region around a line segment and therefore for a specific line segment at object boundaries, half of the information may completely change in two different views (Figure 1).

Similar to the feature matching step, significant research effort has been devoted to find camera motion using point features while not much has been done in terms of using lines. It is even less for using a hybrid approach (i.e., points and lines). Feature point correspondences allow generating a system of polynomial equations from geometrical constraints (Nister et al., 2004). However in poorly textured environments such as indoor scenes, not enough point correspondences could be found; therefore, these methods fail with high probabilities. Since line features are prominent in most man-made environments, they can be employed to alleviate this problem. Line features have been traditionally used to build a multifocal tensor and then estimate the camera motion (Bartoli and Sturm, 2003). Schindler et al. (2006) used additional information from orthogonal vanishing directions to enhance the computational speed of this process. More recently, Chandraker et al. (2009) proposed a hypothesize-and-test framework to estimate the motion of a stereo rig from line segments in real-time. This method avoids computationally extensive optimizations in order to increase speed and hence is only applicable in finding the approximate location of the camera set in an unknown environment. Pradeep and Lim (2010) combined the available information from point and line features to generate a minimal solver for performing online visual odometry. Using the constraints implied by two trifocal tensors, this method builds a system of polynomial equations and then solves it using a quaternion-based direct solution approach. This method also uses approximations in several steps to maintain the real-time performance of the system.

The main objective of this paper is to address the above discussed limitations

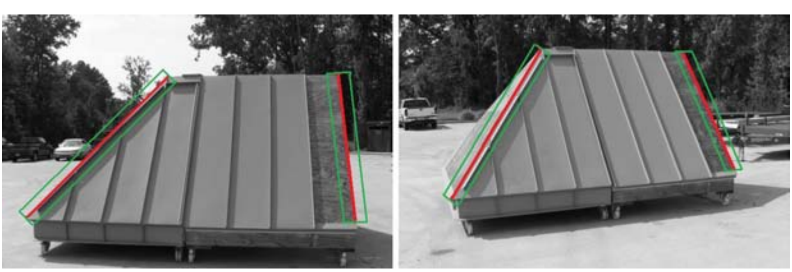

Figure 1: Rectangular pixel support region around line segments used in Wang et al. (2009). Notice completely different pixel information available in one side of the lines at object boundaries.

in line matching and hybrid visual odometry. It aims to present a method that generates descriptor vectors for line segments considering the special case for lines at object boundaries. Furthermore, it proposes a new metric for calculating the reprojection error of line segments. Although this approach is more computationally extensive than the competing ones, it provides more reliable estimation which is the main goal in any as-built documentation applications.

METHODOLOGY

Constructing a descriptor vector for a line segment necessitates defining a local neighborhood for each detected line. The first step in this process is to calculate the orientation of the line segment. This can be done by finding the orientation of the local gradient at all image pixels belonging to the line segment:

$$\alpha = \tan^{-1}(dy/dx)$$

where α is the angle of gradient; dy is the local intensity gradient in the vertical direction; and dx is the local intensity gradient in the horizontal direction. An important feature of the angle of gradient is that α is more or less equal to the orientation of the line segment in 2D image space. Therefore, the orientation of the entire line is estimated by averaging α values for all the pixels on the line.

Once the orientation is calculated, a SIFT-like strategy is used to construct the line descriptor. For this purpose, the local neighborhood is divided into two regions separated by the line segment (i.e., gray and white windows in Figure 2). As illustrated in Figure 2, for each pixel on a line segment two 5×5 windows are considered at each side of the line. The gradient magnitude and orientation is calculated for each pixel in these windows. The relative orientation values are then found by subtracting the line orientation from pixel gradient orientations; this helps to obtain rotation invariance. The 25 relative orientation values at each window are used to form orientation histograms that summarize the content over 8 bins covering the 360 degree range of orientations. Moreover, each relative orientation value is weighted by its gradient magnitude and Gaussian-weighted circular window with $\sigma = 1.5$, as suggested in Lowe (2004). In order to take into account the different length of line segments, the gradient description matrix (GDM) concept proposed in

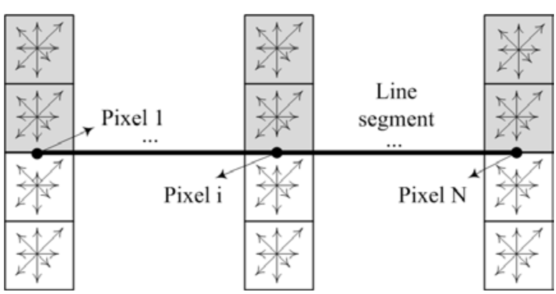

Figure 2: Support region for pixels on a line segment. Each sub-region window is of size 5×5. The line segment consists of N pixels.

Wang et al. (2009) is used twice (i.e., once for gray windows and another time for white windows). Accordingly for each line segment L, two GDMs are formed in which the size of each matrix is $16 \times N$; N is the number of pixels on L. As shown in Wang et al. (2009), the mean and standard deviation of the vectors constructing a GDM is found and then normalized to make the descriptor invariant to linear changes of illumination. The mean and standard deviation vectors are then concatenated to construct a 32-dimensional descriptor vector for each side of the line segment.

Once descriptors are constructed and line correspondences are found, all feature correspondences (i.e., points and lines) should be used to estimate the camera set motion. Initially, two trifocal tensors are calculated from the feature correspondences in two successive pairs of stereo frames (i.e., left and right views before and after motion). On the other hand, since a stereo camera rig is used in this study, the same trifocal tensors could be found as follows. If the rotation matrix and translation vector are denoted by R and T respectively, the projection matrices for the four video frames are:

$$P_A = K_A.[I \mid 0] \quad , \quad P_B = K_B.[R_0 \mid T_0]$$
$$P_C = K_A.[R \mid T] \quad , \quad P_D = K_B.[R_0 R \mid R_0 T + T_0]$$

where $P_A - P_D$ are projection matrices of the four video frames; K_A and K_B are the matrices representing intrinsic parameters of the left and right cameras, respectively; I is the identity matrix; and R_0 and T_0 are the extrinsic parameters of the stereo rig. This information allows us to calculate two trifocal tensors as follows (Hartley and Zisserman, 2004):

$$T^{L}{}_{i}^{qr} = (-1)^{i+1} \cdot \det \begin{pmatrix} \sim a^i \\ b^q \\ c^r \end{pmatrix} \quad , \quad T^{R}{}_{i}^{qr} = (-1)^{i+1} \cdot \det \begin{pmatrix} \sim a^i \\ b^q \\ d^r \end{pmatrix}$$

where $\sim a^i$ is P_A without row i and b^q, c^r, and d^r is the q^{th} row of P_B, the r^{th} row of P_C, and the r^{th} row of P_D, respectively.

Therefore, a system of linear equations can be constructed using the aforementioned relationships. The solution is an initial estimation of the camera set motion. This estimation is further optimized in a Levenberg-Marquardt optimization by minimizing the reprojection error of visual features. The reprojection error for point features is simply the distance between the point and its projection in the image. For line features, this paper proposes to use the normalized area between the line and its projection on the 2D image space; the normalization is based on the length of the line segment.

IMPLEMENTATION AND RESULTS

A prototype was created using Microsoft Visual C# to implement the proposed methods in a videogrammetric framework that allows recovering the 3D structure of a scene from a combination of point and line features. OpenCV was

selected as its main image processing library and ALGLIB was used to perform Levenberg-Marquardt optimization; both of these libraries are free and open source. Two high resolution Flea2 cameras were used to capture stereo video streams. The baseline distance was approximately 27cm and the video resolution was 1600×1200 pixels with a frame rate of 7.5 fps. The available methods in OpenCV were used to calibrate the stereo camera set up.

Two sets of experiments were conducted. In the first experiment, stereo video streams were collected from one side of a roof in a sheet metal roofing jobsite (Figure 3). For the second experiment, video data was captured from a poorly textured façade of a building in the Georgia Tech campus (Figure 3). SURF feature points and line segments were detected using the presented methods in Bay et al. (2008) and Van Gioi et al. (2010), respectively. SURF points were matched according to the Euclidean distance between the descriptors.

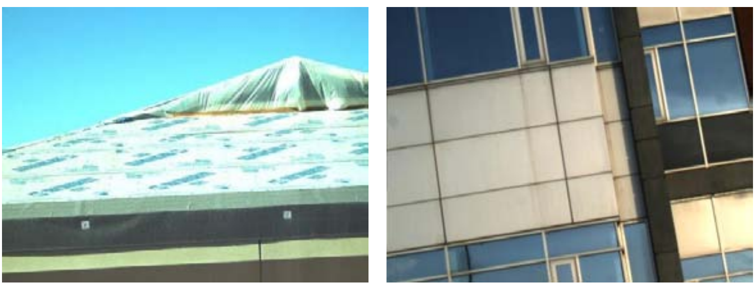

Figure 3: Sample video frames from a roof (left) and façade of a building (right)

For each detected line segment, two multi-dimensional descriptor vectors were found using the proposed method in this paper. When comparing two line segments, the Euclidean distance between any combinations of the four descriptors was calculated; the one with the minimum value was being considered as the difference. Epipolar geometry constraints and the minimum Euclidean distance were finally used to find the best possible match for a line segment in different views. In each experiment, 50 pairs of matched lines were randomly selected to evaluate the performance of the proposed algorithm and their accuracy was inspected visually (this sample size corresponds to 95% confidence level and ±10% confidence interval). The same data set was also used in a C# implementation of the method proposed in Wang et al. (2009). Table 1 shows the comparison results.

The corresponding features were used in the proposed camera motion estimation method and a bundle adjustment algorithm was used to globally optimize the incremental camera motions in the video sequence. Since the ground truth value of incremental motions could not be measured at the jobsite, the Euclidean accuracy of the outcome (i.e., a 3D line set) was used as an indirect metric for performance evaluation of the method. A sample set of 50 lines were selected from the outcome of the method at each experiment (Figure 4) and their length values were compared to the corresponding values acquired by using a total station (Table 1).

Table 1. Preliminary results for performance evaluation of the proposed method

Experiment	Method	Accuracy/Error
Line matching (lines that are not at object boundaries)	Proposed method	95%
	Wang et al. (2009)	95%
Line matching (lines at object boundaries)	Proposed method	92%
	Wang et al. (2009)	87%
Euclidean error of the generated 3D line set (95 percentile error)	Proposed metric to calculate line reprojection error	±44mm
	Distance between line endpoints as reprojection error	±51mm

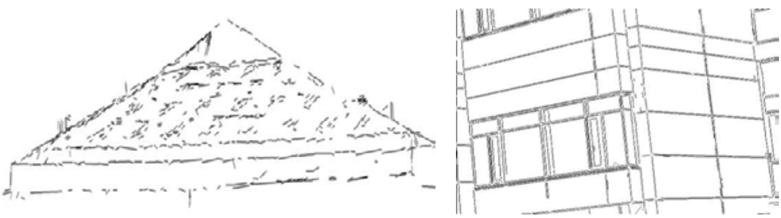

Figure 4: The output of the proposed method - a 3D line set

CONCLUSION

Machine vision-based approaches for as-built documentation of infrastructure are gaining significance in research community due to their lower costs and simplicity. However, further research must still be carried out to address different deficiencies in the process. One of the important limitations of the existing methods is the fact that they heavily rely on point features in several steps of the reconstruction process such as camera motion estimation. Therefore in poorly textured environments, these methods could be unstable due to lack of feature points. It has been shown that a combination of point and line features could potentially alleviate this problem and allow dealing with a wider variety of environments.

Since an abundant number of lines are typically visible in man-made scenes, this paper proposed a videogrammetric framework that benefits from line features in addition to points. This makes the reconstruction process more robust even if no point features can be reliably matched. In this paper, a robust algorithm was also presented to construct descriptor vectors for each detected line segment. Special attention was given to the line segments that are located at object boundaries which led to an average improvement of 5% in the number of correct matches compared to the state-of-the-art algorithm. Moreover, mathematical relationships were provided that allow constructing a system of linear equations for an initial estimation of the rigid body motion of a stereo rig. It was also proposed to use the normalized area between a line segment and its projection on 2D image space for calculating the reprojection error of 3D lines. It was shown that this criterion results in better reconstruction accuracy compared to the case that the Euclidean distance between the line endpoints and their projection is used to quantify the reprojection error.

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CAD/CAE In A Complex Structural Reinforced Concrete Design: Case Study of a Cathedral

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ABSTRACT

The main issues that significantly contribute to problems and delays on construction sites are changing client's requirements, incomplete design information, and poor site monitoring and control. Although experienced designers and construction managers control or minimize such problems during the design stage, the complexity and amount of the information in construction project make such a task very difficult to accomplish effectively. This paper presents an actual case study model for an integrated system which aims at presenting CAD/CAE in 3D using virtual reality. Firstly, the technology enables the designer to walk-through the proposed building perhaps at different construction time intervals-giving a vivid appreciation of the whole situation. Secondly, its enables the users to interrogate the building structural elements to present its details progress thus giving total virtual structural view of the project. Thirdly, the design effect of any changes in the building configuration can be modeled, visualized, and even the cost effect could be calculated. Finally the system enables virtual models to be shared and thus facilitates collaborative global design and construction. A case study involving the design of a 1600 m2 Cathedral with a roof height of 13m and a span of 33m is explored.

INTRODUCTION

The following project is a design project using Autodesk Robot Structural Analysis Professional 2010, a structural analysis program with special purpose features for structural design and analysis of building systems. This program enables the user to do a complete design on all structural elements and shows the steel reinforcement of all the main components that constitute the whole structure. The basic concept of the program is to create one model consisting of the floor systems and the vertical and lateral framing systems to analyze and design the whole structure. The analysis of the structure allows modeling of the deck floors and concrete floor systems that can automatically transfer their loads to main girders. This is a unique approach that would give the project engineer the ability to have full control and to completely access the impact of any changes occurring in the field.

PROJECT GENERAL OVERVIEW

The structure is a Cathedral (Figure 1) located in North Lebanon in a coastal region near the Mediterranean Sea. The structure is composed of two basement floors below ground level (Area = 1,605 m^2), a Ground Level Floor (Area = 1,605 m^2), a Mezzanine Floor (Area = 350 m^2), and a Roof System (Area = 1,605 m^2). The cathedral roof (Figure 2) comprises two side domes of 11.0 meters diameter each and a central dome of 14 meters diameter. The different elevations were pulled out of the perspective Architectural Drawings (Figure 3). The approximate Excavation Depth was found to be 10 meters below ground level giving the duplicated basement floor and 1 m for the mat foundation thickness.

COMPUTER MODELING

The most challenging part of the project was to model the cathedral given its geometric complexity on Autodesk Robot Structural Analysis. The support of AutoCAD was mandatory for reading the drawings provide and to help in the modeling of the geometry on Robot. In order to import the geometry to the Robot Software, the first step was to draw a 3D model (Figure 4) of the complete cathedral in AutoCAD using the centerlines of the walls, beams, columns, and slab extremities. The center line 3D model was saved as *dxf file type and then imported to Robot Structural Analysis where the different structural elements were assigned.

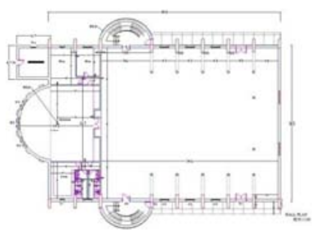

Figure 1. Cathedral Floor Plan

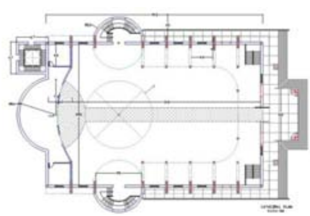

Figure 2. Cathedral Roof Plan

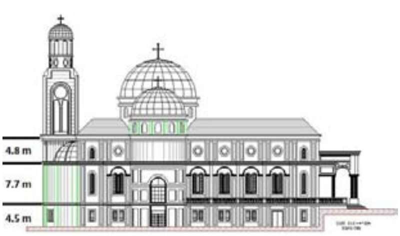

Figure 3. Cathedral Side

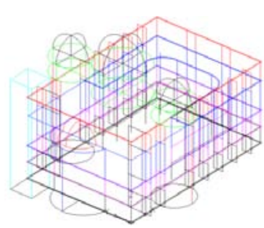

Figure 4. AutoCAD 3D Model

STRUCTURAL MODELING

After importing the AutoCAD centerline 3D dxf geometry of each floor into Robot, the slabs and bearing walls were drawn as panels, and the supporting elements were drawn as reinforced concrete bars treated as columns and beams accordingly. Afterwards, the slab geometry was assigned. Likewise, the dxf 3D centerline model of each floor was imported and drawn on Robot. The beams of the basement floors, the ground floor, and the roof floor were designed as girder T-Beams while the slabs were designed as one way joist slab except for the area of the roof that is supporting the domes. The slab under this part of the roof was designed as a Two-Way slab since it will carry the loads of the central and side domes.

MESHING

In order to avoid any meshing problems between the domes and the floor of the cathedral, the domes were drawn in separate Robot files and their loads were added to the main model as linear loading applied to the circular beams supporting the domes. As the domes were drawn in different files, three openings were introduced to the roof (Figure 9). However, in order to draw the supporting beams of the domes, meshing of the model was necessary as the central beams should be drawn on the mesh nodes.

When performing the Structural verification command, an "incoherent mesh on edges" error was detected along with many meshing problems resulting from either some nodes not being connected or from panels where the software was unable to apply the selected meshing technique. The main meshing problems were the result of a coarse mesh generation, minor geometrical errors, and from incorrect usage of the meshing technique (Figure 10). Finally the meshing problems were solved by refining the global mesh to 0.5 meters element size, by using the local refinement of incoherent mesh areas, by redrawing the panels with inconsistent meshing, and by locally generating the mesh using various meshing techniques.

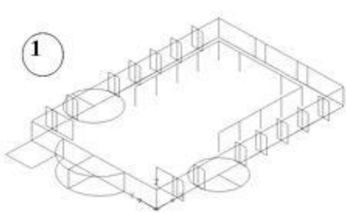

Figure 5. Importing the dxf Model from AutoCAD to Robot

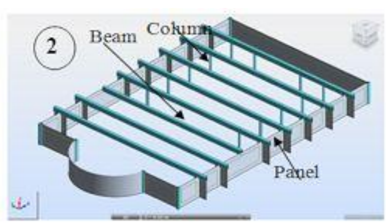

Figure 6. Walls, Columns, and Beams Assignment

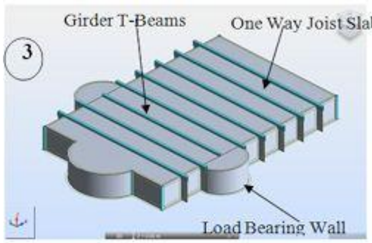

Figure 7. Slab Assignment

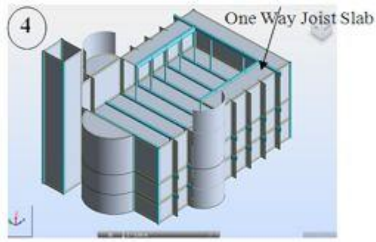

Figure 8. Robot Model up to the Mezzanine Floor

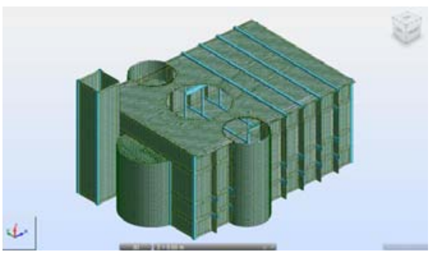

Figure 9. Cathedral Modal Mesh

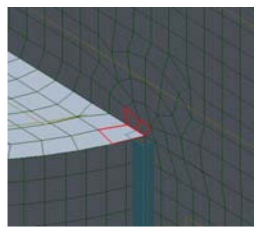

Figure10. Mesh Inconsistency

STRUCTURAL PLANS

The basement floor slab, the ground floor slab, the mezzanine floor slab, and half of the roof slab was designed as one way joist slab supported by girder T-beams with 5 m spacing. In the roof floor, circular beams were introduced beneath the domes; these circular beams were supported by four cantilever beams extending to the exterior walls of the cathedral. Those beams were also connected to another beam crossing from edge to edge of the other side of the cathedral and holding the side circular beams. The roof slab was divided into two separate designs. The part of the roof where the domes were located was designed as a two-way slab whereas the other part of the roof was designed as one way joist slabs supported by the girder T-beams.

The part of the roof where the domes are located is an area of high loading where the two way slab, the circular beams, the cantilever beams, and the beams along 45meters side of the cathedral contribute altogether in supporting the domes. However, one can notice that the girder T-beams that are closer to the domes will hold a major part of the domes' load. Thus, one could expect a higher bending moment on these beams compared to the beams supporting the one way joist slab in the roof or basement floors. The roof plan is shown in details in Figure 11.

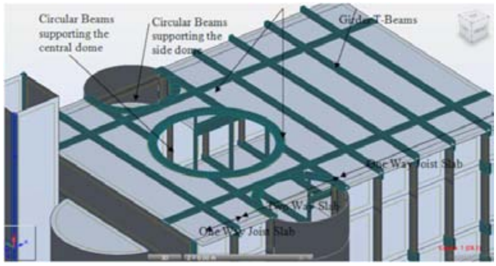

Figure 11. Roof Structural Plan

SELF WEIGHT VERIFICATION

In order to verify the output of the Robot software before proceeding with the load assignment and design analysis, the self weight of the structure was hand calculated and checked versus the total weight given by the software (Table 1). Using the Robot Model, the Self Weight of the Cathedral without the weight of the Domes was calculated.

The Self Weight of the Structure according to ROBOT is 120,315.46 KN ≈ 12,031.6 Tons. The self weight of the structure was also obtained by adding the weight of the floors, the roof, the side walls, the circular walls, the semi circular slabs, the columns, and the bell walls. The manually calculated self weight was found to be 11,744.8 Tons which is very close to the value given by the Robot Software.

Table 1. Self Weight Output from Robot (KN)

Self Weight	FX	FY	FZ	MX	MY	MZ
Sum of val.	0	0	120315.46	6.86	-87.22	-0.35
Sum of reac.	0	0	120315.46	1889706.06	-2434647.47	-0.09
Sum of forc.	0	0	**-120315.46**	-1889706.06	2434642.87	0
Check val.	0	0	0	0	-4.6	-0.09
Precision	1.49E-05	2.22E-12				

LOADS

Dead, live, wind and seismic loads were applied in accordance with the Uniform Building Code (UBC97). The self weight of the structure is automatically applied on the structure by Robot.
The Dead Load (DL) was determined per Table 2 as follows:

- The basement and ground floors DL was calculated by adding the weight of the partition walls and tiles.
- The roof DL was obtained by calculating the weight of the red tiled pitched roof.
- The domes were assumed to have the same loads as the floors.
- The stone cladding dead load was calculated based on 5 centimeters limestone cladding thickness with a unit weight of 2,600 Kg/m^3. This loading is applied on the exterior walls.

Table 2. Dead Loads

Location	Loading
Self Weight	Automatically Generated
Basement Floors	DL = 1 KN/m^2
Ground Floor	DL = 1 KN/m^2
Roof Floor	DL = 2 KN/m^2
Domes	DL = 1 KN/m^2
Stone Cladding	DL = 1.3 KN/m^2

The Live Load was determined per Table 3 as follows:

- The live loads applied to the basement and ground floors were obtained in accordance with the Uniform Building Code (UBC97) for Assembly Areas, Stages and Enclosed Platforms.
- The live load applied to the ground floor was obtained in accordance with the Uniform Building Code (UBC97) for Flat Rise or Rise less than 4 in /ft (1:3).
- The live load applied to the domes was obtained in accordance with the Uniform Building Code (UBC97) for rise (1:1) or greater. Arch or Dome with Rise 3/8 of span or greater.

Table 3. Live Loads

Location	Loading
Basement Floors	LL = 6 KN/m^2
Ground Floor	DL = 6 KN/m^2
Roof Floor	DL = 1 KN/m^2
Domes	DL = 0.578 KN/m^2

The Wind Load on a structure is basically a dynamic problem. However, for tradition and simplicity reasons, it has been usual practice to use a quasi-static approach and to treat wind as a statically applied pressure, neglecting its dynamic nature, especially for relatively short structures. The Structure was designed against wind effect according to UBC97 code.

The forces that a structure must resist due to a Seismic event result directly from the distortions induced by the motion of the ground on which it rests. The response of a structure resulting from a base motion is influenced by the properties of both the structure and the foundation, as well as the character of the existing motion. The satisfactory performance of a large number of reinforced concrete structures subjected to severe earthquake in different areas of the world has demonstrated that it is possible to design such structures to successfully withstand earthquakes of major intensity. However, it is important to draw a distinction between forces produced by wind and forces produced by earthquakes. Occasionally, even engineers tend to think of these forces as belonging to the same category just because codes specify design wind as well as earthquake forces in terms of equivalent static forces. Although both wind and earthquake forces are dynamic in character, a basic difference exists in the manner in which they are induced in a structure. Whereas wind loads are external loads applied and, therefore, proportional to the exposed surface of a structure, earthquake forces are essentially inertial forces that result from the distortion

produced by both the earthquake motion and inertial resistance of the structure. Their magnitude is a function of the mass of the structure rather than its exposed surface. The purpose of the earthquake provisions is primarily to safeguard against major structural failures and loss of life, not to limit damage or maintain function. The structure shall be designed with adequate strength to withstand the lateral displacements induced by the design basis ground motion. Each structure shall be assigned a seismic Zone factor in accordance with Table 16-I of UBC 97 code. Lebanon belongs to the zone 2B; therefore the seismic zone factor Z = 0.20.

LOAD COMBINATION

The load combinations used in this project adopt the strength method factored loads referenced in ACI 9.2:

U =1.4 DL
U =1.2 DL + 1.6 LL
U =1.2 DL + 1 E + 1 LL + 1 W

where:

DL is the dead load
LL is the live load
E is the load effects of seismic forces
W is the wind pressure

and all remaining load combinations considered are automatically generated by Robot.

MAT FOUNDATION LOADS

In order for the geotechnical engineer to proceed with the design of the mat foundation, the Service and Ultimate limit states of the loads were obtained by the aid of Robot. The total load of the structure under the Service Limit State (SLS) was calculated using Robot Structural Analysis Professional Software (Table 5).

Table 4. Total Load under Service Limit State (KN)

Case 9 (C)	FX	FY	FZ	MX	MY	MZ
Sum of val.	0	0	158663.38	9.03	-133.96	-0.63
Sum of reac.	0	0	**158663.38**	2471563.42	-3229016.21	-0.1
Sum of forc.	0	0	-158663.38	-2471563.41	3229011.24	0
Check val.	0	0	0	0.01	-4.97	-0.1
Precision	2.88E-04	2.67E-10				

Service Loads Applied to the mat Foundation = (1 + 6) × 31 × 46 = 9,982 KN
Total Load of Structure under SLS = 168,645.38 KN
Approximately 16,865 Tons (Self-Weight of Foundation Not Included).

The total load of the structure under the Ultimate Limit State (ULS) was calculated using Robot Structural Analysis Professional Software (see Table 6).

Table 5. Total Load under Ultimate Limit State (KN)

Case 10 (C)	FX	FY	FZ	MX	MY	MZ
Sum of val.	0	0	198931.32	11.78	-173.84	-0.78
Sum of reac.	0	0	**198931.32**	3093811.16	-4065441.16	-0.12
Sum of forc.	0	0	-198931.32	-3093811.14	4065435.2	0
Check val.	0	0	0	0.02	-5.96	-0.12
Precision	3.74E-04	3.70E-10				

Service Loads Applied to the Mat Foundation =(1.2×1+1.6×6)×31×46=12,052.8KN

Total Load of Structure under ULS = 210,984.12 KN
Approximately 21,099 Tons (Self-Weight of Foundation Not Included.)

TYPICAL BEAMS DESIGN

In the following section, the analysis, and reinforcement steel design for the all the structural elements of the roof along with the typical supporting elements of the cathedral are performed. The design was performed using Autodesk Robot Structural Analysis Professional. Resizing of the elements was performed in order to meet the structural and deflection criteria. Hand Calculations are used to verify the required steel reinforcement. As shown in the roof structural plan (Figure 12), beams R4 and R7 are the beams that are holding the two way slab, the central dome, and part of the side domes. Those beams are expected to have a larger bending moment than the other beams that are holding the one-way joist slab. As an example, the moment diagram for the beams R4 and R7 obtained in Robot are shown in Figure 13.

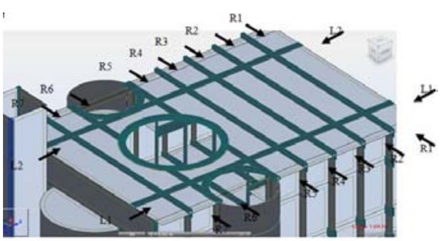

Figure 12. Perspective Showing Beams Designations in the Roofing System

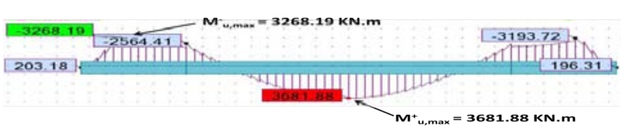

Figure 13. Moment Diagram for Beams R4 & R7 (KN-m)

In order for the beams to pass the structural and deflection criteria, the beam was resized from 50×90cm to 50×130cm. Afterwards the deflection criteria was checked and found to be 3.9 cm. The maximum allowable deflection was obtained in accordance to UBC97 Table 16-D formula for structural members with live and dead loads:

$$\delta_{\max} \leq \frac{l}{240} = \frac{20}{240} = 0.083m = 8.3cm > \textit{Actual Deflection}$$

Since the concrete is weak in tension, the reinforcing steel of the negative moment is placed at the top and that for the positive moment at the bottom.

The reinforcing steel for the cross sections shown in Figure 14 were obtained from Robot and are shown in Figure 15. A similar analysis was conducted for a typical beam reinforcement supporting the one way joist slabs in the cathedral.

Figure 14. Reinforcement Pattern for Beams R4 and R7

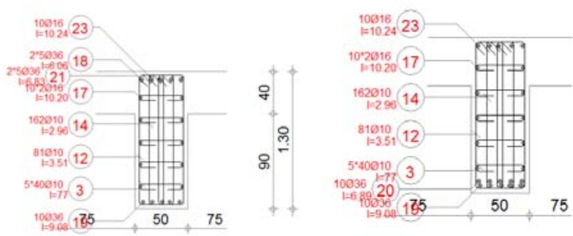

Figure 15. Reinforcing Steel for Beams R4 & R7

CONCLUSIONS

A complete design of a complex structure using ROBOT was accomplished by using the different features of the program: columns, beams, walls, and slabs for each floor and assigning the lateral and gravity low to copy the plans from AutoCAD to ROBOT, and then enter the loads on the slabs and walls. The load cases assigned should be well defined before being assigned by showing all the references used to enter the needed data for defining the loads (from codes and tables).After inputting all of the above data and doing the appropriate meshing for each area, the analysis was performed, Subsequently, then one can start exporting some columns and beams and checking whether the design conforms with the design criteria or not. It is always recommended to check the results with some hand calculations. Major lessons learned are that one can perform a full CAD design and walk through the design and make changes as illustrated in this study and also recalculate the full impact of these changes.

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A Novel Approach for Automated Selection of Key Video Frames for 3D Reconstruction of Civil Infrastructure

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ABSTRACT

Videogrammetry is an inexpensive and easy-to-use technology for 3D scene spatial recovery. When applied to civil infrastructure, the scale of the scene is significantly larger than manufacturing applications. As a result, it usually takes a long time to videotape the scene, leading to a large quantity of frames in the video. In most cases, only few portions of those frames should be processed. In addition, uncontrolled environment will result in motion blur, which significantly affect the performance of the videogrammetric pipeline. To address the mentioned issues, in this paper, a novel method for automating the selection of appropriate frames is presented and validated. In this method, the blurred frames are first removed based on the thresholds determined by experiments and the key frames are then selected from the remaining frames using selection criteria devised by the authors. Experimental results reveal that the proposed method outperforms the existing methods in terms of successful rates of 3D reconstruction while maintaining optimized number of required frames for post processing stages.

INTRODUCTION

Over the past few years, videogrammetry have been considered as cost-effective and easy-to-use method for 3D spatial sensing of different objects, specialy in manufacturing domain (Zhu and Brilakis 2009). When it is applied to civil infrastructure, the feasibility of videogrammetry suffers significantly from two issues. During videotaping of a scene with off-the-shelf cameras, it is difficult to precisely restrict and control the overall camera speed and motion stability. As a result, motion blur will occur, significantly impacting the performance of the reconstruction. Efficiency in processing of video frames is the second issue. Even a short one minute video stream consists of 1500-1800 frames. Obviously it is computationally expensive to process all these frames. To achieve a satisfactory result, only a small amount of these frames is necessary for post processing. Thus

far, there is a lack of effective and automatic methods for selection of informative, high quality frames for 3D spatial sensing of infrastructure using videogrammetry.

Current key frame selection algorithms consider criteria associated with sufficient overlap between frames, avoiding degeneracies, and minimizing reprojection errors. Optimizing the number of extracted frames is another important factor that is neglected by current research efforts. For example, increasing the number of extracted key frames will improve the density and completeness of the resulting point clouds. However, once the results reach a certain level of density and completeness, processing more frames is redundant and makes the procedure computationally ineffective. In terms of applying videogrammetry to practical settings, none of current research undertakings have dealt with motion blur effects contained in captured video, which leads to significantly decreased accuracy of the 3D reconstruction.

Considering the aforementioned gaps in videogrammetric research for surveying civil infrastructure, this paper proposes a novel method of automating the selection of informative, high-quality frames for processing in the videogrammetric pipeline. In this method, in adition to the traditional selection criteria for key video frames, optimized number and quality of obtanained key frames are also taken into account as two significant selection factors. The structure of remaining parts of this manuscript is organized as follows: "Background" section outlines current practices for handling low image quality and video frame redundancy and recent research efforts in this direction. Our proposed method for automating the selection of high quality, informative frames for 3D reconstruction of infrastructure is presented in the next section. In "implementation and results" section, experiments are conducted to test the validity of the proposed key frame selection algorithms and comparing obtained results with other existing methods. Finally conclusions are drawn.

BACKGROUND

Selecting a number of representative (key) frames from a large video sequence is a key step for efficient and robust 3D reconstruction. The criteria that have been applied for key frame selections are primarily focused on different aspects: Seo et al. (2003) considered three criteria when extracting key frames: (a) the ratio of the number of correspondences to the number of features, (b) the homography error, and (c) the distribution of correspondences over the frames. Later on, Seo et al. (2008) improved their method to extract informative key frames by incorporating a fourth criterion, i.e. minimizing the reprojection error of the reconstruction process. Nonetheless, these methods did not consider the degeneracy cases. In Pollefeys et al. (2004), the degeneracy problem is addressed by employing the Geometric Robust Information Criterion (GRIC) (Torr et al. 1998). The next key frame is selected only once the fundamental matrix model explains the relationship between the pair of images better than the homography matrix model through the scores calculated by the GRIC (Torr et al. 1998). Ahmed et al. (2010) proposed another key frame selection method which is based on the weighted score considering the GRIC difference and point to epipolar line cost. Gibson et al. (2002) proposed a method in which the sum of three weighted addends of (1) the fraction of features that were matched in the previous frame pair which cannot be matched in the current pair, (2) the inverse of the square of the homography error, and (3) the squared median epipolar error, is minimized to

selects the frames. Thormahlen et al. (2004) proposed a criterion for the selection of key frames with the lowest expected estimation error of initial camera motion and object structure. At the same time, their method utilized the GRIC to guarantee a sufficient baseline, overlap, and avoid degeneracy cases.

As it can be observed, none of these methods considered the blur as an obstacle. There is also a lack of an optimization strategy in current key frame selection methods. Though current key frame selection methods reduce the number of frames, there is no guarantee that the number of extracted frames is optimum. If the number of extracted frames is less than the number required, it is not possible to generate a high quality point cloud. On the other hand, processing unnecessary extra frames is redundant and time consuming.

Considering the above mentioned gaps in the existing knowledge, the objective of this paper is to propose and validate an innovative key frame selection algorithm compatible with practical applications in civil infrastructure domain. The presented method not only tackles common issues that occur while running a 3D reconstruction pipeline, but also addresses two major practical problems, i.e., the low quality of the captured frames, and optimization of the number of extracted key frames.

AUTOMATED KEY VIDEO FRAMES EXTRACTION: PROPOSED METHODOLOGY

Figure 1 shows the main workflow of the proposed key frame selection algorithm. The technical details of the proposed algorithm are presented in the following steps:

Step1: Low quality video frames filtering: The algorithm starts with removing low quality frames. In order to measure the quality of each frame, we calculate the BluM metric (Crete et. al.2007) and remove the ones with BluM metric lower than specific threshold defined by experiments. Among the remaining high quality frames, the first one is then marked as the first key frame.

Step2: Overlap and baseline filtering: Once the first frame has been selected as a key frame, it is necessary to select a number of consecutive frames as key frame candidates. The selection criteria must guarantee both enough baseline and sufficient overlap between the candidates and the first key frame. To achieve this goal, we use the correspondence ratio defined by Seo et al. (2008) and Ahmed et al. (2010).

Step3: Degeneracy filtering: Among these candidates, those that lead to degeneracy cases and large re-projection errors are also removed. In order to avoid degeneracy cases, we follow a similar strategy suggested by Torr et al. (1998) and Pollefeyes et al. (2008) by calculating GRIC scores.

Step 4: Selecting the next key frame: The next step is selecting the final candidate among the remaining frames. To this end, after calculating the fundamental and homography matrices between the candidates and the key frame using RANSAC, we calculate the percentage of inliers to the total number of correspondences. Then we calculate the S score to select the final candidate:

$$S = (1-\sigma)\frac{S_F - S_H}{S_F}$$

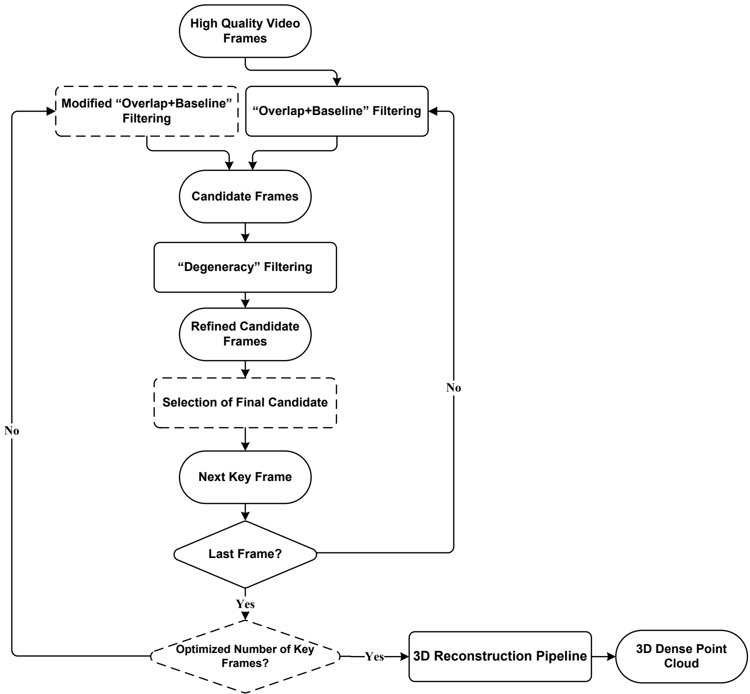


Figure1: Workflow of the key frame selection algorithm

Where S_H and S_F are the percentage of inliers for calculating the homography and fundamental matrices respectively and σ is the standard deviation indicating the uniformity of the distribution of features over the frame.

Step 5: Optimizing the number of key frames: The difference between our method and those of previous researchers lies in the optimization of the number of extracted key frames needed for use in the 3D reconstruction pipeline. First, we define the correspondence ratio as follows:

$$R = \frac{R_C}{R_T} \qquad (\tau_1 < R < \tau_2)$$

In this equation, R_C is the number of correspondence points between the key frame and the next candidate while R_T is the total number of feature points in the first key frame. τ_1 and τ_2 are the lower and upper thresholds . R is inversely proportional to the length of camera motion since, as the camera moves, features tend to leave the scene. Researchers in the computer vision have usually set fixed thresholds for τ_1 and τ_2 based on experiments conducted on a few datasets. However, it is not ensured that an optimum quantity of key frames can be selected. In our case, instead of assigning fixed values as the upper and lower thresholds, we define a specific range for each one based on three important

factors: desired number of extracted key frames, approximate speed of camera while traversing, and complexity of the civil infrastructure scene.

Given a defined set of ranges for the upper and lower thresholds, we use a linear programming method to optimize the number of the required frames:

$$Goal: \quad p_1 \le p \le p_2$$

$$Constraints: \quad \begin{cases} \tau_{l\min} \le \tau_1 \le \tau_{l\max} \\ \tau_{u\min} \le \tau_2 \le \tau_{u\max} \end{cases}$$

In the first equation, P is the percentage of key frames over the entire number of frames existing in the sequence and P_1 and P_2 indicate the optimum range for the percentage of the number of key frames. The optimum range for the number of key frames is pre-defined based on the capturing rate of the camera, movement speed of the videotaper, and through experiments. In second equation, $\tau_{l\min}$, $\tau_{l\max}$, $\tau_{u\min}$ and $\tau_{l\max}$ are acceptable ranges for the upper and lower thresholds which can be obtained through experiments in various scenarios.

IMPLEMENTATION AND RESULTS

A C#-based prototype was implemented to test the validity of the proposed key frame selection algorithm. Considering the variety in civil infrastructure scenes, we captured 25 video streams from 8 different scenes, i.e., two highway bridges, three campus buildings, one residential building, one sport facility, and one concrete water reservoir. The lengths of the video streams varied from 4 to 10 min. To validate the degeneracy cases, we ensured that some video streams contained planar scenes such as walls, and in some cases during the process of capturing videos, the video taper was intentionally stopped for a while and the camera was simply rotated without any translations. We firstly qualitatively evaluated the impact of blur effects on the results of 3D reconstruction. To this end, the frames from the video of a highway bridge were artificially blurred. Then, the blurred frames were passed into the reconstruction pipeline. For each case, the BluM value, the number of extracted and matched feature points, and reprojection errors were computed. As an example, 6 sample blurred frames are illustrated in Table 1. As observed, in all cases, blur has a significant effect on the number of extracted features and reprojection errors; in most cases, the number of features extracted from the blurred frames was not even sufficient to reconstruct the scene.

Next, values for τ_{lmin}, τ_{lmax}, τ_{umin} and τ_{umax} are calculated. For the bridge video, these thresholds are 0.45, 0.55, 0.7 and 0.8 respectively. In the next step, we measured the performance of the proposed key frame selection algorithm. A number of key frames were extracted from each video sequence using our key frame selection algorithm and the methods developed by Pollefeys et al. (2004), Seo et al. (2008) and Thormahlen et al. (2004). In addition, a number of frames equal to the number of key frames by our method were selected at equally distributed intervals without using any key frame selection method. These extracted key frames were processed in the videogrammetric pipeline and the percentages of failure cases as well as reprojection errors for successfully

reconstructed cases of each method were computed. The obtained results are summarized in Table2.

Table1. Impact of blur on number of extracted feature points and reprojection errors

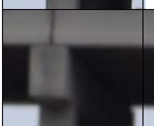
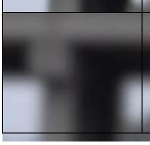
	BluM value	Number of extracted feature points	Number of matches	Reprojection error
	0.259	2984	657	0.0225
	0.465	2077	474	0.0423
	0.622	1017	316	0.0548
	0.704	147	24	0.132

Table 2: Failure percentages and re-projection errors for different key frame extraction methods

	Method	Average failure percentage (%)	Average reprojection error	Average number of extracted key frames	Running time (key frame selection)	Running time (3D reconstruction)
1	Uniformly extracted frames	54.54	0.0754	432	-	13
2	Pollefeys et al. (2004)	36.36	0.0358	619	0.02	21
3	Thormahlen et al. (2004)	27.27	0.0208	509	0.05	15
4	Seo et al. (2008)	45.45	0.0439	573	0.07	18
5	Our method	22.72	0.0275	432	0.18	12

* Re-projection error is the distance between projected 3D points on the image and their detected 2D location.

As it can be observed from Table 2, our method outperforms almost all other methods in terms of failure cases and average re-projection errors. Moreover, in this specific case, the number of extracted key frames is within the desired range. Despite the fact that our method is slightly more time consuming in the phase of key frame selection, the optimized number of extracted key frames

drastically reduces the computational time of post-processing, and thereby optimizes the entire efficiency of the videogrammetric pipeline.

CONCLUSION

Video clips captured from civil infrastructure sites contain a sheer volume of blurry, noisy, or redundant frames. This problem is associated with several factors, e.g, lens distortions, motion blur and high speed rates of frame capturing. As the result, filtering redundant, low quality frames and selecting an optimized number of informative high quality frames is a challenging task. This paper presented a novel method for extracting high-quality, informative frames from a video stream. The resulting key frames could be fed into the videogrammetric pipeline to effectively generate dense point clouds of civil infrastructure. The proposed algorithm automated the processes of removing blurry frames and selecting a number of frames in a way in which computational efficiency was achieved and common degeneracy cases were minimized. The experiment results revealed that the proposed key frame selection algorithm eclipsed the existing methods in a relatively high successful rate of the 3D reconstruction, while maintaining the best reprojection accuracy. In addition, applying the proposed key frame selection algorithm significantly reduced the risk of failure in 3D reconstruction pipeline.

ACKNOWLEDGMENTS

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Real-time 3D Positioning and Visualization of Articulated Construction Equipment: Case of Backhoe Excavators

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ABSTRACT

Construction equipment generally consists of a set of rigid bodies connected by joints, which is termed as a kinematic chain. The relative motion and constraints between successive bodies of the chain make the real-time 3D visualization a challenge, which requires minimizing the number of sensors as needed by practical applications in construction. In this paper, we investigate a methodology for efficient real-time 3D visualization of articulated construction equipment. The Denavit-Hartenberg (DH) technique which has been widely used in robotics research is introduced and adapted for computing relative motions of various components in the articulated equipment system based on a minimal quantity of input parameters. The 3D position of articulated construction equipment can be analytically fixed by analyzing point coordinates and joint movement parameters. This analytical method is validated by simulating a backhoe excavator in a computer environment, where the absolute location of the backhoe' tracks is computed by tracking three control points, and the relative positioning states of the cabin, boom, stick and bucket are deduced by using the DH technique.

INTRODUCTION

Heavy equipment such as excavators, cranes, and tunnel boring machines plays a leading role in achieving efficiency and productivity on heavy and civil construction operations. During the cycle of handling a job under practical constraints, operators need to frequently relocate the absolute position of the main body of the equipment on site while meticulously adjusting the relative position of each mechanical part of the equipment. For example, the base of a backhoe excavator moves on tracks to a particular location on site; the operator then adjusts the position of the cabin, the boom, the stick and the bucket by a sequence of maneuvers in order to execute a particular bucket-excavating cycle.

Hirabayashi et al. (2006) revealed that vision is the main source of information that equipment operators count on for positioning equipment and avoiding obstacles on site. However, on a dynamic construction site, the vision can be blocked frequently by numerous obstacles such as materials, temporary or permanent facilities, other equipment, and even workers. In particular, the visual information is extremely limited in underground construction environments. Further, in the current practice, some construction equipment such as micro-tunnel boring machines needs be operated remotely in a working environment that does not allow human entry.

The use of real-time sensor data to update 3D virtual scenes of construction equipment provides a straightforward solution to enhance the operator's situational awareness on a construction site. Real-time 3D positioning and visualization of the construction equipment is defined as the technology that takes advantage of real-time sensor data to update the computer generated 3D virtual scenes of the construction equipment working on site. With the real-time 3D visualization, construction equipment can be correctly positioned in a geo-coordinated site system with respect to current site constraints. The desired direction of movement as per the design can be determined and visualized in the immediate future. Additionally, revealing spatial relationships between the equipment and surrounding structures and facilities on a real time basis helps the equipment operator prevent collision accidents. Real-time 3D positioning and visualization of construction equipment also provides the prerequisite to enable more effective automation control or tele-operation of construction equipment in the field.

However, accurate 3D positioning and modeling of construction equipment working on site presents a distinctive challenge. As reported by Lytle and Saidi (2007), the National Institute of Standards and Technology (NIST) developed the Automated Steel Construction Testbed to experiment with a robotic crane, which entailed accurate 3D positioning and modeling of the crane's components in real time. A complex and expensive laser-based site measurement system was mounted on the testbed. The system uses stationary, active-beacon laser transmitters and mobile receivers to provide millimeter-level positioning data. Furthermore, the requirement of line-of-sight by transmitters and receivers would restrain the application of the measurement system for 3D positioning of articulated equipment in the field. The practical site constraints can make line-of-sight limited and sensor installations on the equipment infeasible.

In our previous research, by tracking a limited quantity of control points fixed on the object, cost-effective computing methods were successfully implemented for 3D positioning of a "single solid object", including Triad, Quaternion (Shen et al 2010), and singular vector decomposition (SVD, Liang et al. 2011). The point coordinates can be fixed at mm accuracy level and in an automated fashion, given line of sight between a total station and the control points is available. Then the position and orientation of the solid object can be computed by using the point coordinates collected. Such methods can be easily adapted to deal with the 3D positioning of the base of construction equipment (e.g. the chassis of a backhoe excavator, or the body of a TBM). Nonetheless, it is not feasible to treat each component that makes up the articulated construction equipment as a separate single solid object for independent 3D positioning due mainly to the following:

(1) because the equipment may consist of many parts articulated by mechanical joints, positioning a large quantity of control points in one surveying cycle would entail frequent interruptions to the continuous equipment operation; and (2) line of sight to particular control points on certain parts of the equipment may be unavailable or not guaranteed during dynamic site operations, hampering the application of laser-based positioning technology; And (3) direct installation of measurement instruments (such as gyroscopes and angular sensors) for accurate real-time 3D positioning of all the components of the articulated equipment system can be too expensive in the field.

This paper presents an efficient methodology for real-time 3D positioning and visualization of articulated construction equipment working on site. Generic data models and analytical procedures are proposed to deduce translation and rotation matrices for positioning each equipment component with respect to the base frame, resulting in the 3D model of construction equipment showing an accurate pose at its current working location. This methodology does not need the direct measurement of point coordinates for each component. Instead, lengths of cylinder rods on the equipment, which are much easier to gauge by using commonly used equipment sensors such as linear encoders, provide input data for analytical calculation. Data collection by using these sensors does not require line-of-sight between equipment and sensors.

OVERVIEW OF PROPOSED METHODOLOGY

In this paper a backhoe excavator is studied as an example for describing the proposed methodology and illustrating the application process. It is noteworthy that the methodology is generic and can be adapted to any type of articulated construction equipment. Figure gives the logical flow of the proposed methodology. First, the generic data model for construction equipment is introduced, which is then specifically customized to model the backhoe. Then, 3D geometric models of the backhoe's components are prepared by using a 3D CAD tool based on the data model. The data model decomposes the backhoe into components by following a hierarchical tree structure. Note the data model is still a static model that does not reflect real construction site operations at this stage. In order to determine the correct pose, the rotation matrices and position vectors for each solid component of the equipment need to be updated according to their actual poses at a particular time on the site. This is achieved through integration of data-collection sensors with a kinematic model.

Kinematics is the study of the motion of objects without consideration of the causes leading to the motion (Beggs 1983). The motion of an object is described in computer by the location and orientation changes in two time frames. The kinematic analysis is about applying mathematics to define the connections between joined objects (such as different components of an equipment system) and determine the movement of real world objects in relation to one another in an analytical way. The kinematic model being proposed is intended to minimize the quantity of sensors required to obtain the pose data of the equipment; the collected sensor data are processed through an adapter

which contains essentially data transform equations defined for equipment kinematics modeling.

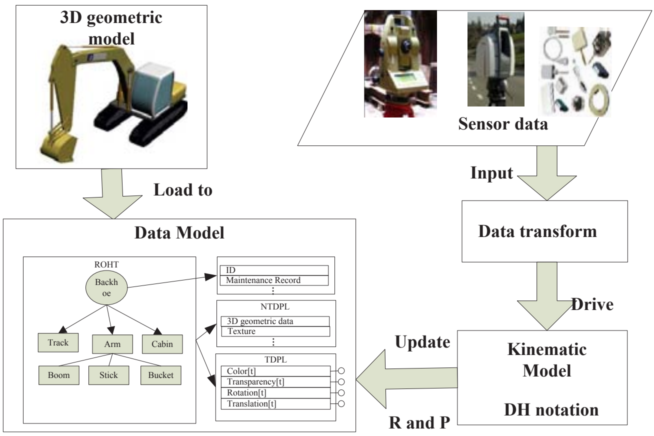

Figure 1. The logical flow chart of the proposed methodology.

Six parameters are used to describe the position changes between two position states of an object, which can be viewed as the movement of the object between two time events. However, in order to correctly render 3D computer graphics, all the data in the 3D models need to be transformed from the previous state to the new state. Basically, the coordinates of all the points in the 3D model are transformed into new coordinates. This is achieved by using a 4×4 homogeneous transformation matrix (Grigore and Coiffet 2003). In linear algebra, a point's three coordinate values can be represented by a three dimensional vector ($\bar{x}$). The homogeneous transformation matrix is applied to transform the vector into a new form which represents the new location of that point: $\vec{x}' = T\vec{x}$,Where T is the 4×4 homogeneous transformation matrix, as given in Eq. (1):

$$\mathbf{T} = \begin{bmatrix} \cos\theta\cos\varphi & -\sin\emptyset\sin\theta\cos\varphi + \cos\emptyset\sin\varphi & \cos\emptyset\sin\theta\cos\varphi + \sin\emptyset\sin\varphi & \Delta x \\ \cos\theta\sin\varphi & \sin\emptyset\sin\theta\sin\varphi + \cos\emptyset\cos\varphi & -\cos\emptyset\sin\theta\sin\varphi + \sin\emptyset\cos\varphi & \Delta y \\ -\sin\theta & \sin\emptyset\cos\theta & \cos\emptyset\cos\theta & \Delta z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Where $\emptyset, \theta,$ and φ are the three rotation angles, namely, roll, pitch and yaw; Δx, Δy and Δz describe location translation between the two time events. If elements of the matrix are expressed as functions of time, then the matrix represents the motion of an object along the time dimension. Multiplying the three coordinate numbers of a point in

the first time frame (before moving) by the transformation matrix yields the point coordinates in the second time frame (after moving).

POSITIONING AND VISUALIZAITON PROCEDURE

A kinematic modeling technique, first proposed by Denavit and Hartenberg (Denavit and Hartenberg 1995), is adapted for real-time 3D positioning and visualization of typical articulated construction equipment which is generally characterized as an open kinematic chain. The backhoe excavator is used as a case study to demonstrate the modeling process.

The first step in the development of a kinematic model is to attach coordinate frames to each solid body of the equipment. Note once positioning frames established, the relative position and orientation between a frame and a solid body cannot be changed. Thus all the frames suffice to represent the position and orientation of all the solid bodies. The frame assignment process observes a set of rules and conventions as follows:

The z-vector, z_i of a frame F_i coincides with the axis of a revolute joint connecting two adjacent components. The only possible exception to this rule is the last frame. As shown in Figure , the z-vector of the first frame F_0 (the base frame attached to the track) z_0 is assigned on the axis of the revolute joint connecting the track and the cabin.

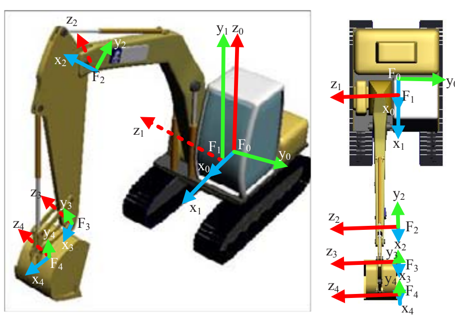

Figure 2. Frame assignment on a backhoe.

By the same rule, $\mathbf{z_1}$ is assigned on the axis of the revolute joint connecting the cabin and the boom, $\mathbf{z_2}$ on the axis of the revolute joint connecting the boom and the stick, and $\mathbf{z_3}$ on the axis of the revolute joint connecting the stick and the bucket, respectively. One special frame is the one attached to the end link of the articulate chain (i.e. the bucket in the backhoe case). It is the only frame that does not require the alignment of its z axis with a revolute joint axis. However, in order to simplify the computational procedure given in the next section, it is advisable to align the z axis of

the end link of the articulate chain with the z axis of the previous frame, for instance, $\mathbf{z_4}$ is aligned with $\mathbf{z_3}$ in the present case.

The x-vector, x_i of a frame F_i is assigned on the common perpendicular to axes z_{i-1} and z_i , and is oriented from z_{i-1} to z_i. Note the only exception is the x axis in the first frame x_0 which can point to any direction; for simplicity, the direction of x_0 is usually consistent with the direction of x_1. If the axes of z_{i-1} to z_i are parallel, the common perpendicular can be at any point along the two axes. In this case, the axis x_i is located at the point where the axis z_i intersects with the axis x_{i-1}. As shown in Figure , x_2, x_3 and x_4 are located following this rule.

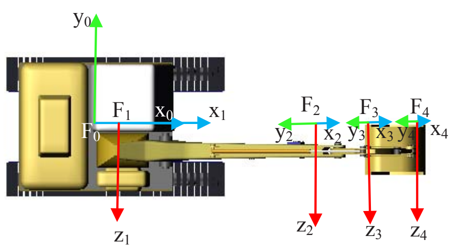

Figure 3. Top view of backhoe showing the frames assigned.

The y-vector, $\mathbf{y_i}$ of a frame $\mathbf{F_i}$ is determined by the right hand rule: using right hand to hold the z-axis with the pollex pointing to the same direction of axis z, and the y-axis is oriented from x-axis with a 90-degree rotation. Following the above three rules, all the frames can be established to define components on any construction equipment.

The DH technique models the kinematic chain by describing the 3D relationships between one current frame and its preceding frame along the chain. As shown in Eq.(1), the representation of one frame in relation to another is obtained by using a 4×4 transformation matrix based on six independent parameters, namely, three rotation angles and translation in x, y and z coordinates on a point. However, with all the frames established by following the frame assignment rules mentioned in the previous section, the use of four DH parameters is sufficient to determine the position and orientation of one frame (or a solid object) with respect to another.

In order to simplify the matrix computation, if possible, the frames should be assigned on such locations that would make most of the parameters equal to zero. As shown in Figure A and Figure B, the frames F0 and F1 are both assigned according to the DH rules described in above section. However, the link length between F0 and F1 is d_1 in Figure A while it equals zero in Figure B. As shown in Figure C, the backhoe excavator has five solid bodies that are connected by four revolute joints. Thus a total of sixteen (4X4) DH parameters suffice to determine the relative position of the four frames attached on these four joints. However, proper assignment of the four frames can make eight parameters equal zero, and the remaining eight none zero parameters

are $a_1, \alpha_1, \theta_1, a_2, \theta_2, a_3, \theta_3$ and θ_4, among which only θ_1, θ_2, θ_3 and θ_4 are time dependent parameters corresponding to the rotation angles of four revolute joints, denoted as $\theta_1^t, \theta_2^t, \theta_3^t$ and θ_4^t in following calculations.

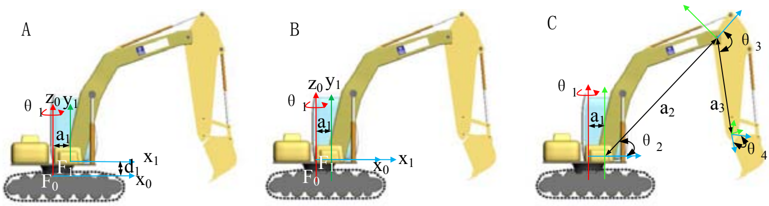

Figure 4. The DH parameters of the backhoe example.

The kinematic model that represents the relative motion in the backhoe's components can be summarized in Table 1. The kinematic model will be used to calculate the 3D position of each component of the backhoe by using mathematical equations.

Table 1. DH Parameters of the Backhoe Example.

Frame	d	a	α	θ	Joint Type	Component
1	0	a_1	90	θ_1	Revolute	cabin
2	0	a_2	0	θ_2	Revolute	boom
3	0	a_3	0	θ_3	Revolute	stick
4	0	0	0	θ_4	Revolute	bucket

Given the DH parameters (shown in Table 1), the transformation matrix (relative positions) from track to bucket can be calculated as follows:

$$T_1^t = A_1^t = \begin{bmatrix} c_1^t & 0 & s_1^t & a_1 c_1^t \\ s_1^t & 0 & -c_1 & a_1 s_1^t \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$T_2^t = A_1^t A_2^t = \begin{bmatrix} c_1^t & 0 & s_1^t & a_1 c_1^t \\ s_1^t & 0 & -c_1 & a_1 s_1^t \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_2^t & -s_2^t & 0 & a_2 c_2^t \\ s_2^t & c_2^t & 0 & a_2 s_2^t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^t = A_1^t A_2^t A_3^t = T_2^t \begin{bmatrix} c_3^t & -s_3^t & 0 & a_3 c_3^t \\ s_3^t & c_3^t & 0 & a_3 s_3^t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{ and } T_4^t = A_1^t A_2^t A_3^t A_4^t = T_3^t \begin{bmatrix} c_4^t & -s_4^t & 0 & 0 \\ s_4^t & c_4^t & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where, $c_1^t = \cos(\theta_1^t)$, $s_1^t = \sin(\theta_1^t)$, $\gamma_i^t = \cos(90) = 0$, and $\sigma_1^t = \sin(90) = 1$, a_1 is a constant and other parameters all equal zero.

CONCLUSION

This paper has described the methodology for real-time 3D positioning and visualization of typical articulated construction equipment working on site. The expression of each equipment component as a solid body in the 3D virtual world is the same as the single solid object, which requires a rotation matrix and a translation vector to uniquely determine the location and orientation in the 3D space. However, the proposed technique for articulated system is different from the one used for single solid site object in that a kinematic model is introduced to minimize the sensors required to locate the solid bodies of the equipment. The kinematic model is a mathematical representation of the relative position and orientation between two conjoint solid bodies which are normally linked with a revolute joint or a prismatic joint for typical articulated construction equipment. The DH notation which has been widely used in the robotic research is applied to develop the kinematic model for typical articulated construction equipment. In order to clearly illustrate the methodology, a backhoe excavator is chosen to demonstrate the modeling process. However, this methodology is generic and can be easily adapted to other construction equipment, lending effective real-time 3D visual aid to operators, e.g., tele-operations of tunnel boring machines in microtunneling, underwater construction.

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An Augmented 3D iPad Mobile Application for Communication, Collaboration and Learning (CCL) Of Building MEP Systems

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ABSTRACT

The goal of this research is to gain better understanding of how BIM models can be used to create mobile 3D game environments for some serious purpose other than entertainment. This project was motivated by the perspective that the capability of BIM creating realistic 3D virtual game environments for collaboration, communication and learning (CCL). The wide dissemination of mobile devices is driving many computer applications toward the direction of ubiquitous mobile accessibility. Considering the popularity of the iPad mobile device, a BIM model of an institutional building was created for this 3D mobile game application on iPad. This game application allows users to visualize and interact with the HVAC BIM components. In this paper, we reported our preliminary findings in developing a BIM-based iPad 3D game application for CCL activities in architecture, engineering, and construction (AEC). Technical barriers of using BIM models to create mobile 3D CCL applications were also discussed. The detailed system architecture and implementation framework were presented in this paper. Differences between the developed program and the existing BIM mobile programs were elaborated to distinguish the developed program from the off-the-shelf BIM mobile programs, such as Vella and Autodesk Inventor mobile viewer. The preliminary results indicated that fairly complex BIM models including multiple building systems can be imported and created through 3D virtual-built environments to conducted CCL activities in the AEC domain.

INTRODUCTION

Interactive 3D computer applications have been recognized as effective virtual learning tools (Gil&Trezentos 2011; Liu et al. 2011; Chittaro 2006) in architecture, engineering and construction (AEC) due to its value in providing strong visual context for communication, collaboration and learning (CCL). Interactive 3D virtual environment has made a significant impact on educational thinking (Mallan et al. 2010; Goldparvar-Fard et al. 2010). Web-based virtual 3D game environment was

proved helpful in managing, accessing, and evaluating construction process (Rhalibi et al. 2009; Cook et al. 2011). Augmented reality (AR) (Azuma 1997) was loosely defined as using computer generated virtual, graphical and textual information to help people to understand physical world. Mobile AR (MAR) is one of the fastest growing research areas in AR, largely due to the recent penetration of smart mobile devices into people's daily life (Azuma et al. 2011).

Building information model (BIM), as a 3D information repository, has been gradually integrated into AEC industry as well as education community. Limited research papers were found in some explorations of BIM's application in AEC using virtual game environment. The covered topics ranged from design to construction (Khanzode et al. 2008; Rüppel et al. 2011; Kumar et al. 2011).

Improved hardware performance enables more sophisticated 3D graphical functions on mobile devices. For example, many graphical learning applications were developed based on iPad platform. However, very limited BIM applications can be found on this new mobile media.

In this paper, the authors introduced a case study of implementing a mobile BIM application of a medium-size institutional building on iPad. The goal of this project is to better understand the complexity and technical barriers of implementing a mobile BIM application to create a mobile augmented 3D virtual environment for collaboration, communication and learning (CCL). The main objective of this research is to test how realistic a complex BIM model can be implemented in a mobile device such as iPad.

The scope of the project focused on a building's MEP systems. The selected building is a student community center located on the campus. This building was often used as a project in many construction management courses. The authors expected that the selection of this building's MEP system will be instrumental to demonstrate the feasibility and potential value of the implemented mobile BIM application.

TECHNICAL CONSTRAINTS OF MOBILE DEVICES

Despite improvements of mobile devices' performance, there are significant technical constraints and challenges when implementing BIM application on mobile platforms. Some technical constraints are more notable than others: 1) the reduced processing power of the mobile CPUs will affect the graphical effects on the mobile device; 2) the bandwidth of wireless communication is still lagging behind the regular wired communication, which will affect the client-server system configurations; and 3) the touch-screen based input method will affect the user interface design and users experience.

As the results of these technical constraints, detailed BIM building models are often too complex and large to be implemented on mobile devices using existing 3D game engines. It is necessary to be selective when importing complex models into the game environment while maintaining the necessary property information of BIM components.

An efficient and secure solution for data sharing and communication needs to be considered in the designed system, such as data security, speed/quality of connection and service support, which challenge the design of system, and require more considerations compared to wired game environment.

Additionally, mobile applications are likely to have issues with hardware devices and issues with updating contents compared to standalone game applications. Most of the time, the system performance is limited by the computational resources such as processor speed, memory size and disk capacity.

RELATED WORKS

Research on BIM applications in architecture, engineering and construction (AEC) has been active in recent years. A recent paper by Suermann and Issa (2009) revealed that there were widely perceived values from the construction industry regarding using BIM in business practice. A more relevant case study by Khanzode et al. (2008) discussed using BIM to implement virtual design and coordination of MEP systems in a healthcare facility. Rowlinson et al. (2009), in a separate case study, discussed how BIM implementation in AEC projects affects the coordination of two selected projects.

Research on the combination of BIM and game engine started gaining momentum recently. The following are some notable ones. Yan et al. (2010) used game based BIM models to achieve real-time design visualization from deference parties. Rüppel et al. (2011) used BIM models in their game application for fire evacuation training and evaluation. Kumar et al. (2011) developed BIM-Unity3D based game applications for evaluating healthcare facility designs.

Very limited research was found on BIM application in mobile devices. Two of the most recently published papers were found through extensive literature search. Woodward et al. (2010) presented a mobile augmented reality (MAR) system to visually compare the scheduled BIM model with actual site progress. Yeh et al. (2010) conducted a controlled field test to compared users' performance of using 2D drawings and their development of location-based 2D BIM information system.

Off-the-shelf mobile BIM or BIM-like programs are in their very early stage of production development as well as marketing. Autodesk Inventor Mobile Viewer was published for iPad or Android Pad devices. Mobile Viewer allows users to view and interact with 3D Inventor models and see model information (Android 2012). Mobile Viewer is a standalone program with viewing 3D models and animations as its primary function. Vela Systems developed mobile BIM applications called "Field-BIM" for iPad primarily for field use of construction projects (Vela 2012). Field-BIM allows field users to access and to update building components information in BIM models. The BIM models on iPad serve as a database user interface.

The presented research is significantly different from the two off-the-shelf mobile BIM applications mentioned above. The primary function of Mobile Viewer is to view 3D models and/or animations created by Inventor. What can be viewed totally depends on what information is in the design model. Vela's Field-BIM, on the other hand, is essentially a 3D BIM database interface, despite its under-development walk-

through function. However, the presented mobile BIM application is a game-centered application, in which user scenarios, interactions between game users and BIM models, game physics, particle animations, and even interactions among multiple users are primary concerns. Although, the authors did not develop all the mentioned game functions in this demonstration project, those mentioned game functions can be developed using the same platform.

DESCRIPTIONS OF THIS PROJECT

Despite the tremendous progress in mobile BIM application, research on a domain-specific, augmented MEP BIM mobile application, is yet to be found. The authors believe that there are significant values in developing augmented mobile capacity in this domain. The developed capacity through this project can potentially be used in many other AEC applications, such as: 1) real-time equipment status check, in which mobile BIM models can demonstrate real-time operating data on the selected mobile devices. This will provide tremendous help for facility management and inventory management of building MEP systems. 2) Augmented on-site training and learning of MEP systems. Equipment specifications and design data can be pulled out from the 3D models on the mobile devices. Students will have the ability to access rich information of the equipment on site. 3) Building energy retrofitting, in which the augmented MEP BIM system can provide realistic 3D contextual information and navigation function for engineers and contractors to evaluate the conditions of existing MEP systems.

The ubiquitous accessibility to 3D BIM information through mobile devices such as the iPad, will potentially have significant impact on our way of communication, coordination, and learning in AEC domain. We hope the findings from this project can be instrumental to further research and development in the MAR area. After extensive research and evaluation, Unity3D (Unity3D 2012) was identified as the game engine to implement this project. Unity3D has the cross platform capacities of supporting applications in deferent operating systems. Unity3D is an open source game engine. It has a fairly decent interoperability performance in importing FBX files, which is one of the supported exportation file formats in Autodesk Revit Architecture and MEP. Unity3D game engine also provides a number of animation functions, such as lighting, particle, and rendering. It also supports multiplayer game functions and avatar creation, though the multiplayer function was not implemented in this case study.

THE IMPLEMENTATION FRAMEWORK AND RESULTS

The overall framework of the implemented system is shown in Figure 1. We provide a three-layer system, which included the offline game and model deployment, mobile platform application, and a server-side database using MySQL. This three-layer system design provided flexibilities in the configuration of client-side devices. In this way, platform changes on clients-side had minimum impact on the other two layers of the system. The interactive functions and object behaviors in user-model are

defined using the scripting language functions embedded in 3D game deployment. In game development step, the objects were imported into Unity 3D game engine as "asset" from BIM authorizing tools, such as Revit MEP, through FBX file format.

Secondly, we need to form a seamless interaction cycle between the digital model environment and real world information to develop a serious game for a primary purpose other than entertaining, such as education, training and technical barriers exploration. The notable components in proposed project are stored in MySQL database on server side, which support the graphical and non-graphical information interaction. The data will be pulled out when users click the corresponding objects and functional buttons during game testing. The data was also used to control the effects of the specific simulations at different building locations such as the volume of environment voice, light strength and airflow level.

Finally, the 3D interactive environment will be export to mobile platform- iOS in this project. The client-server solution scaling down to mobile devices and tablet computers can thus be made to serve the need of system.

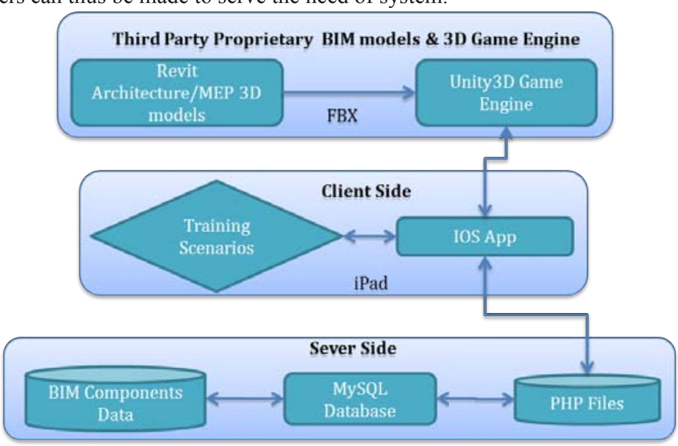

Figure 1.The system framework of the implemented game environment

The functional details of each layer are illustrated in Figure 2:

1) 3D user interface was designed and exported through the game engine. The interface layer will receive input from the user through touch screen, and to response with the predefined behaviors controlled by the embed scripts within the objects.
2) Middle layer, the operating system and device layer, is responsible to interpret the input from the mobile device, and execute the embedded scripts. It also connects to the server side database to pull out data from MySQL database through PHP.
3) Database server is an important part of this system. It stores knowledge-based data of this case study. For example, BIM component information, material

properties, and equipment status, etc. Holding a large amount of data on the sever side can reduce the work load of the mobile device, which is critical due to the performance constraints of the mobile device. More importantly, the server-side database is scalable without affecting the performance of the mobile device. Such example is handling large amount of real-time data of HVAC equipment.

Mobile computing with PHP files provides solutions for efficient database access control and also guarantees the security of the server. At client side, when users make a function call (JavaScript functions) to PHP file, at the server side, PHP scripts will select corresponding data from MySQL database and make a respond to the target function. As a result, the user would see the corresponding data on mobile screen.

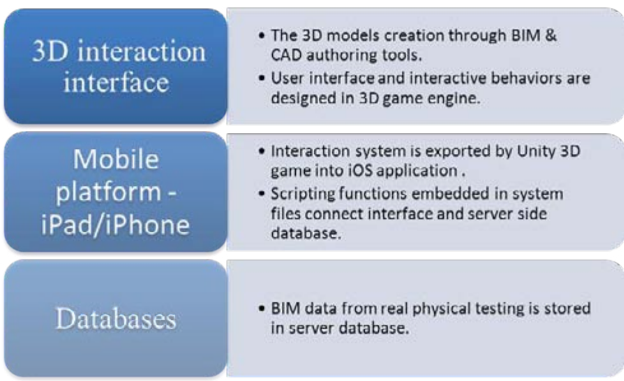

Figure 2 the mobile client-server three-layer design

Unity 3D provides the virtual camera system aims at controlling a camera or a set of cameras to display actions and scenarios in the 3D virtual world. Frist person shooter view is often used in games for entertaining purpose to create unpredictable encounters and surprise scenes. For serious game, the game for education, training or research purpose, fixed camera views or constrained camera views are often more desirable, because these views can reduce distractions and direct users' attentions to the desired and intended contents.

To make the game both educational and entertaining, the authors implemented two types of camera views to draw a balance between unpredictable user behaviors and well-controlled fixed scenarios training. Game users will have a free walk and look around in first person mode to walk around the 3D building models. On the other end, in the fixed camera mode which focuses on specified events/scenarios, unnecessary walk-through/unintentional moving will be banned. A particular top view in fixed camera can be used for users' navigation to help user navigate through complex and large-scale building models. We believe that the multi-camera viewing

is a good way to control the scenarios contents to reduce the waste of time on meaningless navigation.

Figure 3 shows a fixed-point view, in which the user can touch a piece of equipment to show the desired properties, design specifications, and/or real-time operation data. For example, in this view the equipment technical specifications were shown to users. We believe this function of the augmented 3D BIM tool will be very helpful when conducting site visit, or inventory MEP equipment in facility management. Figure 4 shows the actual view of the lobby vs. the augmented model view of the lobby, which shows the duct works concealed above the ceiling.

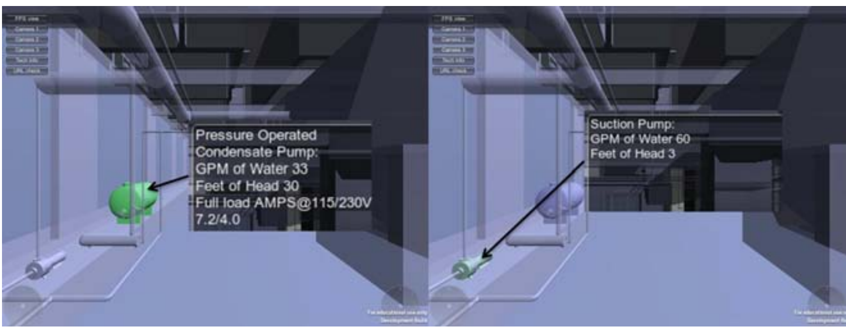

Figure 3. Augmented views of the mechanical room in the basement

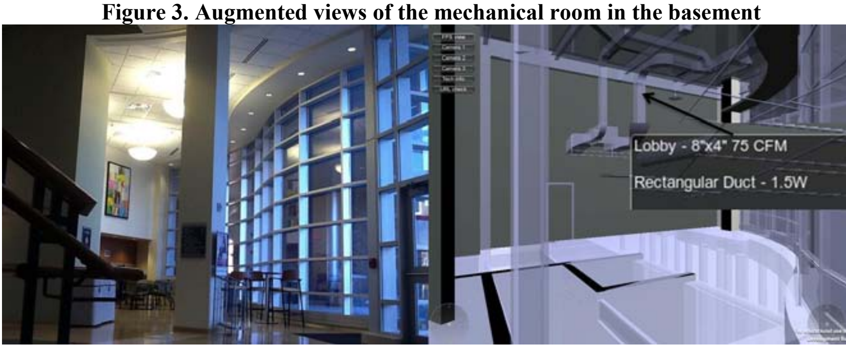

Figure 4. Actual lobby photo (right) vs. augmented 3D model view in the game (left)

CONCLUSIONS, LIMITATIONS, AND FUTURE RESAERCH

In this paper, the authors presented a case study on implementing 3D BIM game systems on iPad mobile platform. In this project the researchers achieved: 1) importing a fairly complex BIM model into a 3D game environment on a mobile device; 2) being able to control the views and 3D objects, and to navigate through the building using the touch screen; 3) being able to specify the behaviors of the game

objects in response to users' input through the touch screen; 4) being able to connect the mobile game objects to the server-side database using PHP.

Though preliminary, the implementation results, as reflected by the achieved functions, indicated that the iPad could be used as a mobile platform to implement serious augmented virtual reality games to facilitate CCL in the AEC community. The implemented three-layer client-server framework proved feasible in handling complex models on mobile devices.

Some limitations of this study might affect the extrapolation of the findings. Some notable ones are: 1) Most of the functions implemented in this mobile BIM platform were relatively simple. More and more sophisticated game functions need to be tested in the future. 2) Only a medium-size BIM building model was tested. More complex and larger BIM models might affect the performance and user experience of the mobile game. As a mater of fact, the authors already experienced some performance issues even on this medium-sized BIM model.

Future works will include more extensive tests of functions as well as scalability of this mobile BIM platform. This research will also be extended to include location-aware functions using indoor WiFi signals.

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Formal Specification of the IFC Concept Structure for Precast Model Exchanges

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ABSTRACT

The Industry Foundation Classes (IFC) provides a rich and redundant schema for interoperability. However, IFC lacks semantic clarity in mapping entities and relationships resulting in multiple methods to map the same information. This research explores a software engineering methodology based on engineering ontologies to develop a formal, consistent and machine-readable structure for IFC entities, attributes and relationships. Various issues such as the need for a logical framework, the current semantic approaches in AEC/FM and advantages of ontology for IFC are addressed. Details of the approach are illustrated by building application ontology for precast model exchanges. This research is expected to impact the overall interoperability of BIM tools by providing a formal and consistent taxonomy and classification structure for creating model view definitions (MVD) using IFC.

INTRODUCTION

The Industry Foundation Class (IFC) schema is accepted as the industry standard for interoperability (IAI 2003, ISO 2005) and is currently in the process of becoming an official international standard - ISO/IS 16739 (buildingSMART 2010). However, model exchanges based on IFC are still error prone and incomplete (Kiviniemi 2007). The current model view development methodologies, which are based on use-cases leaves scope for different interpretations based on end-user requirements and lacks a formal framework. Moreover, the granularity and atomicity with which such model views are defined is not consistent across the industry (Venugopal et al. 2012). This adds to the overhead for software developers and hinders IFC based implementations (Eastman et al. 2011).

This research aims to improve the interoperability of BIM tools in the AEC/FM domain by providing a formal definition of IFC entities, relations, attributes and methods for information exchange, using engineering ontology. Ontology is a formal representation of an abstract, simplified view of a domain that describes the

objects, concepts and relationships between them that holds in that domain (Gruber 1993). There are different classifications of ontologies, based on parameters such as level of granularity, their use and types of relationships (Gruber and Olsen 1994, Van Heijst 1997, Fensel 2000, Gomez-Perez et al. 2004). Ontology in this regard can be considered as a machine-readable set of definitions that create taxonomy of classes and subclasses and relationships between them. Explanation of developing an ontological foundation for IFC is provided and is applied in the development of model exchanges for precast/pre-stressed concrete industry.

SEMANTICS AND INTEROPERABILITY

The scope and potential of BIM is ever-increasing as a result of new and IT-enabled approaches to facilitate design integrity, virtual prototyping, simulations, distributed access, retrieval and maintenance of project data between multiple disciplines (Fischer and Kunz 2004, Smith 2006). Interoperability enhancements require common understanding of industry processes and the information required for and resulting from executing these processes. Two sets of semantics are at the core of any model view specification, namely, (i) the user/application functional semantics defining the information that must be exchanged, and (ii) the representational semantics available in IFC or other data-modeling schema for representing the user intentions (Venugopal et al. 2012). There are parallel approaches to introduce semantics into building information modeling, by means of using web standard technologies (W3C) and techniques (Yang and Zhang 2006, Bohms et al. 2008, Beetz et al. 2009). *Semantic web* is an example of inter-linked data available in a standard format, reachable and manageable by automated tools. *Web ontology language* (OWL) is the formal ontology language developed for the semantic web. Similar sets of issues were faced by the semantic web development effort as compared to IFC interoperability. By building an ontology structure, we define the semantics of each of the objects, relations, and other constructs used in IFC according to their often-implicit meanings. With its highly intuitive, compact syntax and well-defined formal semantics, ontology is able to represent knowledge and defines the relationship between terms allowing applications to interpret their meaning in a flexible and unambiguous manner and enable reasoning capabilities.

AN ONTOLOGY FOR PRECAST MODEL EXCHANGES

The objective is to formalize IFC definitions for a robust model exchange solution. In terms of the modeling criteria, a corpus or body of knowledge needs to be constituted. Entities are selected from the available domain-specific documentation according to the ontology requirements. The *precast national BIM standard* model view (Eastman et al. 2010) in general and the building components in particular are selected as the corpus in this case. The objective of the ontology definition is to add detail where necessary, incorporating formalisms wherever helpful, and generally enhancing the consistency and modularity of IFC entities, attributes, and relations, as shown in Figure 1. A sound base is important for building any hierarchy. This is achieved in this research by structuring the ontologies on a foundational ontology

such as *descriptive ontology for linguistic and cognitive engineering* (DOLCE) (Masolo et al. 2002). This is the most abstract layer, introducing the basic modeling concepts and generic design guidelines for the construction of actual ontologies. The second layer consists of super theories such as *mereology, topology* and *systems theory* (Borst 1997), that are reusable modules according to which ontology is organized. The final layer comprises of application specific ontologies such as structure of object (precast specific material, geometry, etc.) and properties. The application layer refines the ontology to be used for precast model exchanges by adding classes and relations for practical application of ontology. In this case, the precast application ontology is built from (i) components, (ii) connections, (iii) system, (iv) placement, (v) material, (vi) geometry and (vii) requirements ontology, as shown in Figure 2.

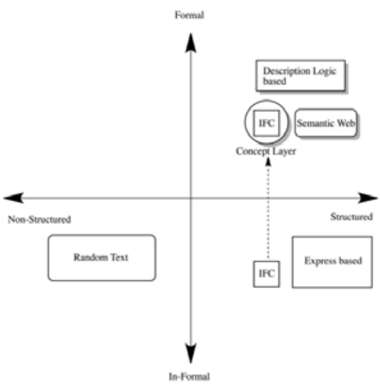

Figure 1. Ontology based concept layer to improve formalism of IFC.

Figure 2. Structure of the application ontology for precast model exchanges.

Ontology definitions: Application ontology is built on top of engineering ontologies. The *precast application ontology* defines how a precast model should be specified in general, in the form of a set of theories. A precast piece can be modeled using the above-defined engineering ontologies, which are a part of the application ontology. Depending on the needs we can define a precast piece ontology using component, connections, system, etc. and adding classes for requirements, placement, and geometry. The following paragraphs provide excerpts of the ontology definitions. The components ontology is used to represent the components in a building model and their part-whole decomposition in this research. A component is a general concept that encompasses all individuals used to describe the structure of an object. A component is considered to be atomic if it cannot be decomposed into any further parts. Components can be part of an assembly as well. However, assemblies can be made up of atomic components or smaller assemblies. Part-whole relationships are of two types, namely, *'part-of'*, and *'proper part-of'* relations. '*Part–of'* is the general relationship that covers all the individuals in this ontology, whereas *'proper part-of'*

restricts this relationship, that implies the individual cannot be distinguished from the sum of its parts. A perfect example is the slab-beam aggregation. A slab is the aggregation of individual beams, which means that beams are a proper part of the slab. The project-site-building-building story hierarchy is simply a '*part-of*' relationship. Moreover, in the case of *'proper part-of'* relationship, the geometry of the parent is the resulting sum of the individuals. Taking binary product of two individuals can check overlap. A beam is resting on a column, these two individuals are not supposed to overlap. Hence, they cannot have a dot product, and therefore the shared part has to be assigned only to one of the individuals. The binary sum is the individual that encompasses at least one of x and y. The difference x-y is the individual that is a *'proper part-of'* x but does not share a part with y. Sum provides a boolean addition to a precast piece, such as a corbel. Difference can be used for voids. Any individual from the component ontology can be elevated to the level of type. Instances are related using the *'type-of'* relationship. Connection ontology provides the connections between objects by means of the *'is-connected-to'* relationship. The relationship *'in system'* aggregates individuals in to a system.

The structural ontology is qualified by three relationships '*has representation'*, *'has material association'*, and *'has placement'*. An object has material associated with it, however the material requirement is extended and defined in the *requirements ontology*. Every individual has a placement relationship and can be realized by three different mechanisms, namely, absolute placement, placement relative to a grid, and placement relative to another individual. The requirements ontology contains main concepts needed for the representation of the function and behavior of individuals. For example, the requirements for a precast piece can be decomposed into requirements related to performance, design criteria, delivery methods, etc.

The objective of the ontology layer is to remove the ambiguities associated with differing viewpoints. For example, Figure 3. (a) shows a precast piece to be exchanged between the structural engineer and a precaster. A precast piece such as a floor slab can be represented as a monolithic slab entity in the structural model (Figure 3. b) developed by engineer, whereas the fabrication model developed by precaster will include the high level details of discretized hollow core slabs for the entire span of the floor along with the connection details, finishes, joints, embeds, reinforcing, tensioning cable layout, lifting hooks, etc. (Figure 3. c). The corresponding IFC entities and relationships will also be different as shown in Figures 4 and 5. The structure of a model view for the exchange of product model data between various BIM application tools depends on the extent to which building function, engineering, fabrication and production semantics will be embedded in the exchange model at the source and the capability of any receiving application to comprehend them. In order for the importing application to infer knowledge from the exchange, the exporting application should structure the data based on an agreed upon standard. The ontology definitions provide a means to remove ambiguity in such scenarios, by using constraints that define the relationships and also provide equivalences between individuals.

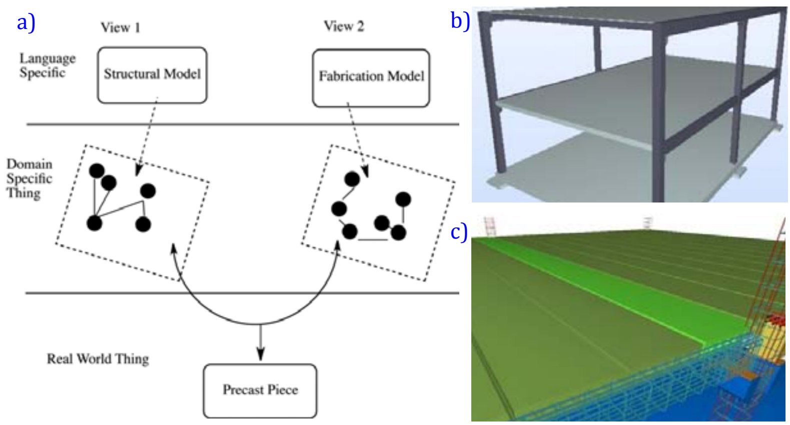

Figure 3. The different view points of same objects in different domains

APPLICATIONS OF THE ONTOLOGY LAYER

Ontology specifies how the application's functionality is to be implemented and it serves roles similar to ER diagrams, object models, and object patterns. In the case of model exchanges, the ontology is intended to provide the structure of the model view. For this purpose, the ontology layer developed in this research is converted to an object-oriented class library. This additional layer of mapping is used for implementations. IFC entities, relations, attributes, etc. are mapped onto the application ontology developed in the previous phase. This allows ontology language and definitions and modeling representations such as IFC to stay invisible to the end user (similar to data hiding in object oriented design). This significantly lowers the barriers for practitioners (software developers). This library is meant to be an extensible one and it is envisioned that future model views will be developed based on this library.

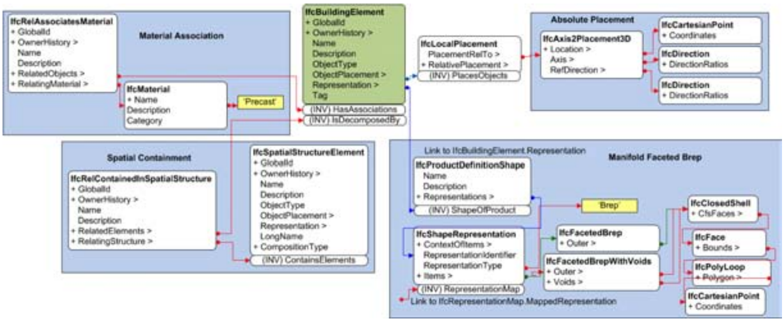

Figure 4. IFC mapping for a monolithic precast floor slab

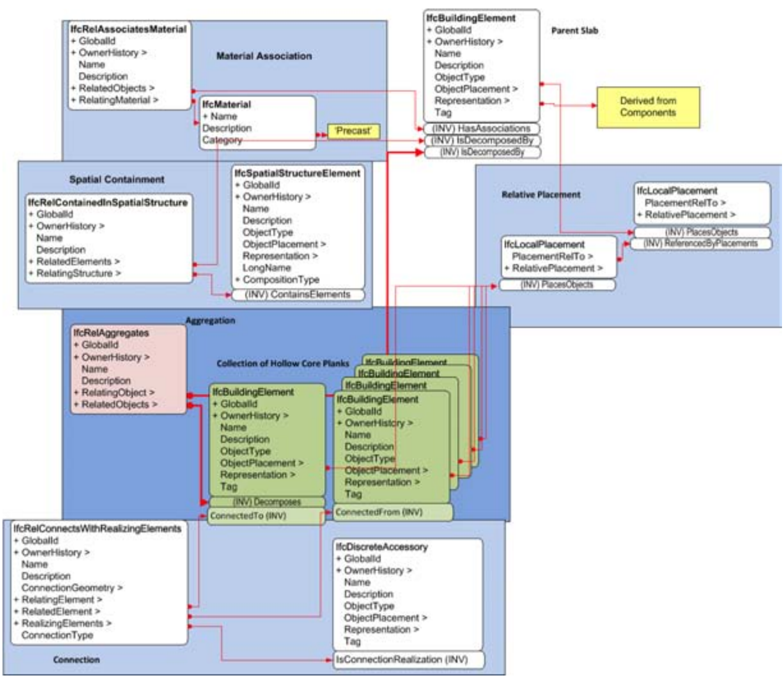

Figure 5. IFC mapping for a floor slab with discretized hollow core precast slabs

CONCLUSION

IFC is a rich model that addresses the needs of different applications and provides a variety of ways to define the same part of a building. Hence additional layers of specificity such as model views are required for IFC implementations. This

brings to the forefront the need for a more logical framework to specify model views. The number of research and industry-based initiatives to develop model views in different areas underlines this need. This research specified a formal classification structure in the form of ontology, for the IFC entities, relations, and attributes to be followed in the development of model views for precast/pre-stressed concrete industry. The usefulness of ontologies for specifying model views in a consistent manner is illustrated. There are plans to develop an object-oriented library based on the ontology definitions and specify exchange requirements directly based on this library. Once fully implemented and tested, such an approach can be followed for creating industry-wide model views.

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BIM Approach for Automated Drafting and Design for Modular Construction Manufacturing

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ABSTRACT

Industrialization creates new requirements for design. Designers need to consider not only building performance, but also production plan needs. This requires a well-structured Building Information Model (BIM) to support the manufacturing needs for design and drafting. BIM, in combination with CAD tools such as AutoCAD and ArchiCAD, can be used for this purpose. These, however, are not sufficient to support the level of detail needed for the manufacturing process.

The proposed research establishes a methodology for the automation of design and drafting for the building manufacturing of residential facilities based on the platform construction framing method. The proposed methodology has been incorporated into a computer model called MCMPro, which was developed using Visual Basic for Applications (VBA) as an add-on to a CAD model. MCMPro incorporates BIM technology based on CAD parametric modelling and manufacturing requirements in a 3D-model, in order to generate sets of shop and fabrication drawings.

INTRODUCTION

A primary motivation behind a shift towards manufacturing industrializing the building process is to reduce cost and time-to-build, improve the quality of the

buildings, and produce more energy efficient buildings. Industrialization creates new requirements for design. Traditionally, building performance has been the only factor considered by architects and engineers, and building drawings and specifications as the outputs of the design and engineering process. In factory-based construction, designers need to consider not only the building performance, but also production plans, transportation plans between the factory and the project site, and installation plans. Automating the design and drafting process is the first pillar of the industrialization of the building construction process or modularization. Design and drafting plays a major role in the cost-effectiveness, timeliness, and quality of the entire process. Advantages in terms of reducing redundant design activities, providing an infinite number of solutions, eliminating assumption and design errors, and shortening the time needed for any modification can be obtained from automating the design and drafting modeling process.

A novel systematic way of construction is the solution for current construction challenges. This systematic methodology covers a project's construction process from its early design stage until the final delivery. A special focus on the design process is required, because managing the design process is a core issue in the Architect/Engineer/Contractor (AEC) sector, it plays a major role in the cost effectiveness, timeliness and quality of the entire project (Chua et al. 2003). Having a well-defined and detailed set of construction drawings is also essential for better communication and coordination among construction project team members (Gao et al. 2006).

The proposed methodology in this paper focuses on two main directions: the development of a construction manufacturing technology and an automated system for design and drafting of manufacturing of buildings for the North American building construction industry, focusing on wood-framing construction. The manufacturing technology and the utilization of best practice for the platform-frame method has been incorporated into BIM models as a set of scenario-based analysis (SBA) rules that mimic human intelligence, incorporating the building code requirements and structural and architectural design needs.

LITRATURE REVIEW

STATE-of-the-Art Literature of the Application of Building Information Modeling (BIM) in Construction. The multidisciplinary nature of modular construction manufacturing, which implies the need for a model to integrate all the

different aspects of a project, makes BIM the right technology for the construction industry. BIM provides a core model loaded with project data that facilitates the data transfer process among the different project stakeholders. This research focuses on the development of an intelligent system that utilizes BIM as a technology to integrate the architectural and structural design, modularity concepts, and framing best practices into one model that helps the end-user during the decision-making process.

The current commercial generic BIM applications prevent BIM technology from reaching its optimum efficiency in the construction industry. Factors such as construction projects unique nature and efficient communication methods among the projects various teams have to be focused on when developing a BIM application.
Current BIM applications utilize generic components to represent different types of construction projects; however, they do not account for the unique design requirements and specific details that can vary from one project to another. For instance, a connection between two walls is represented in commercial software without any special details, while the platform framing practice implies that this connection needs to have different types of wooden stud formations (L connection or U connection). Figure 1 shows two walls intersecting using an L connection type, first in actuality and then in ArchiCAD, a BIM commercial software.

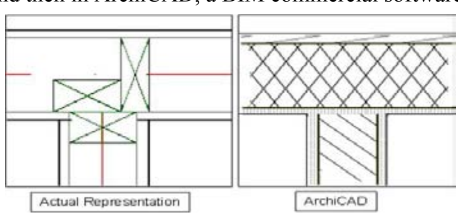

Figure 1. Two walls' connection representation comparison

In terms of communication and coordination among AEC teams and the various construction trades, it has been proven that BIM as a technology improves the information transfer process (Salazar et al. 2006). However, current commercial BIM applications are still unable to deal with this feature efficiently: They have different versions for the projects' various stakeholders, i.e. Architectural AutoCAD, Structural AutoCAD, Mechanical AutoCAD, and hence do not provide a unified platform that clearly reflects the consequences a change in one specific discipline has on an entire project. A proper information transfer process requires not only a tool that allows the information to be shared, but also indicates when to transfer and what type of information needs to be shared. Delays in the completion date, project cost

increases, and poor quality of the end-product are expected when sub-optimization of only a single discipline's performance occurs as a result of failing to provide a communication vehicle (Haymaker et al. 2005). A single platform for a project's multi-disciplinary processes provides an environment wherein input data from the various stakeholders are integrated to represent the knowledge of the effect an unplanned change in one discipline has on the others.

Modular Construction Manufacturing (MCM). Unaccounted for on-site conditions can result in an increased number of changes during the construction phase. This can reduce the effectiveness of advanced technologies such as BIM and Lean construction. Construction manufacturing, in contrast, is a process where building units are manufactured in a factory under controlled conditions and shipped to the construction site to be assembled.

The modular construction manufacturing (MCM) process consists of three main stages: (1) panel prefabrication, (2) production line in the factory, and (3) on-site model installation. The production line is divided into four phases - walls, slabs, electrical, and mechanical - whereby each phase in the production line has a different number of stations. Specific sets of shop drawings are required for each phase. This stage finishes when a unit is manufactured.

Previous Research. Utilizing BIM technology to support the design and drafting process of wood framing has been the focus of several researches. The home building industry was a primary area of interest for a previous study (Manrique rt al. 2007). A core model loaded with a project's information was used as an information management system, which provides the needed data to automatically develop shop drawings for wall panels. The development of repetitive drafting tasks was supported by 3D and parametric modeling, which facilitates the generation of construction drawings for wood framing, sheathing, and interior drywall.

In addition to shop drawings, the core model provided a take-off list of materials, optimum materials' cut list, and advanced construction methods incorporating innovative technologies, such as optimization methods, into that model.

RESEARCH METHODOLOGY

This research focuses on two main objectives: the development of a construction manufacturing process and an automated system for design and drafting of MCM for the North American construction manufacturing industry, with regard to wood-framing design and construction drawings. For the purpose of fully automating

the design and drafting for modular construction manufacturing, Scenario-Based Analysis (SBA) and Building Information Modeling (BIM) have been used as an integrated computer design tool called Modular Construction Manufacturing Tool (MCMPro).

Main Stages of the Modular Construction Manufacturing Process. This research proposed process follows the procedure shown in Figure 2, where three main stages have been identified including, panel prefabrication, production-line in the factory and on-site unit assembly.

The production line is divided into four phases—walls, slabs, electrical and mechanical—through which all the project units pass in order to produce the final products that are ready for on-site installation. Each phase has a different number of stations accordingly. The process starts with assembling the walls; these walls are tagged with discrete numbers which will be used when connected to framed units. The second step includes slab and ceiling components. At this stage, a framed unit is produced and is ready for the following stages: Mechanical and electrical systems including plumbing pipes, fixtures, HVAC units, HVAC pipes, electrical wiring, electrical panels and different types of plugs are installed, and a unit is manufactured and ready for the final stage on-site installation.

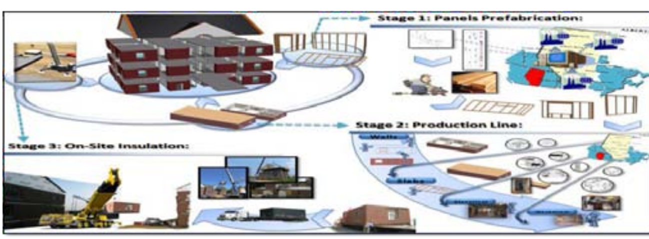

Figure 2. Modular construction manufacturing process

Automated system for design and drafting for modular construction manufacturing. The second objective of this research is the automation of design and drafting for modular construction manufacturing through an integrated computer tool called MCMPro, which is developed using Visual Essential for Applications (VBA) by means of CAD software. This tool utilizes a scenario based analysis (SBA) in order to automatically generate the needed sets of shop drawings. SBA interprets the tool input, criteria, and standards into sets of rules that incorporate human intelligence, national building codes requirements, city bylaws, the framing method, manufacturing concepts, architectural and structural designs, etc., into the tool core

BIM. Figure 3 shows the input, standards, and criteria required by the SBA in order to generate the core BIM, the upgraded model based on the construction manufacturing concepts, detailed sets of construction drawings and take-off lists of materials. This research proposes the development of cutting lists of materials and beyond optimization analysis by implementing optimization techniques on the take-off lists of materials.

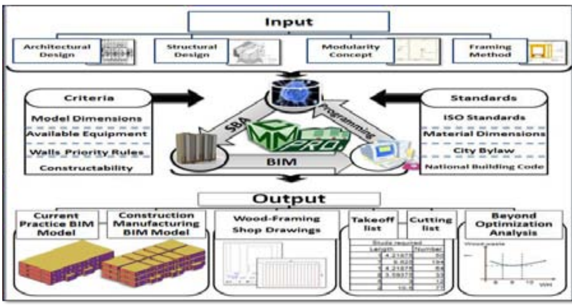

Figure 3. MCMPro analysis process

The automated system MCMPro provides the needed set of structural shop drawings needed for modular construction manufacturing. This system is designed using AutoCAD Visual Essential for Applications (VBA) 2009. The shop drawings developed in the CAD environment require essential information from four main sources: architectural components, structural requirements, modular concepts, and framing method. Architectural components are represented through the 2D layout of the project—the layout specifying all essential design information including spaces, openings, wall locations, story heights, etc. The architectural design must yield to city bylaw requirements in terms of the size and number of windows and doors, setback, and indoor air quality. Structural requirements specified by a design in line with building codes are used for defining the element components for each wall, door, window, beam, and column. Modular concepts provide a set of rules needed when dividing the layout into a number of units. This set specifies allowable model dimensions based on road regulations, acceptable dividing elements, dividing roles and procedures, and rules related to slab thickness adjustment for each unit. The framing method uses framing best practice to specify different types of wall connections, framing elements, and openings. These requirements are included in the parametric algorithm (referred to as MCMPro).The parametric algorithm passes through three main stages, each stage composed of numbers of steps as follows:

Stage 1: Generation of the Building Information Model

1. Transform lines into wall groups, windows groups, door groups, connections, balconies, and corridors.
2. Assign openings and connections to each wall.
3. Generate a BIM.

Stage 2: Generation of Modular Construction Manufacturing BIM

1. Divide the layout into modules using interior walls as separation walls.
2. Generate a slab element defined by each modules boundary.
3. Generate an upgraded BIM.

Stage 3: Detailed Shop Drawings Generation

1. Adjust walls thickness according to the structural design.
2. Adjust walls length in order to generate accurate connection based on the framing method.
3. Analyse each module and frame its walls.
4. Generate shop drawings and take-off list.

The research proposes that the take-off list can be optimized in order to generate cutting lists that minimizes wood waste. Having generated the optimum cut length for a specific wall height, an analysis that goes beyond optimization can be performed. This analysis utilizes wall heights as input data to generate several optimums cut lists. The effect of wall-height on wood waste will be displayed using a curve with wall height as the horizontal axis and wood waste as the vertical one.

This tool has been tested using Building3, Grad Housing, University of Alberta. The architectural standard values for the case study are illustrated in Table 1. The case study 2D CAD input drawings for the lower floor, a 3D MCM BIM, and wall panels shop drawings are illustrated in Figures 4, 5, and 6.

Table 1. The case study's standard values (in cm)

Input Parameter	Value	Input Parameter	Value
Exterior wall thickness	26	Wall Height	300
Interior wall thickness	12	Slab thickness	30
Mechanical wall thickness	12	Door Height	220
Interior door width	90	Window Sill	100
Exterior wall width	100	Window Header	220
Window width	150		

CONCLUSION

This paper proposes an innovative construction manufacturing concept which covers the manufacturing process starting from components pre-fabrication, to factory

production line assembly, to the final stage: on-site unit installation. A parametric algorithm (referred to as MCMPro) which provides a complete set of structural shop drawings has been demonstrated.

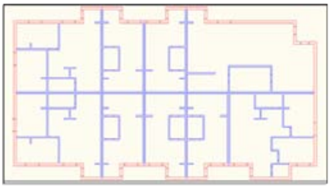

Figure 4. Lower floor 2D CAD

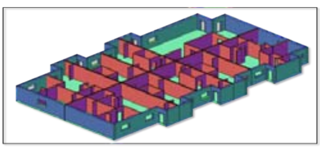

Figure 5. Lower floor 3D MCM BIM

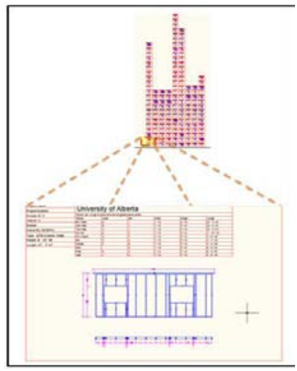

Figure. 6 wall shop drawings

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Using Delphi and AHP in Information Systems Development Methodologies

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ABSTRACT

Research on information systems development methodologies (ISDM) adoption has been widely undertaken to highlight the experience of developed countries. Studies concerned with the status of ISDM in developing economies including the factors that influence and motivate their use, current trends, difficulties, and barriers to adoption are lacking. This paper explores these issues in a developing economy, namely Oman, and proposes an ISDM adoption decision model using Analytical Hierarchy Process Analysis (AHP) and Delphi consultation. The findings from the survey reveal a lack of knowledge of ISDM amongst Omani Information Systems developers and the reliance on ad-hoc software development methods. Conversely, analyzed data reveals a trend whereby a majority of Omani organizations are gradually moving towards increased ISDM adoption and deployment.

INTRODUCTION

Despite the arguments about the usefulness of ISDM, ISDM are expected to be largely used in the current era more than ever before (Avison, 2003). A review of literature shows that there is insufficient empirical research on ISDM adoption (Davis and Williams, 2003). A survey of prior studies of ISDM adoption shows clear differences between the number of studies of ISDM adoption that have been undertaken in developed and third / developing countries (Wynekoop and Russon, 1997). None has been conducted in Oman or the greater Middle East region.

In 2002, the National Science Foundation reported that more than 84 percent of the world's scientific and technological production is concentrated in developed countries. Developing countries have only marginally increased their participation, which emphasizes the scientific and technological gap that exists with the developed world. Also, in several of the information technology installations that were created and adapted for organizations in developing countries, local (regional and national) factors were not taken into account. This has resulted in outcomes that do not fit the needs of the direct beneficiaries in the developing nations (Straub, et al, 2001). Previous research highlights the idea that technology adaptations in developed countries occur continuously in response to misalignments, gradually leading to a successful alignment (Vorakulpipat and Rezgui, 2008). This is in contrast to

developing countries, which tend to rapidly adopt technology created by developed countries, often in an ad hoc way (Archibugi, and Pietrobelli, 2003).

The objective of this research is to investigate Information Systems Development Methodologies (ISDM) adoption in a developing country, namely the Sultanate of Oman. The research contributes to the body of knowledge in ISDM by providing insights into ISDM adoption practices in a developing country across different types of Omani organizations. In addition, it identifies and analyzes the variables which contribute to effective evaluation and selection of ISDM, and investigates the usefulness of combining Delphi and AHP techniques to develop an ISDM adoption decision model that could be used in similar environments.

RELATED WORK

There is no standard accepted definition (Huisman and Iivari, 2006). The British Computer Society (BCS) Information System Analysis and Design Working Group defined ISDM as "A recommended collection of philosophies, phases, rules, techniques, tools, documentation, management, and training for developers of information systems". (Avison and Fitzgerals, 2006) extended this definition as follows: "A recommended means to achieve the development, or part of the development, of information system based on a set of rationales and an underlying philosophy that support, justifies and makes coherent such a recommendation for a particular context". The recommended means usually includes the identification of phases, procedures, tasks, rules, techniques, guidelines, documentation and tools. They might also include recommendations concerning the management and organization of the approach and the identification and training of the participants. In terms of ISDM classifications, various classifications of ISDM were identified in the literature such as those reported by (Iivari, and Huisman, 2001), and (Charvat, 2003). Davis and Williams (2003) identified three major types of ISDM, including structured methodologies (e.g. SSADM), rapid application development (e.g. DSDM), and Object-oriented methodologies (e.g. RUP). Avison and Fitzgerald (2006) introduced a more comprehensive classification of ISDM that includes: Process-oriented methodologies, Blended Methodologies, Object-oriented methodologies, Rapid development methodologies, People-oriented methodologies, Organizational-oriented methodologies, and Frameworks.

ISDM adoption remains a controversial issue among many organizations (Fitzgerald, 1998), (Avison and Fitzgerald, 2003). Many practitioners view ISDM as the means for improving the quality of the information system development process, at the same token there are considerable arguments against the use of ISDM, including (a) mismatches with organizational or Information Systems (IS) projects requirements, (b) ISDM vendor dependency, (c) system development delay, (d) system development stagnation (Fitzgerald, 1998).

A review of literature shows that while some organizations claim that they use ISDM successfully with positive results and view them as an essential approach to improve the quality and to increase the productivity of the software development process, others argue about the benefit of using these methodologies and affirm that they do not use any ISDM in practice (Avison and Fitzgerald, 2003). Moreover, while

various researchers argue that ISDM are an important resource in business and industry and have a critical potential impact on performance (Davis and Williams, 2003), there are many concerns when an organization attempts to adopt and deploy ISDM. In fact, the issue remains open of whether or not the organization will acquire a quality information system as a result of adopting and deploying a particular ISDM (Avison and Fitzgerald, 2006). In a survey conducted by (Wynekoop and Russon, 1997) regarding ISDM usage studies, it was found that most applicable studies were conducted during the 1980s and 1990s, and that the vast majority of ISDM studies were undertaken to address the experience of developed countries (Rahim, and Seya, 1998).

METHOLDOOGY

This study was conducted using three research methodologies: survey, Delphi method, and Case study. Survey mode of enquiry was employed to obtain data beyond the physical vision of the researcher in order to provide insights into ISDM adoption practices across Omani organizations. Delphi method was used to identify and analyze the variables that contribute to effective evaluation and selection of ISDM. The research model was developed using a combination of Delphi, and Analytic Hierarchy Process (AHP) techniques aiming to assist IS managers to determine which ISDM is most suitable for their organization's IS development. The case study therefore, was a supplementary research methodology to customize, quantify, and examine the usefulness of the model.

The main objective of the study was to describe the information system environment, the activities performed, and the use of system development methodologies in IS departments in the surveyed organizations within the Sultanate of Oman, as well as to develop a suitable model for ISDM adoption for Omani organizations using two decision-making tools: Delphi technique, and AHP. The model was designed to detect the most appropriate choice among various alternative ISDM. The research sought to resolve the following three main research questions:

Q1. What is the current status of ISDM practices in the Sultanate of Oman?
Q2. What are the critical variables and their level of importance in evaluating and selecting the most suitable ISD methodology?
Q3. What is the requisite model for ISDM adoption to assist organizations to evaluate and select the most appropriate ISD methodology for their software development activities?

The results of the study provide three main contributions. First, the survey stage of the study reported important information for both the research community and to practitioners. For the research community not much is known about the use of ISDM in developing countries. Far less is known about their use in the Gulf Corporation Council (GCC) countries, and more specifically no study has been conducted regarding the use of ISDM in the Sultanate of Oman. For practitioners, this research could assist them in changing or improving their current systems development practice. This is very important for Omani organizations when they consider entering the international market, or when they desire to obtain ISO 9000-3

certification, as one of the ISO 9000-3 certification requirements is to employ a formalized information system development processes (Huisman, and Iivari, 2001), (Fitzgerald, 1998). Secondly, on the conceptual side, the study shows how two well known decision-making approaches, Delphi technique, and AHP, could be combined effectively to develop an ISDM decision model. Initially, Delphi technique was suitably employed to analyze and produce reliable variables for decision making. AHP was subsequently employed for model development and for detailed analyses of these variables. On the application side, the study shows how Delphi technique and AHP could be used to develop a requisite group model of ISDM adoption for a large organization in Oman, for selecting the most suitable ISDM. Third, the models were developed as a decision support tool. With user friendly software, decision-makers may improve their decision-making processes by running sensitivity analyses, applying the models based on their available information, intuition, and experience, visualizing their decision outcomes, and modifying the models to other relevant issues or scenarios.

FINDINGS, DATA ANALYSIS, AND DISCUSSION

Current status of ISDM practices (Research Question 1). The results of the study indicate that the information systems adopted by Omani organizations are operated in a multi-platform environment, supported by multiple operating systems, using both local and wide area networks, and supporting a variety of development/programming languages. It is worth noting that certain hardware and software platforms, including PCs (computing terminals), Oracle (software), UNIX and Windows (operating systems), and local area networks based environments are the most dominant among Omani organizations.

In relation to the activities of IS departments in the responding organizations, the findings reveal that the IS departments spend 44.3% of their time on system support and maintenance, 30.7% of their time on IS project outsourcing, 13.9% on the development of new in-house IS, and 11.1% on the customization and integration of commercial packages.

In relation to ISDM usage, the data analysis reveals that 12.2% of responding organizations adopted ISDM to develop their information systems, 33.33% of those adopters are Consultants/Software Houses/IT vendors. Larger organizations and larger IS departments are more likely to adopt ISDM. In addition, the results of the study show that the older the IS department, the more likely it is to adopt ISDM for IS development. Furthermore, in-house methodologies are the most common ISDM in Omani organizations, followed by Oracle Development Methodology. Finally, Internet-Speed Development (ISD) was identified as the most intensively used in the surveyed IS departments. This is followed by Rapid Development Method and Information Engineering Methodology (IEM).

In relation to the decision-makers of ISDM adoption, the findings of the empirical survey reveal that a large percentage of the respondents indicate that the decision to adopt ISDM is undertaken by IS managers. This suggests that IS managers are the key decision makers for ISDM adoption. In addition, the ISDM training provided by organizations to their developers largely relies on in-house trainers followed by external trainers, external institutes, or self-training. Furthermore, an

important finding of the empirical survey indicates that the trend of ISDM adoption among Omani organizations will increase over time.

The empirical survey tested a number of variables to examine the extent to which these variables affect ISDM adoption. Nine variables were empirically tested including type of organization, business activity, organization size, IS department size, age of IS department, knowledge barrier, relative advantage, complexity, and compatibility. The findings of the survey reveal that a significant relationship is lacking between type of organization and ISDM adoption, and between complexity and ISDM adoption. However, the remaining seven variables were found to have some relationship with ISDM adoption and the degree of the impact of these variables varies from one variable to other.

Variables and Their Level of Importance (Research Question 2). The purpose of the second empirical stage of this study was to identify and analyze ISDM adoption variables that contribute to effective evaluation and selection of ISDM. In order to achieve this purpose, the study utilized Delphi technique to establish a communication medium between a group of IS experts in order to elicit their opinion about ISDM adoption variables. This approach involved three iterations of Delphi surveys and was conducted to achieve consensus. As a result, a final list of 40 ISDM variables with their statistical descriptions was generated. The data analysis of the third questionnaire produced three important types of information for each variable in the questionnaire as follows:

- **Rating of assent**: used to determine the applicable ISDM variables for decision making. For this purpose a median value of 2 was selected to identify the accepted variable for the final list of ISDM variables. That is, all variables rated below median value of 2 were excluded, whereas all variables rated 2 or above were included and considered relevant for the study. The level of assent was extremely high on the final round, as the results shows that all variables received a high level of assent.
- **Degree of consensus**: the interquartile range (IQR) was employed to determine the level of consensus for each variable identified from the Delphi study. The IQR represents the middle 50% of responses. The IQR value indicates the degree of consensus. That is, a large value of IQR shows less degree of consensus, whilst a small value of IQR shows a high degree of consensus. In relation to this study, the data analysis of the third round revealed that 24 variables received the highest degree of consensus, 16 variables received the average degree of consensus, and no variables received the lowest degree of consensus.
- **Level of importance**: identified by using the statistical median for each variable. That is, a large median value indicates a high level of importance, while a small median value shows a lesser level of importance. For example, if a particular variable received a median value of 4 then this would indicate that at least 50% of the participants rated this variable as very important. In relation to this study, the findings of the research revealed that all 40 ISDM adoption variables were rated at a level of importance of 3 (i.e. moderately important) or 4 (i.e. very important).

Requisite Model of ISDM Adoption (Research Question 3). The third empirical stage of this study focused on developing a general ISDM adoption decision model based on the variables obtained from the Delphi technique. In addition, this stage concentrated on adjusting and quantifying the general ISDM model based on the selected organization employees' perspective in order to examine the practicality of the model. The design of the ISDM adoption model allows decision-makers to decide which ISDM is more appropriate for their IS department. The model developed in this study consists of four levels. The top level represents the goal/objective of selecting suitable ISDM in order to adequately meet the organization requirements, needs, and preferences. The last level is represented by the ISDM alternative. The second and third levels constitute the main variables and sub variables respectively, which affect the decision to select the appropriate ISDM. These variables, affecting the choice of ISDM, were determined from the literature review and subsequently evaluated and analyzed using Delphi technique. The model is simple to use and the computations can be run using available specialized software such as "Expert Choice". AHP technique was employed for ISDM evaluation and selection for the case study. The model development comprised three stages: structuring the problem/objective, driving information and values, and evaluation.

The first stage was to identify the objectives that the case study is aiming to achieve. Then, all potential ISDM alternatives were identified for evaluation under a set of specific variables. The five ISDM alternatives perceived to fulfill the needs of the IS department of the case study objective are: Dynamic Systems Development Method (DSDM), Extreme Programming (XP), in-house methodology, Structured System Analysis and Design Methodology (SSADM) and Rational Unified Process (RUP). Each of these ISDM alternatives was evaluated using the same variables. High level variables consisted of relative advantages, features of ISDM, and case study environments. Each high level variable was sub-divided into low level variables, including specific issues detailed from the main variables.

During the second stage, respondents were asked to weigh the level of importance (i.e. a pair-wise comparison judgment) of each criterion and then score all the alternatives against the specified criteria. The last stage evaluated the alternatives and conducted sensitivity analysis using the ExpertChoice software. Results from the AHP analysis revealed that the preferred ISDM was in-house methodology and the second alternative was RUP.

In effect, the proposed model of ISDM adoption helps decision-makers to increase their level of understanding and solving of problems, compares the rational results with their intuition, detects possible relevant reasons behind objective results, and allows them to improve their decision-making by adjusting weighting and scoring, and conducting sensitivity analyses.

CONCLUSION

This research "ISDM Adoption within the Context of a Developing Country" combines three study areas of information systems: information system development methodologies adoption, Delphi technique, and Analytical Hierarchy Process.

The findings of this study indicate that a very small percentage of Omani organizations utilize ISDM for their IS development. The findings also reveal that the adoption of ISDM is related with the nature of business activities in which an organization operates. Furthermore, a clear difference in ISDM adoption was noticed between different size organizations and IS departments. Such a difference was also noted between mature and novice organizations. Interestingly, most of the factors believed to be a reason for not using ISDM could not be supported by the survey results. However, lack of understanding and lack of appropriate knowledge of ISDM concepts and principles and their implications is a significant barrier to adoption; successful adoption exists only if those concerned have a full understanding of the ISDM.

The proposed model of ISDM adoption based on Delphi technique and AHP analysis demonstrated an easy procedure to select the best alternatives from various conflicting variables. Using the model may help IS practitioners evaluate ISDM alternatives more efficiently and effectively, compared to the traditional method. First, AHP is a suitable tool for ISDM evaluation. Second, AHP software applications are inexpensive and available in the market. Third, the software applications are easy to learn and use within a short time. Fourth, outcomes from an AHP analysis can be compared with the intuition or experience of decision-makers and provide insight into differences. Fifth, AHP allows decision-makers to conduct sensitivity analysis to test for different scenarios and conditions of problems. Sixth, the proposed model mitigates conflicts and promotes consensus of group decision-making by identifying reasons of outcomes. Finally, an AHP analysis is applicable to other issues in regard to choice selection or alternative evaluations.

This study has examined a systematic way of assessing alternatives of ISDM, which is a complex and controversial issue. It has endorsed the idea that good decision-making should focus on objectives and not on alternatives. It has drawn attention to the use of the Delphi technique and Analytic Hierarchy Process (AHP) in evaluating ISDM alternatives in a complex decision-making process.

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BIM-Enabled Building Commissioning and Handover

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ABSTRACT

Building commissioning is one of the most effective means to ensure the building systems and equipment will perform as designed in its lifecycle when handed over for operation. Current practice of commissioning is labor intensive and the commissioning deliverables are heavily 2-D documents and images that are inefficient and ineffective to utilize in operation and maintenance of the building. The research thus looked at BIM as a facilitator for a more viable approach for building commissioning. Per its definition, BIM is a lifecycle information repository of a construction project. With a project delivery embedded commissioning scenario, this BIM-enabled commissioning facilitated the commissioning process at each phase of the project lifecycle by accomplishing critical commissioning tasks, empowering enhanced project team collaboration and streamlining commissioning documentation generation. Two case studies were given at the end to demonstrate the best practices in the industry that used BIM for building commissioning and handover.

INTRODUCTION

The Architecture, Engineering, Construction and Operations (AECO) industry today has set much more stringent standards on ensuring building operational performance in sustainability, safety and productivity when a project is handed over. Building commission is one of the major quality assurance tools adopted in the industry. According to ASHRAE Guideline 0-2005, the *Commissioning Process*, is “a quality-oriented process for achieving, verifying, and documenting that the performance of facilities, systems, and assemblies meets defined objectives and criteria.” Building commissioning brings manifold benefits to facility operation and maintenance, as Department of Energy (DOE) has suggested that “it ensures that a new building or system begins its life cycle at optimal productivity and improves the likelihood that the equipment will maintain this level of performance throughout its life. Building commissioning is the key to quality assurance in more than one way” (DOE 1998). It also has significant impacts on economy and environment. In 2004, Lawrence Berkeley National Laboratory (LBNL) estimated $18 billion per year of potential savings from commissioning throughout the United States (Mills et al. 2004). Mills (2009) concluded that “commissioning is arguably the single-most cost-effective strategy for reducing energy, costs, and greenhouse gas emissions in

buildings today… at the highest level, building commissioning brings a holistic perspective to design, construction, and operation that integrates and enhances traditionally separate functions."

Despite the significance of commissioning, the practitioner community recognizes that the market uptake has been slow. Mainstreaming of building commissioning is impeded by front costs, increased complexity of building systems and inefficiencies in the availability of consistent and completed building performance data due to the fact that current practice lacks standardization in commissioning procedures and every commissioning agent uses their own sets of data formats during the commissioning activities. (Mills 2009, Ahmed et al. 2010, Turkaslan-Bulbul and Akin 2006).

This research evaluates a building information modeling (BIM) enabled approach of building commissioning and handover. The National Building Information Model Standard (NBIMS) defines BIM as "a digital representation of physical and functional characteristics of a facility and it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward" (NIBS 2007). BIM within the construction industry is expanding but the primary uses remain 4D simulation, costing data/estimates, and collision detection (McGraw-Hill Construction 2008). These uses generate tangible return on investment (ROI), but they are far from the full potential that BIM has to offer in supporting the lifecycle of the project (Lucas et al. 2009) that extends beyond the design and construction phases. An essential promise held by BIM is to provide the project team with a unified representation of the project with comprehensive level of details that can facilitate the seamless information exchange among project stakeholders as needed at different phases during the project delivery. This makes it possible for the building commissioning team to extract, evaluate, monitor and update information that is related to the commissioning workflow relying on a common and credible information repository. The goal of this research is to identify the opportunities to incorporate BIM and related technology into current commissioning practices and building handover with improved efficiency and cost-effectiveness.

THE COMMISSIONING PROCESS

Regardless if the project is a new construction or renovation, the commissioning process begins at project inception (during the *Pre-Design* or *Planning Phase*) and continues for the lifecycle of the facility (through the *Occupancy and Operation* or *Post-Construction Phase*). It includes specific tasks to be conducted during each phase in order to verify that design, construction, and training meet the Owner's Project Requirements (OPR) (ASHRAE 2005). Figure 1 illustrates the flowchart of the commissioning process with essential tasks listed at each phase. The flowchart works as general guidance and its principles are applicable to whole building commissioning, retro-commissioning as well as re-commissioning process.

Current practices typically allocate the entire focus of system evaluation to the post-construction phase and attempt to make commissioning a one-time, one-phase effort. The biggest problem associated with this approach is that it gives up the

opportunity to evaluate the project quality and identify potential significant design/construction defects before it is too late and too expensive to make changes. In contrast, in the embedded commissioning approach proposed by Turkaslan-Bulbul and Akin (2005), commissioning is defined as a building delivery embedded process which persistently verifies and validates design intent throughout the building lifecycle. They concluded that to ensure the effectiveness of building commissioning, the commissioning process should be systematic and standardized. Test procedures, evaluation methods and the commissioning data should not differ between various commissioning providers. To reduce the labor cost and errors in manual documentation, the commissioning process should have computational support. Managing different phases of building evaluation from programming phase to facility occupation requires effective commissioning tools and building commissioning information should be kept digitally for data exchange purposes. The commissioning information should be continuous and data produced during the commissioning process should feed other evaluation procedures throughout the different phases of building lifecycle.

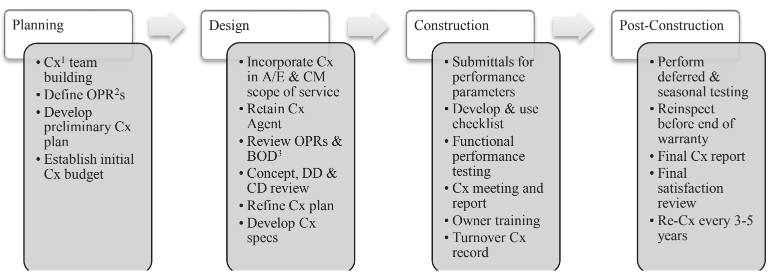

Figure 1. Non-BIM building commissioning workflow (Adapted from GSA 2005).

[1] Commissioning
[2] Owner's project requirements
[3] Basis of design

BUILDING INFORMATION HANDOVER

In a time that heralds the introduction of a new generation of software to the AECO industry, conventional project delivery methods have been transferred and now largely depend on intelligent digital platforms. For building commissioning and handover in particular, Claridge (2004) discussed the potential of using simulation models in various commissioning types, and detailed the selection of popular simulation tools at each stage of the commissioning process. The problem, however, of using distinct software packages for different commissioning tasks resides in the costs due to lack of interoperability. Interoperability is defined as "the ability to manage and communicate electronic product and project data between collaborating firms and within individual companies' design, construction, maintenance, and business process systems" (Gallaher et al. 2004). In that regard, BIM holds up to be a much preferred option in the information-centric new paradigm of project delivery, the integrated project delivery (IPD). Per its definition, BIM is appreciated for the following aspects, as identified by Fallon and Palmer (2007):

- The single, non-redundant information repository supports a broad range of activities in the building life cycle, including design, analysis, cost estimating, procurement, detailing, construction simulation, construction/ erection, maintenance and operation. Interoperability is a non-negotiable requirement of such a data store.
- Managing models of this size and complexity cannot be done manually. Thus, BIM data must be structured data, capable of machine-interpretation.

Use of interoperable building information models helps adopters speed informed design decision-making. It enables rapid iteration of simulations of building performance and construction sequencing. It also streamlines information flow and reduces time-to-complete in certain supply chains, substantially reduces field problems and material waste during construction, or even makes off-site pre-fabrication feasible to improve the quality and longevity of building components and assemblies. Key owners have also recognized the potential for capturing the information needed to fine-tune building system performance, establish appropriate maintenance practices and schedules and evaluate the feasibility of proposed expansions or renovations (Fallon and Palmer 2007). Nevertheless, use of information models in commissioning, operation and maintenance is relatively rare and yet to be exploited. A few academic publications have investigated the benefits of integrating BIM into healthcare project commissioning (Chen et al. 2011) or using multi-dimensional building performance data management for continuous commissioning (Ahmed et al. 2010).

One of the few pilot projects that seek to reduce the cost and improve quality of information handover from commissioning to operations and maintenance is the Construction Operations Building Information Exchange (COBie) project initiated in 2006, funded by U.S. National Aeronautics and Space Administration (NASA). The objective of this project is to identify the information exchange needs of facility maintainers, operators, and asset managers of data available upstream in the facility lifecycle. The COBie project acknowledges the practical constraint that much of today's information content is locked within documents or images of paper documents (East 2007). The COBie approach envisions capturing this information incrementally throughout the facility planning, design and construction, and closeout commissioning processes. COBie is part of the National BIM Standard effort, and it relies on the information extracted from BIM entities over the project life cycle through various information exchange mechanisms.

BIM FOR BUILDING COMMISSIONING & HANDOVER

As a lifecycle information management tool, the following features of BIM legitimate its implementation in building commissioning and handover process:

- BIM is data rich and comprehensive as they cover all physical and functional features of a building.
- BIM is able to store, share and exchange data with internal/external applications, through open information exchange standards such as IFC, and/or other business mechanisms such as Extensible Markup Language (XML).

- BIM is able to perform various intensive and complex building analysis and simulations in cost-effective manner, and produce relevant results in standardized documentation format.
- BIM cover all the lifecycle phases and the state of these phases can be processed by BIM in order to sequence and schedule the process.
- BIM facilitates project team collaboration and communication as the "one source" of project information.

At each phase of the commissioning, there are 1) critical tasks, 2) leading stakeholders, 3) expected project team interactions, and 4) standardized documentation/deliverables to accomplish. In contrast to the non-BIM commissioning process as depicted in Figure 1, the BIM-enabled commissioning process utilizes the information captured in the BIM model(s), benefits from the BIM-facilitated collaborative working environment, and conducts commissioning activities relying on interoperable information exchange between BIM and other internal/external applications, facilitated by open information exchange standards such as IFCs. Noticeably, as the project proceeds, commissioning information is handed over from phase to phase, so do the BIM model(s) that are constantly updated and keep evolving (Figure 2).

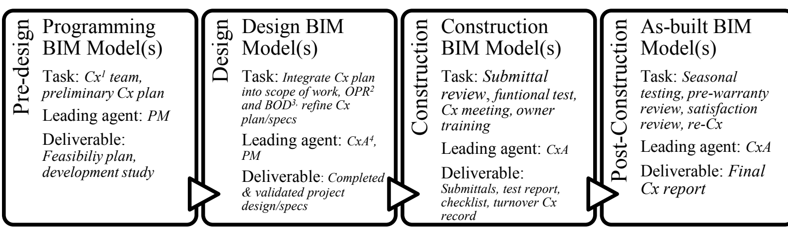

Figure 2. BIM-enabled building commissioning workflow.

[1] Commissioning
[2] Owner's project requirements
[3] Basis of design
[4] Commissioning Agent

In the BIM-enabled building commissioning and handover process, model performance and human factors are still significant. Major issues that need to be addressed may include:

- Model accessibility: how to ensure the Cx team will have access to model components wherever and whenever they need them.
- Information management: how to streamline the generation of desired Cx reports out of existing model information.
- Security: how to ensure the Cx information will be delivered in a secured manner within the Cx team or outside when it is necessary.
- Model ownership: what legal clauses and contractual tools are available to clearly define the ownership of the commissioning-contained BIM model(s).

CASE STUDIES

The following case studies demonstrate the use of BIM and COBie in building commissioning and handover process. Both case studies are provided by Vela

Systems, Inc., and involve the usage of their Field BIM solutions, as illustrated in Figure 3.

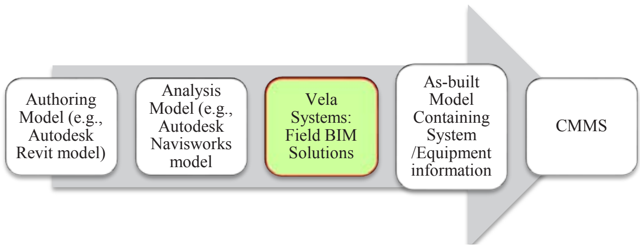

Figure 3. Fill the gap with Vela Systems' Field BIM solution (Adapted from Kanner 2011).

Case No.1: University of Massachusetts Medical School. This project was an expansion of power co-generation facility that involved the installation of a new 7.5 mega-watt (MW) gas-fired turbine and a 4000-ton electric chiller unit. The owner was the University of Massachusetts Medical School and the contractor was Skanska USA Building, Inc. The owner challenged the project team by demanding to make BIM useful in the construction field and use the BIM model for commissioning so they can get a BIM "digital" asset at handover.

The project took an Autodesk-Vela solution. The commissioning process was constantly updated through the evolution of the building information models across the different stages of project delivery. When the project was ready for closeout and handover, the latest Navisworks model (as-built model) contained all equipment installed for the plant. To complete the startup process and capture key information for handover to the owner for operation, the workers used Vela's iPad app (*Vela Mobile*) to scan the bluetooth barcodes associated with each piece of equipment right in the field so they could then access all attached equipment information such as product data, operation data and operation and maintenance (O&M) manuals from manufacturers, on the basis of which the team completed the functional test checklist, and published the results back to the model to update the facility information on the fly (Figure 4), with BIM's capacity to link external information into its database.

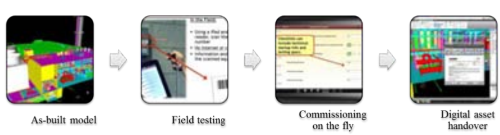

Figure 4. Autodesk-Vela solution commissioning workflow (Source: adapted from Kanner 2011).

So when the commissioning process was completed and the project was handed over, the owner did not only get all the deliverables of building commissioning, but also a digital asset that offered comprehensive information and benefits for future operation and maintenance, as well as facility management. Noticeably, with the rapid development of cloud computing technology, such information is now possibly deployed in the cloud to give the owner and facility managers even more flexibility in

managing the lifecycle performance of the building whenever and wherever they need the information.

Case No.2: University Health Systems Project. This multi-phased project at the University Hospital, San Antonio Medical Center, is part of the University Health System Capital Improvement Program Mission, Target 2012. The scope of the project includes a new Hospital Tower under just 1 million square foot with supporting infrastructures including surface parking expansion, parking garage, underground major utility corridor and renovation of existing hospital structure. The owner is University Health Systems of San Antonio, Texas, and the contractor is Zachry-Vaughn-Layton (ZVL) Joint Venture.

The project used Vela Field BIM solutions to conduct the commissioning, similar to Case No.1. Nevertheless, the new challenge here was the mandate from the owner that all commissioning and handover information needed to be following the COBie2 (an updated version of COBie) format. Thanks to the interoperability between COBie and major BIM authoring/analyzing tools, as well as O&M side software products such as Computerized Maintenance Management Systems (CMMS), it was possible for the project to produce the COBie2-compatible deliverables from the BIM models cost-effectively. Figure 5 illustrated the COBie2 format of the commissioning data on systems and equipment of this project. A huge advantage of having the commissioning data in COBie2 format was that it made the building commissioning information turned into facility management information right away.

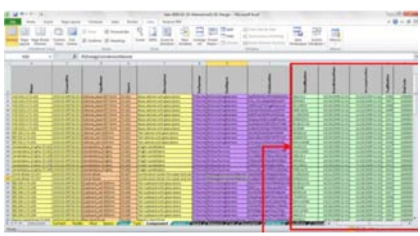

Figure 5. Vela Systems commissioning data on systems and equipment (Source: Kanner 2011).

CONCLUSION

The slow uptake of building commissioning in the AECO industry can be improved with more efficient and cost-effective strategies. This paper investigated a BIM-enabled approach for building commissioning and handover. The commissioning process and requirements, and typical building information handover in the new information technology (IT) context were reviewed. The features of BIM as a lifecycle information tool were analyzed, and possible BIM applications in the commissioning process were discussed. Two case studies were given at the end to demonstrate the implementation of BIM and COBie in building commissioning and handover. Future research will focus on detailing the procedures and possible automation of the BIM-enabled building commissioning process. Another interesting research topic may be to develop an effective delivery mechanism for the multidisciplinary information exchange between a myriad of software applications and stakeholders.

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Skeleton-Based 3D Reconstruction of As-Built Pipelines from Laser-Scanned Data

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ABSTRACT

Three-dimensional (3D) reconstruction of as-built pipelines has been considered for a wide variety of purposes, including plant operation, maintenance, and expansion of existing facilities. However, the current method of generating 3D models of as-built pipelines from laser-scanner data requires costly and labor-intensive manual processes. The objective of this study is to develop an automated as-built pipeline-modeling method. The proposed approach consists of two functional parts. The first is segmentation of cylindrically formed pipelines based on medial axis approximation and curve skeleton extraction. The second is surface-model generation of cylindrically formed pipelines based on a parametric modeling method. The initial experiment was performed at an operating plant facility to evaluate and validate the proposed method. The preliminary experimental results revealed that the proposed method enables reliable 3D as-built models of pipelines, which could be successfully incorporated into the development of an as-built plant information modeling method and utilized to assist maintenance tasks, such as inspection, repair, replacement, or revamping.

INTRODUCTION

The pipelines are an integral part of the operation, maintenance, and expansion phases of existing chemical, power, and refinery plants (Jin and Lin 2012). Many installations, including equipment and instrumentation that have various functions in those plants, are connected only by the pipelines to exchange or pass gas, water, and oil between them; thus, the pipelines play a vital role as an intermediary (Tangelder et al. 1999; Jin and Lin 2012). Accurately constructing a 3D as-built model of an entire pipeline enables efficient inspection, part replacement in maintenance and operation phases, and efficient planning for expansion or modification of existing plants (Veldhuis and Vosselman 1998; Tangelder et al. 1999; Ermes 2000).

In practical applications, in order to construct a 3D as-built model of an entire pipeline, laser scanners are used to measure 3D plants and then users manually construct a 3D as-built model from laser-scanned data using several commercial software packages (Chunmei et al. 2009). The laser-scanned data of the existing plant are not only huge, but the pipelines are also intricately entwined like a net (Tangelder et al. 1999; Chunmei et al. 2009; Kawashima et al. 2011). Hence, the users must identify 3D data corresponding to each pipeline to be modeled in huge laser-scanned data sets (Chunmei et al. 2009). After identification of 3D data corresponding to each pipeline, the users construct pipeline models by using some functions in commercial software. However, in order to accurately identify 3D data corresponding to each pipeline, the users need to have some knowledge about the pipeline direction and the design (Chunmei et al. 2009). In addition, manually identifying each pipeline from the enormous and complicated laser-scanned data is nearly impossible and is a very time-consuming and labor-intensive process (Kawashima et al. 2011). Therefore, little research has been conducted to effectively construct 3D as-built models of a pipeline (Rabbani and Huevel 2005; Masuda and Tanaka 2010; Bey et al. 2011; Kawashima et al. 2011). Fully automated construction of a 3D as-built model of an entire pipeline from laser-scanned data is still a challenging and laborious problem.

The aim of this study is to propose a fully automated process that allows construction of a 3D as-built model of an entire pipeline composed of elbows, T-junctions, and straight pipes from laser-scanned data. The rest of the paper is organized as follows. Related works that have been conducted on constructing 3D as-built models of existing plants from laser-scanned data are briefly discussed in Section 2. In Section 3, an overview and details of the proposed 3D reconstruction process of as-built pipeline are provided with experimental results. Finally, conclusions and recommendations for future research are given in Section 4.

RELATED WORKS

So far, several research studies have been conducted to construct 3D as-built models of existing plants from laser-scanned data. Rabbani and van den Heuvel (2005) proposed an algorithm for detecting cylinders, which are most frequently used in plant design, from laser-scanned data to construct 3D models of plants. In their algorithm, 2D Hough Transform was used to determine the direction of the cylinder and 3D Hough Transform was used to estimate the radius and position of the cylinder. These parameters enable a 3D cylinder model of a plant to be constructed. Masuda and Tanaka (2010) developed a system that consists of offline and online processes for constructing 3D models of plants by recognizing planes and cylinders from incomplete laser-scanned data. Through the offline process, laser-scanned data are converted to a Mercator image and mesh models. Through the online process, the user manually selects a region to be recognized, and then the planes and cylinders are extracted from a mesh model. 3D models of equipments and pipes in plants can be constructed from extracted planes and cylinders. Bey et al. (2011) proposed a framework for constructing a 3D model of cylinder parts from laser-scanned data using a 3D as-planned model. A Bayesian formulation was proposed to define the similarity between an as-planned model and laser-scanned data. Then, a cylinder is randomly generated from laser-scanned data and an optimal configuration of the cylinder is computed using the greedy method. 3D as-built models of cylinder parts are constructed

based on cylinders of high similarity. Those research studies illustrate the possibility of automatic/semi-automatic construction of 3D as-built plant models from primitives such as cylinders and planes with the greatest proportion in the shape to plant equipments and pipelines. However, those research studies only provided a solution for straight pipes, which are the parts of pipelines composed of elbows, T-junctions, and straight pipes. Thus, an additional manual process is required to construct a 3D as-built model for an entire pipeline.

Recently, Kawashima et al. (2011) proposed an automated pipeline recognition algorithm to construct a 3D as-built model of an entire pipeline from laser-scanned data. Laser-scanned data of plant equipment are classified into two classes by analyzing normal tensors of the laser-scanned data, the pipe point, and the non-pipe point. Then, the plane is fitted to the pipe point using the random sample consensus (RANSAC) to calculate radius and position of the straight pipe. After cylinder fitting is performed based on the calculated radius and position of the straight pipe, each non-pipe point is recognized by analyzing the connecting relationship of the straight pipe and others. However, the parameters to construct the 3D as-built model are calculated only for the straight pipe, making it difficult to say that a 3D as-built model for an entire pipeline was constructed.

A PROPOSED MODELING METHOD

The key improvement upon previous methods is that this method allows the modeling of both straight and curved portions of a pipeline. This pipeline modeling process utilizes extraction of skeletons and computation of radii to generate a model with laser-scanned data obtained from the process plant as the input. The pipeline modeling method consists of four main steps. The first step is to extract an approximating medial axis based on Voronoi diagram filtering in order to produce an accurate skeleton. The second step is to skeletonize the approximating medial axis based on Laplacian-based contraction. The result is used as the new medial axis of the pipeline model. The third step is to compute the segment and radius. Finally, a 3D as-built pipeline model is generated by the parameters such as the new medial axis and radius.

In laser-scanned data obtained from the as-built process plant, they contain not only points of pipelines, but also points of other objects, such as structural components and engineering items. However, in this research, in order to focus on the 3D reconstruction of as-built pipelines it is assumed that the points of other objects of laser-scanned data are roughly removed by manual pre-processing and that the input data to generate the 3D pipeline modeling algorithm only contain points of pipelines.

Approximating Medial Axis Extraction. In order to generate a 3D as-built pipeline model, the parameters, radius, and medial axis are required (Van Gosliga et al 2006). In this paper, the medial axis of the pipeline is computed by skeleton. To extract an accurate skeleton, the approximating medial axis extraction is performed first using the algorithm proposed by Dey and Zhao (2004). The algorithm takes as input the laser-scanned data that contain points of pipelines. The approximating medial axis extraction algorithm embarks on computing the Voronoi diagram. The Voronoi diagram is one of the fundamental concepts in computational geometry (Barequet et al 2011). That plays a central role in capturing shape information (Dey and Zhao 2004).

The Voronoi diagram of the laser-scanned data is filtered with the angle condition and ratio condition to extract an approximating medial axis using its dual Delaunay edges from the Delaunay triangulation of the sample points.

Angle condition θ can be described as follows,

$$\max_{ptu \in U_p} \angle n_{ptu}, t_{pq} < \frac{\pi}{2} - \theta$$

where p and q are sample points of input data, U_p is an umbrella that is extracted from Delaunay triangulation, t_{pq} is a tangent vector from p to q, and n_{ptu} is a normal to a triangle ptu. Ratio condition ρ can be described as follows,

$$\min_{ptu \in U_p} \frac{\|p - q\|}{R_{ptu}} > \rho$$

where R_{ptu} is the circumradius of a triangle.

After filtering, the Delaunay edges remaining are only those that satisfy both conditions. The remaining set of Voronoi facets from the Voronoi diagram create the approximating medial axis (Dey and Zhao 2004). Figure 1(a) shows the laser-scanned data, and Figure 1(b) shows the approximating medial axis.

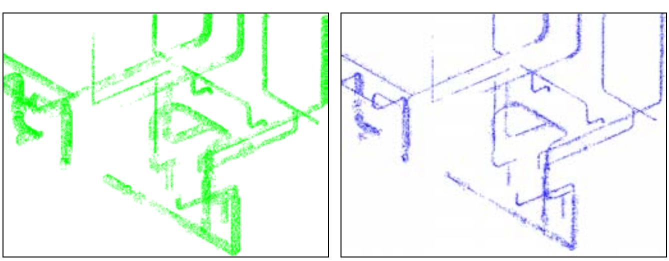

Figure 1. (a) Original point cloud. (b) Approximating medial axis.

Approximating Medial Axis Skeletonization. In order to extract an accurate skeleton, the skeletonization from an approximating medial axis is performed using the algorithm proposed by Cao et al. (2010). The skeletonization algorithm takes as input the vertices of the result of the previous process. The algorithm embarks on the geometric contraction of the vertices based on implicit Laplacian smoothing, which removes details of the input data along the normal directions. The algorithm automatically chooses some anchor points to maintain the original shape of input data during the contraction. After the contraction process, the skeletal shape of the input data remains as a result.

The geometric contraction first constructs a one-ring structure for all vertices. It is needed for using the Laplacian matrix to compute the normal direction of the vertices. To define one-ring neighbors, therefore, an approximate neighborhood of the vertex as a point p_i is extracted by finding k nearest neighbors and projecting the neighbors on its tangent plane.

The contraction process can be described as follows. Assume that the following equation is solved for P^{t+1},

$$\begin{bmatrix} W_L^t L^t \\ W_H^t \end{bmatrix} P^{t+1} = \begin{bmatrix} 0 \\ W_H^t P^t \end{bmatrix}$$

where superscript t is used to denote the t-th iteration, L is a $n \times n$ Laplacian matrix with cotangent weights, P is the input data, and W_L and W_H are the diagonal weight matrices balancing the contraction and attraction forces. Then, the diagonal weight matrices $W_L^{t+1} = S_L W_L^t$ and $W_{H,i}^{t+1} = W_{H,i}^0 S_i^0 / S_i^t$ are updated, where S_i^t and S_i^0 are the current and original neighborhood extents of point p_i respectively. Finally, the new Laplacian matrix L^{t+1} is constructed with the new point cloud P^{t+1}. The contraction process stops when the solution converges. The input data become a skeletal shape C.

The result of geometric contraction is not a 1D curve skeleton. Further steps are required to extract the 1D curve skeleton. The 1D curve skeleton is extracted by imposing an initial connectivity and computing edge contraction. Figure 2 shows the 1D curve skeleton from the approximating medial axis.

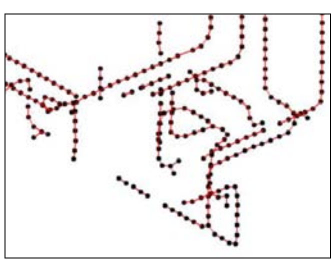

Figure 2. 1D curve skeleton from the approximating medial axis.

Pipe Model Generation. ***Skeleton Segmentation.*** In order to classify the type of pipe components such as elbows, T-junctions, and straight pipes, a skeleton segmentation is performed using junction points and threshold angle. The skeleton segmentation takes as input the 1D curve skeleton extracted from the points of pipelines. The skeleton segmentation is a process of skeleton decomposition that embarks on checking junction points of the 1D curve skeleton. The junction points of the 1D curve skeleton and neighboring skeleton points first are classified as skeleton points of T-junction.

After the classification of the skeleton of T-junctions, 1D curve skeleton segments of elbows and straight pipes are left. The segments can be classified into a skeleton of elbows and straight pipes by angles of points. First, angles of all points on the 1D curve skeleton with neighboring points are calculated. Then, calculated angles are compared with threshold angles. If a calculated angle is bigger than the threshold angle, it is classified into the skeleton of elbows. In this paper, the threshold angle is set as 25 degrees. As a result of segmentation, the 1D curve skeleton is classified into three main groups—elbows, T-junctions, and straight pipes—and decomposed into a number of segments. Figure 3 shows the segmented 1D curve skeleton. The bright gray skeleton denotes the skeleton of T-junctions, the dark gray skeleton denotes the skeleton of elbows, and the black skeleton denotes straight pipes.

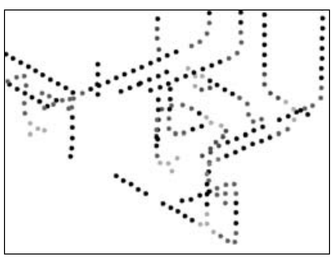

Figure 3. Segmented 1D curve skeleton.

Radius Computation. In order to generate a pipeline model, radius information for every classified skeleton is needed. The radius of a segment is computed by the average distance from the skeleton points of a segment to original points of pipelines. The radius r of a segment is computed by the following equation

$$r = \frac{1}{n}\sum_{i=1}^{n} d_i$$

where distance from the skeleton point m_i to original pipe is d_i.

Pipe Model Generation. Once the classified skeleton segments and corresponding radii are obtained, the pipeline model is generated automatically by the parameters. Given a list of skeleton points and radii, the procedure to generate the pipeline model begins with checking the ends of each skeleton segment and their connectivity. Then, a cylindrical model is generated along the skeleton segments as the centerline with their radii. Figure 4 shows the as-built pipeline model.

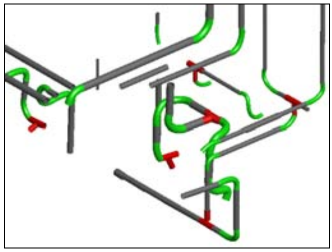

Figure 4. 3D as-built pipeline model.

The proposed modeling method was validated for precision, and the result is presented in Table 1. The average precision of the method was 94.20%. Based on the preliminary result, it can be concluded that the proposed method can be used to accurately construct the 3D as-built pipeline model by the automated process.

Table 1. Performance of the proposed modeling method.

	Detected Objects	True Objects	Precision
Elbow	20	20	100.00%
T-junction	6	7	85.71%
Straight	31	32	96.86%

CONCLUSION

This paper proposes a new method that can automatically construct an as-built pipeline model from laser-scanned data. The skeleton of the pipelines is calculated by the medial axis extraction and skeletonization. Then, the pipelines are classified into elbows, T-junctions, and straight pipes by 1D curve skeleton extraction. The radii of the classified pipelines are computed by average distance from the skeleton points of a segment to laser-scanned data of the pipelines. The pipeline model is constructed based on the classified skeleton segments and corresponding radii. The feasibility of the proposed method were validated by real laser-scanned data obtained from a process plant; the results demonstrate that the proposed method can successfully construct the 3D as-built pipeline model. The proposed method has the advantages that it is automated and it models not only straight portions of a cylindrical pipe, but also curved portions. Thus, it is possible to generate the entire pipeline model automatically, and it could be successfully incorporated into the development of as-built plant information modeling. However, the proposed method could also be applied to the laser-scanned data that only contains pipelines. Thus, future research will be focused on segmentation of the points about the pipelines from laser-scanned data that contains other points.

ACKNOWLEDGEMENTS

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As-Built Documentation of Structural Components for Reinforced Concrete Construction Quality Control with 3D Laser Scanning

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ABSTRACT

As-built BIM is a relatively new concept to the AEC/FM industry and has not been applied to many project elements yet, including structural components. The conventional methods of as-built documentation of structural components, such as rebar cage, do not provide sufficient information and often lead to rework and project delay. A comprehensive dimensional quality control of installation of structural rebar and anchor bolts is very time-consuming and labor intensive with traditional surveying systems. It is impractical to check every rebar and anchor bolt within the structure with sparse data collection. However, laser scanning is capable of bridging this gap by providing dense point cloud data of such components at construction site. This paper introduces the use cases of scanning structural rebar in reinforced concrete construction. A successful experiment of scanning structural rebar was conducted in a construction project. As-built conditions of rebar cages and anchor bolts were documented in BIM environment and compared against as-planned model. The result of the comparison and the benefits to the contractor are explained in the paper.

INTRODUCTION

Using BIM is now considered almost a standard at large construction firms in the US. According to the survey conducted by (Mutai and Guidera 2010), about 40% of the top 400 contractors listed in the 2008 Engineering News Record (ENR), who were identified as having over 80% of their projects categorized as general building, claimed that they utilize BIM in between 21-40% of their projects. These figures are rapidly rising as smaller firms start to recognize the benefits of the technology as well. However, the mainstream implementation of BIM in the industry has been at the design stage of the project life cycle (Hwang and Liu 2010), while it can be used for construction and occupancy phases as well. The major reason behind this limited utilization lies behind current design oriented use of the technology. BIM can be populated with any type of information associated with the project, which can be either as planned or updated to the actual conditions. Since the modeling process usually starts at the design stage of a project and if not, the only available information is the as-planned; the created model contains as-planned information accordingly. Even if the contractor, construction

manager, and designer do not share the same model, all models are created based on the as-planned information that is delivered by the design team. Different parties develop their own model in different ways to suit their particular needs but they all share the same basis of as-planned information.

Despite the increasing adoption of BIM in both design and construction sectors of the industry as a data repository to store and exchange the project design information, it has not been generally considered for storing as-built information as the project progresses during construction. Hence, as the project progresses, neither the contractor nor the architect updates the model to the actual condition of the job site. There is usually no contractual requirement by the owner to deliver an as-built BIM at the end of the construction phase. Even if BIM was used during design and construction phases extensively, the contractor is contractually obliged to deliver 2D as-built drawings to the owner as if no BIM was utilized in the project. The 2D as-built documents are usually the design documents with an unorganized set of mark ups and notes attached to them, describing the difference of as-built condition with the design, which certainly needs manual processing by human to become practically useful. Moreover, there is no guarantee that all the changes to the design were captured by the contractor and even if captured, reflected in the as-built documents appropriately. As-built documents do not attempt to capture accurate locations of building elements. For instance, as-built drawings of structural reinforced concrete are certainly not accurate maps of reinforcing or other elements embedded in the connections.

The ultimate BIM utilization covers the entire project life cycle, but the industry has not reached that point yet. The designer and contractor develop BIM to store and exchange project as-planned information. While the as-planned information is now created and exchanged in digital format, the as-built information is still collected, stored, and processed manually in daily job site reports. This difference is the major reason why BIMs do not get updated to the actual condition. However, this requires reliable data acquisition sources for modeling existing/new facilities and updating their BIMs frequently based on the needs and changes. The advanced data acquisition systems that capture and deliver the as-is condition of the job site in digital formats can bridge this gap. 3D laser scanning is one of such systems and is described further in the next section. However, whether as-built information is collected manually or with the aid of advanced technologies, as long as it is stored and exchanged in 2D drawings, its applications and functionalities are subjected to 2D format limitations.

AS-BUILT BIM WITH 3D LASER SCANNING

BIM utilization for project control has not advanced beyond early stages of construction (Hwang and Liu 2010) and unavailability of as-built model is the main underlying reason (Meadati 2009). Trying to extend BIM utilization into construction and occupancy stages of project, Meadati suggests using Robotic Total Station (RTS) to collect as-built spatial information of the project (Meadati 2009) but the traditional measurement and surveying methods are relatively time consuming and labor intensive. They also provide sparse measurements (Huber, et al. 2010), and are usually 2D oriented. The variety of type and size of as-built information that can be carried by 2D drawings is not even comparable with those of BIM. Adding notes to design 2D documents, that are

generated by BIM, in order to develop as-built documents instead of updating the design model means downgrading BIM utilization to a 2D drawing generating tool, which defeats the main purpose of using BIM. The field data acquisition systems, such as 3D laser scanning, are potentially able to play this role of feeding into a central database with real-time project information (Hajian 2009). BIM, coupled with 3D laser scanning, provides a new way of capturing and storing a wide variety of real-time digitally formed information.

AS-BUILT DOCUMENTATION OF STRUCTURAL COMPONENTS IN BIM ENVIRONMENT

This study focuses on using 3D laser scanning during construction to capture as-is condition of structural components and identifies its applications. As-built documentation with 3D laser scanning can be performed at three different levels, based on the level of process of scanning output raw data. Archiving the raw point cloud is the first level of as-built documentation, which can be furthered to the next levels any time needed. The next level of documentation is to recognize the scanned objects in the point cloud and creating a 3D CAD model based on it. Converting the CAD model to BIM is the highest level of as-built documentation processing with the aid of 3D laser scanning. The scan-to-BIM process involves intermediate CAD modeling and manual modeling of point cloud data (Hajian 2010). Some research studies have improved the process by developing object recognition algorithms and automated reconstruction of CAD model objects (Bosche 2008)(Bosche 2009). However, it is considerably time consuming and labor intensive and still the biggest challenge of the process. Commercially available point cloud processing software solutions can fit objects with regular shapes, like cube and cylinder, to point cloud data. This capability includes only a small group of objects that are usually present in a construction site. The long and expensive point cloud data processing has been the major reason why 3D laser scanning has not been widely used as a real time data acquisition system to capture and store as-built condition of the project. There have been some studies on automating the process but mainly at research stage (Brilakis 2010).

However, modeling structural components is relatively easy compared with other objects in a construction site since it does not require as detailed modeling as architectural components. For example, rebar can be modeled as cylinders and steel sections can be selected from AISC standard section list. Compare that with the complexity of modeling building façade that may contain so many geometric details. While new architectural components with different sizes and geometric details are designed and built, the structural components of building structures do not change often. In addition, structural components are usually among the very first group of objects that get constructed or installed, which makes the scanning process easier and smoother by having less visual occlusions in the scan scene. It also often makes it easier to directly use the point cloud and overlay it with the design model. This characteristic makes as-built documentation of structural components with the aid of 3D laser scanning both possible and practical at different levels. 3D laser scanning has been used for scanning structural components for different purposes but it has not been tested for structural rebar. Documenting the as-built condition of structural rebar in cast-in-place reinforced concrete structures has some potential applications especially for the contractors. The authors have

identified the potential use cases of employing 3D laser scanning technology for rebar mapping in this section.

REBAR MAPPING

There are many cases where the contractor and sometimes the owner need to add new embedment to a concrete slab or shear wall in a reinforced concrete structure. This is usually the case in infrastructure projects, including railroad and nuclear power plants where additional rebar or other steel sections need to be embedded into the main structure after it is built. The sequence of work usually requires pouring the concrete and then drilling it to make a mechanical, structural, or electrical hole. However, once the concrete is poured, the rebar cage is buried underneath and cannot be mapped easily. The rebar placement construction documents are schematic drawings for rebar detailers and do not show the exact location of each rebar. Even the rebar detailer's drawings are not reliable sources for locating rebar buried under concrete since they do not necessarily reflect the actual location of placed rebar cage on site. Therefore, drilling the concrete often leads to hitting existing rebar and more spots need to be drilled the same way. This trial and error process results in rework and damages the structural integrity of the concrete. The situation is more problematic in sensitive structures such as nuclear power plants, where the integrity of structure is of great importance.

Post-Tensioned (PT) cables are increasingly used in reinforced concrete structures, especially in parking structures. Installation of PT cables needs to be done following specific instructions, including those related to the safety of laborers. Once the cables are stressed, good care should be taken to avoid any contact of external objects, particularly those with sharp edges, with them. The situation is very similar to the previously described case; however, hitting a PT cable and damaging it not only reduces the structural strength of the slab, but also may put the laborer's lives at danger. Since the cable is under enormous stress, if it snaps for any reason at any part, the two separated parts will be released like an uncontrollable lash, which can cause serious injuries to the laborers working on site. Drilling and hitting PT cable may happen when bracing concrete shear wall or column formwork to the slab during construction or it may happen after construction by the owner, adding any attachments to the existing structure. All these situations are the result of unavailability of the placement as-built documentation.

Availability of accurate rebar as-built documentation can be essentially useful in retrofitting reinforced concrete structures. The seismic design code of reinforced concrete structures often change and may require more reinforcements. Adding rebar and pouring new concrete around the existing structure is usually one of the popular options in retrofitting such structures. These types of projects usually involve drilling the old structure to add steel reinforcements to the existing structure for structural strengthening. Having exact location of rebar cage in the original structure will be of great help to the contractor to avoid contacting existing rebar and to drill the right spots. Keeping in mind the high density of steel reinforcement in such structures, it is so hard to find a clear spot to drill and add new reinforcement through trial and error. Retrofitting building structures may also involve similar situation. As you can see in figure 1, the horizontal beam needs to be drilled for retrofitting with epoxy rebar and new cover of concrete. Knowing the exact location of clear-to-drill spots would considerably expedite the process and avoid

the risk of hitting existing rebar and damaging the integrity of existing concrete. There are some cases where manual recording and communication of the as-is condition in text or 2d image format is very time-consuming and usually insufficient. For instance, when a structural member is relocated or reoriented, it is considerably easier to communicate the situation in a three dimensional environment rather than descriptive text of daily log sheet or mark ups on the structural plans and sections. Deviations from the design can be checked with different tools and methods, including 3D laser scanning. However, using BIM for communicating the deviation among engineer and contractor can ease the process significantly.

Figure 1

Automated as-built documentation of structural rebar in reinforced concrete structures has not been tested in the industry. Lack of cost effective technology development has been one of the main reasons. Ground Penetration Radar (GPR) is developed to scan beyond surfaces and is now used for locating existing utilities, such as pipeline, but its several limitations has hindered wide deployment in the industry. Its output is not easy to process and not accurate enough for mapping rebar cage placed in concrete. In contrary, 3D laser scanning is capable of capturing where each rebar is placed accurately. Once the as-built BIM of the rebar cage is created, the contractor can navigate through the model and locate clear spots for drilling and set up points of interest. On the other hand, recent advancements in BIM technology provide integration with RTS by exporting the coordinates of points of interest to it. The RTS shows the exact spot, which is clear for drilling, by pointing its laser beam to it.

REBAR DETAILING

3D laser scanning can also be useful for rebar detailing by capturing the spatial information of the irregular shapes that are to be paved with reinforced concrete. Figure 2 is an example of this situation. It shows a reinforced concrete wall of an animal cage in a zoo. The wall is formed by many curves and linear surfaces. Detailing rebar placement is very difficult as the background wall on which the reinforced concrete will be constructed has a very irregular shape. Digital photography and site visits do not provide accurate topography of the wall to the rebar detailer. The shape of the wall is also too irregular so that it requires long surveying

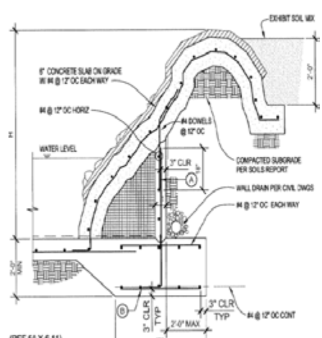

Figure 2

operation, using RTS. However, 3D laser scanning is capable of capturing all geometrical aspects of the wall in one or two scan shots. The rebar detailer can use the 3D as-built model, created from the scan point cloud, as an accurate and reliable basis of his or her work. It also makes it possible for the rebar fabricator to assemble the rebar cages with irregular shapes in shop and install the entire cage at the job site.

STRUCTURAL STEEL INSTALLATION QUALITY CONTROL

Quality control is of essential importance during construction of both steel and reinforced concrete structures and especially at the interface between them, such as anchor bolts and embeds. Although advanced tools are used in current procedures, they all work based on traditional surveying methods. Lu, et al. (2011) investigated integration of RTS and BIM for onsite visualization and quality control of structural components erection (Liang, Lu and Zhang 2011). They used sparse control points on the components to track their location and orientation and assumed rigidity of the objects of interest. However, some structural components, including rebar, are not rigid enough to use their end points for accurate measurement. In addition, rebar cages are usually consist of too many rebars, tied to each other that makes it almost impossible to shoot all of them one by one. In addition, the rebar cage's dimension and overall shape has much less tolerances because it will be buried under the concrete, whose dimensions and size should be very accurate. Therefore, one cannot shoot a specific point on a rebar cage with RTS and use it as a control point. In other words, RTS is not a good candidate to capture as-built condition of structural rebar. Akinci, et al. (2006) developed formalism for active construction quality control through utilization of 3D laser scanning. They demonstrated the capability of the technology to detect the construction defects and deviations in general. This research intends to introduce the effectiveness of implementing 3D laser scanning for structural components, particularly concrete reinforcing steel.

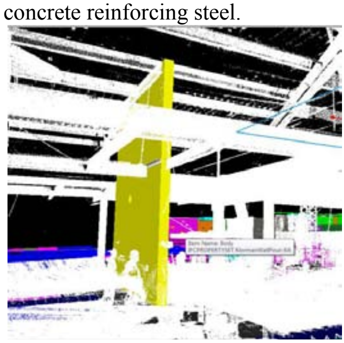

Figure 3

We tested the capability of laser scanning for quality control at a construction project as a proof of concept. The structural concrete had developed its own model, mainly for constructability control, cost estimating, formwork preparation, etc. We chose three areas as the scan scene, where the contractor was interested to have an as-built documentation and compare with the design. A DWG file was developed as the as-built model and got integrated into the design model. The contractor was able to immediately determine that the majority of the new concrete and structural steel construction was confirmed to be erected well within the industry tolerances. Figure 3 shows the registered point cloud, overlaid with the design model. As the picture shows, the first experiment was done when the structural steel was completely erected and the dowels were in place to be tied to those of the shear wall. Two beams, installed on the second floor, will cap the top of the wall. So, the wall needs to fit exactly into the space between the two beams. Integrating the as-built model with the design model, the horizontal

beams, located on the second floor (approximately 45 feet above grade), were identified as being installed outside of contract requirements and tolerances. The construction sequence for the project was changed because of this early defect detection, which resulted in structural steel being installed prior to supporting concrete members in place. This re-sequencing has increased the difficulty of concrete work, which needs to marry the structural steel. The early identification of the out of tolerance structural steel allowed the engineer and owner to make educated decision timely ahead of concrete construction in this area. It also allowed the structural concrete contractor to anticipate the modification that will be required at the joint of wall and horizontal beams. Finding this tolerance error after partial erection of the shear wall formwork would cause rework and delay. The second scanning location contained several base plates and reinforced concrete walls. Steel templates were placed to hold the anchor bolts at the right location to mirror the holes in the base plates. The actual base plates are welded to the columns and will be erected on site together. Since the base plates are very thick and welded to the column, the anchor bolts should be accurately placed in order to fit the coming base plate. Hence, the acceptable tolerance is so small (1/8 in) and accurate anchor bolt placement is essentially important. The contractor currently uses an RTS system to control the locations of anchor bolts; however, since it takes too much time to check all bolts with it, some bolts are checked randomly. Modeling the anchor bolts and surrounding rebars and integrating with the design model, showed the spatial offset between the design requirement and the as-built condition. This defect identification could not be achieved unless all bolts of the base plate were checked with RTS, which is very time consuming, or at the time of column installation, which would cause long delays and additional costs associated with crane operation and laborers.

In addition to the quality control of the new installations, laser scanning has allowed studies of existing site and building conditions to be reconsidered for interface of the new structure. Laser scanning provides an unparalleled record of the project on a given day. There is so much information captured, not all of it can be recognized or utilized in a single review. Since the scan point cloud contains so much native information and can be adapted or enhanced by BIM tools, the information can be reused and queried for multiple studies in the future. One of the prospective applications is to use the data as a comprehensive spatial record of the jobsite for potential construction litigations. The 3D laser scanning can identify existing conditions that vary from what is believed to be in place, which potentially could be sources of error in different construction operations.

CONCLUSION

This paper introduces a new application of 3D laser scanning to create as-built BIM of structural components with a focus on structural rebar and anchor bolts. This study discusses implementation of as-built BIM for construction phase of project life cycle, as opposed to one-time use of laser scanning for newly constructed buildings or existing facilities in most of the aforementioned applications and research. 3D laser scanning has not been used for as-built documentation of structural rebar in construction projects. Research studies consider as-built BIM most beneficial to the owners and facilities managers, while our goal is to introduce its benefits to the construction

contractors, rebar fabricators, and construction managers as well and multiple use cases are identified.

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Development of a Process Model to Support Integrated Design for Energy Efficient Buildings

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Abstract

To improve energy efficiency of existing buildings, various analyses, computational simulations and performance monitoring are conducted throughout the lifecycle of the building, especially during the planning and design phases. One of the most common shortcomings in the current computing infrastructure is that there are bottlenecks in the building processes due to imperfect information exchange, causing frequent and significant delays as, for example, the missing information and data need to be re-produced.

This paper discusses the development of a building systems process model being developed as a part of a major energy efficient building initiative that focuses on energy-efficient renovation of medium-sized commercial and multi-family residential buildings. The map aims to depict an integrated building design process flow, especially for analyses, simulations, and information exchanges among the core activities contributing to key decision-making points. In particular, this paper focuses on the development of such a process map through literature review of existing integrated processes and workshops, and defines the requirements and strategies for efficient and seamless information exchange among project participants from different disciplines.

Keywords: Integrated Process, Building Systems, Energy Efficiency, Retrofit Project

1 Introduction

Building process models depict the big picture of entire building project workflows throughout the lifecycle of the building. The processes help all project team members to better understand other stakeholder's role; provide a foundation for defining workflows for integrating computational modeling and simulations using digital tools particularly between disciplines. These workflows, in turn, improve project efficiency as well as information exchange; identify key decision making points; and improve transparency and dependency among activities within the process.

Although there are several process models for building projects, most of them are at high levels, and thus prove difficult for practitioners to implement on their projects. Consequently, it is common that design and construction firms develop their own processes from best practices and refine their process to fit the company needs based on their previous project experience.

Furthermore, a successful design is dependent on the coordination of the built environment and the systems involved in these spaces. Building systems such as HVAC, lighting and structural systems should be considered during each phase of a building process, as they change based on the building use and the client's requirements. Thus, a required outcome can be produced only by proper integration of the systems with the architectural aspects of a building.

To this end, the goal of this research is to develop an integrated building process model at the building systems level that allows project teams to design and visualize the lifecycle process, enabling interdisciplinary team collaboration to deliver energy efficient buildings. The research focuses on retrofit construction applications for typical commercial buildings, but also intends to support new construction projects. The process also aims to provide a framework for identifying appropriate processes and workflows which can be supported with digital modeling solutions.

2 Background

Several process models have been developed to address problems such as uncertainty and inefficiency that exist in traditional building project workflows. This section summarizes some of the process model initiatives.

Firstly, the Integrated Building Process Model (IBPM) (Sanvido et al., 1990) is a generic integrated process model in the IDEF0 function modeling method. The model clearly depicts core activities at five different levels with specific inputs, outputs, conditions and mechanisms throughout the lifecycle of a building (planning, design, construction, operations and maintenance) and implicitly represents workflows.

The Generic Design and Construction Process Protocol (GDCPP), also known as Process Protocol, aims to allow a wide range of project stakeholders to work together seamlessly (Kagioglou et al., 1998). The GDCPP provides a common set of definitions, documentation and procedures. Process Protocol Level I was initially developed based on the analysis of practices in the manufacturing industry and then the sub-processes were developed to complete the first process as well as specifying Information Technology (IT) support.

The HVAC design process models in Information Delivery Manuals (IDM) aims to serve as the integrated reference for processes and data required by Building Information Modeling (BIM). An IDM identifies the discrete business processes within the building lifecycle, the information for their execution and the results of that activity (Wix, 2007). IDM consists of Process Map, Exchange Requirements and Functional Parts.

The Integrative Design Process developed by 7 Group and Reed (2009) concentrates on green building design processes. The process follows an integrative design pattern, which is an iteration of workshops and research/analysis throughout the lifecycle of a project from the discovery phase throughout the maintenance of the project.

On the other hand, the structural engineering process model developed by Andrew Crowley in conjunction with buildSMART International (Norway) looks at a structural design of a system as a whole (buildingSMART International 2007). The focus of this work shows the progress from analyzing and designing a structural system in the early stages of design to the construction documentation stage. While focusing on the earlier phases, the majority of the tasks in great detail actually deal with how to generate and produce structural models. The process models follow the Business Process Model and Notation (BPMN) mapping notation for process representation. The models include limited other systems and, collaboration and coordination tasks (mostly architecture and construction), similarly for the exchange requirements focus mostly on the structural information needed and/or generated.

3 Development of an Integrated Building Lifecycle Process (IBLP) Map

3.1 Overview

The activities at the third level of the Integrated Building Process Model (IBPM) (Sanvido et al., 1990) are used as a foundation for the IBLP development. Systems-level activities for each of the IBPM activities were identified through extensive literature reviews of existing process models, a workshop with practitioners and surveys with domain experts. Lifecycle phases defined in the Integrated Project Delivery (IPD) (AIA, 2007) are used to shift the expectations for phases in this process development. As the first step, this paper focuses on identifying core activities at systems level for HVAC, lighting and structural systems along with fundamental architectural tasks for the main target systems for energy efficient building renovation projects.

3.2 Conceptualization Phase

Figures 1 and 2 show systems-level processes conducted during the Conceptualization Phase. The first step is for the owner to assign a project planning team for the project. The team studies and defines the owner's needs and corresponding constraints, and develops initial requirements and their priorities from diverse perspectives such as spatial, functional and financial. Common methods include interviewing the owner, surveys and studying the owner's previous projects and current facilities. As shown in Figure 1, based on the requirements, HVAC and lighting teams collect relevant data such as climate data, occupancy data, operating hour data, and budget. For building renovation projects, surveying existing conditions of the target building is one of the most crucial tasks to develop the project objectives and scope. These data are then used for initial

estimation of HVAC and lighting loads. Using the estimation results, specific objectives and scopes for each system are developed.

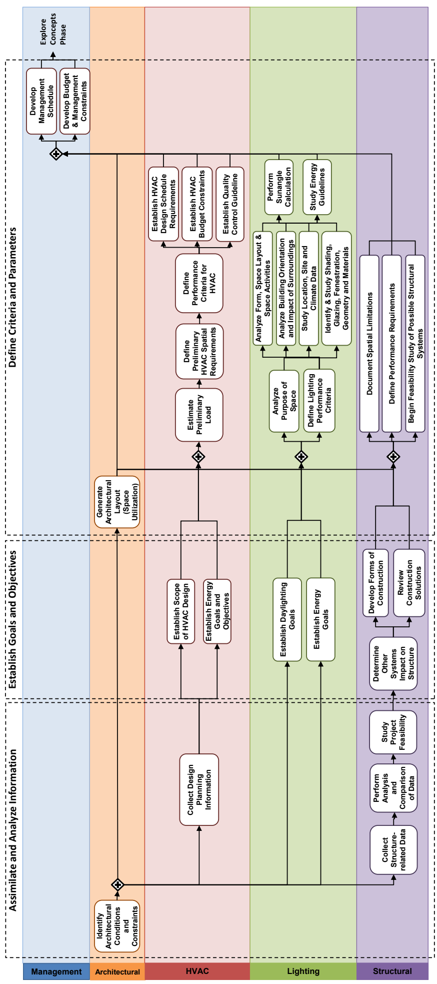

Figure 1 A process for understanding functional requirements

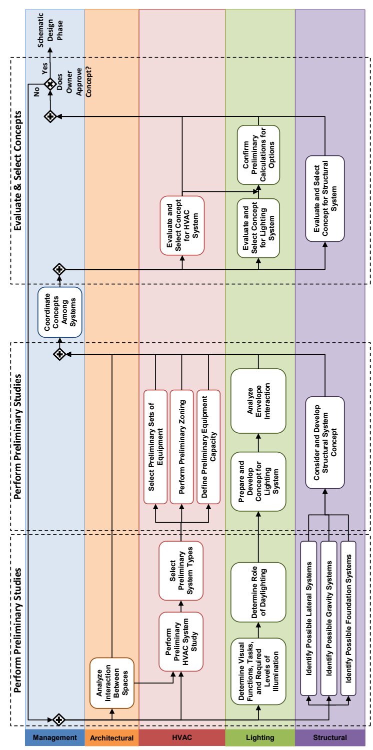

Figure 2 A process for exploring Concepts

As shown in Figure 2, the HVAC and lighting systems teams focus on exploring options and alternatives, develop core principles, and propose possible solutions that meet the project's goals and requirements. The proposals are then evaluated and coordinated with other systems. At the end of this phase, the most suitable concepts are selected for developing further in schematic design. In this phase, preliminary HVAC systems are studied and appropriate system types and sets of corresponding equipment are selected. Similarly, the lighting team conducts fundamental studies and analyses such as local daylight conditions, building materials and different passive daylighting systems by performing visualization and physical modeling. For the structural system, based on the information previously gathered, specific objectives and requirements for the structural system are developed and documented. Then, the team analyzes and compares possible systems and determines the alternatives for actual structural design. Next, the results and selections from the initial studies are coordinated with other systems to check fundamental conflicts and errors. Finally, the most suitable concepts are selected and approved by the owner.

3.3 Criteria Design Phase

Figure 3 depicts a process for the Critical Design Phase. The goal of the Criteria Design Phase is to develop initial system schemes. Principles and possible solutions are qualitatively and quantitatively analyzed and coordinated. Based upon the architectural design, fundamental requirements of the HVAC and lighting systems are developed and selected. For the lighting system, the requirements of active and passive systems are defined and a preliminary lighting layout is developed. For the structural system, the selected options developed from the Conceptualization Phase are further defined. Once criteria designs are developed for each system, coordination with other systems is performed to check compatibilities and conflicts among systems as well as codes and regulations.

3.4 Detailed Design Phase

Figure 4 depicts a process for the Detailed Design Phase, in which the team for each building system develops detailed design with system components and determines their layouts. Based on the detailed architectural design, advanced analyses and simulations are conducted to review the design from the perspective of each system. Sizes of equipment are calculated based on the estimation of load and their distribution methods are determined. Similarly, lighting fixture types and layouts are determined based on the results of a series of simulations, which check to see if the design meets the luminance and illumination criteria. The structural team finalizes their selection of the structural system, designs full details of structural components and optimizes the system as necessary. Next, the detailed design of each system is coordinated with other systems at the integrated level. Final codes and regulations checks are performed for validation. This is followed by development of deliverables such as preliminary drawings, specifications and schedules, which are then submitted to the owner for approval.

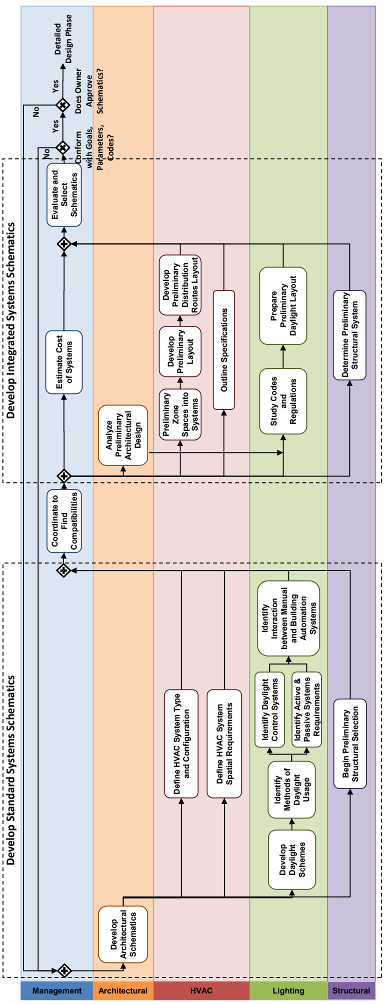

Figure 3 A process for developing system schematics

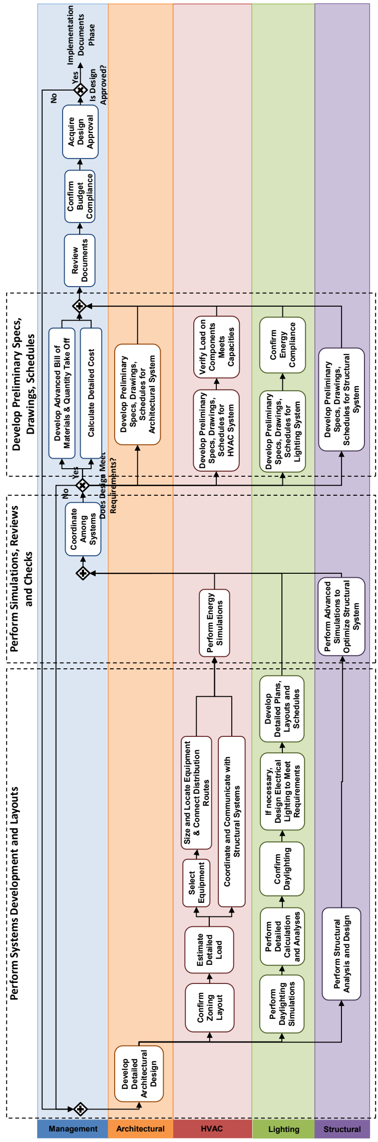

Figure 4 A process for develop detailed design

3.5 Implementation Documents Phase

Once detailed design is approved, the next phase is implementation of documents for construction. The project team of each system develops post-design drawings and specifications; reviews the documents; delivers the documents to the owner for final design approval. The documents should be able to include how the design will be implemented during the construction phase. Based on the detailed design documents, contractors create shop drawings as necessary. All the documents are finalized when the owner approves the documents.

4 Conclusions and Future Work

The paper describes the development of a building process model at the systems level, focusing on the Conceptualization Phase through Criteria and Detailed Design Phases to Implementation Documents Phase.. Core activities are identified through extensive literature review and interviewing domain experts. We expect the process plays a core role in better understanding project stakeholders' role, providing a foundation for defining detailed workflows for integrating computational modeling and simulations using digital tools, improving transparency and dependency between activities within the process.

The process discussed in this paper depicts systems-level activities for HVAC, lighting and structural systems. Future work includes further development of the process by identifying other systems such as plumbing, electrical and fire protection systems as well as developing the integration elements for bringing the systems together. The process model will also be extended to include Construction and Operations Phases. Additionally, information exchange requirements among the activities will be identified and represented to support and facilitate effective BIM use within the entire process. Finally, the process map will be evaluated and validated using energy-efficient building renovation projects currently conducted by the Greater Philadelphia Innovation Cluster (GPIC) for Energy Efficient Buildings, An Energy Innovation HUB as well as other projects appropriate to be used for the validation.

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Configurable Model Exchanges for the Precast/Pre-stressed Concrete Industry using Semantic Exchange Modules (SEM)

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ABSTRACT

Model View Definition (MVD) procedures are accepted by buildingSMART™ as the de facto industry standard in AEC/FM for specifying information exchanges between software applications using Industry Foundation Class (IFC) schema. However, current model view development approaches are time consuming, lack semantic clarity, are expensive to test and validate, and result in static model views with limited reuse in industry. As a result, software companies are required to duplicate efforts in preparing export functions that contain the same exchange structures multiple times, for each view. To address these issues a new framework for composing model views based on object-oriented, testable and reusable modules of information called Semantic Exchange Modules (SEM) is under development. We define a set of guidelines for developing SEMs and a methodology for specifying model views based on SEMs. The approach is validated using the precast concrete domain model exchanges as the test case. Comparison of current methods to the new approach using SEMs highlights the impact of this research.

INTRODUCTION

A Model View is a qualified subset of a building product model schema that provides a complete representation of the information concepts needed for a particular information exchange in an AEC/FM workflow (Hietanen 2006, Eastman et al. 2011, Venugopal et al. 2012). However, current methodologies for developing model views result in static and domain specific definitions with limited re-use in industry, thereby requiring software companies to duplicate efforts in preparing export functions that contain the same definitions multiple times, for each view. Moreover, the actual workflows for exchanging model data are more complex than has been addressed. Writing effective translators for product model exchange is very tedious and time consuming. The modeling languages and schemas available are very detailed because of the need to define the wide range of possible information for different objects, for different behaviors and functions. Part of the complexity is due

to the level of information being structured in languages like IFC and EXPRESS. They are low-level and have complex structure in order to address the varied ways that information may be referenced and combined, making translators written to or from the languages also very complex. However, once a certain level of exchange functionality has been defined and implemented, it should be re-usable as a module. If different modules are well partitioned, then a module should be able to be re-used in all settings in which it is possible to use it. We call these Semantic Exchange Modules (SEMs).

SEMANTIC EXCHANGE MODULES (SEM)

A SEM is a structured, modular subset of the objects and relationships required in each of the multiple BIM exchange model definitions. It has two raisons d'être: (1) to enable BIM software companies to code import and export functions in modular fashion, such that a function written to export or import model objects according to any given SEM can be tested and certified once, and then re-used to fulfill multiple exchange model exports/imports without modification; (2) to provide a common high-level specification structure that allows non-programmers to compose a Model View Definition (MVD) at run-time by defining it in terms of SEMs, allowing multiple heterogeneous platform users to specify a SEM and to facilitate automatic compilation of the MVD on both sides to the exchange.

A SEM can be defined as a binding to a set of IFC entities, attributes, relations, and functions and a corresponding binding to a set of native model structures that carry the information associated with the IFC SEM definition (Figure 1). The SEM carries the functions (methods) needed to reliably map data between the native and IFC structures and other methods to integrate the two structures with associated SEMs. After implementation and thorough testing, SEMs can be used to compose a model view, composed from a selection menu in a structured fashion by users to define any combination of information supported by the exchange applications. By selecting the same SEMs on their platforms, the two applications generate an exchange with predictable information for reading and writing.

SEM LIBRARY STRUCTURE

SEMs are defined in the form of modules binding together entities addressing a similar aspect. For example, *geometry* is a set of SEMS, for addressing a similar model aspect. Similarly, *building elements* and *building element types* are two families of SEMS that have largely the same structure, allowing the family to be easily implemented together or by re-using their structure.

The structure of SEMs specified in this work are organized by the following criteria:

1. They are aggregated units of IFC entities and structures that internally do not restrict combinatorial use;
2. Each SEM must address all potential uses, as allowed by its IFC release. This means that its definition must be insert-able in the proscribed order sequence, able to integrate with both its predecessor and successor SEMs;
3. If IFC structures are always used together, they should belong to the same SEM.

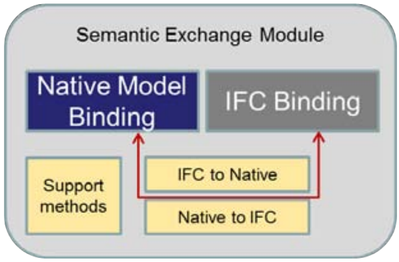

Figure 1. Basic structure of a single Semantic Exchange Module (SEM)

Based on the above criteria, an initial SEM library is defined as shown in Figure 2. It is envisioned to follow an *open-closed principle*. Once a SEM family is fully defined, it is ‘closed’ for modifications whereas the SEM library is ‘open’ to extensions in the form of new SEM families. Each of the large boxes in Figure 2 identifies a SEM family. Within each SEM family are different detail information specifications that have similar implementation at their aggregate level. Different implementation combinations identify different translator semantics. The selections correspond to DLLs that can be linked at runtime into a custom translator. A list of existing SEMs and their definitions can be found in (PCI NBIMS 2012).

MODEL VIEW GENERATION FROM SEMS

Overview: We define four different sets of roles in the industry. These are as follows; (1) *the information modeler* – the one who specifies the SEM families for each domain along with the mapping to IFC schema, (2) *the software developer* – who implements the SEM structure in the native model export and import, (3) *the BIM expert* – who is a domain expert and aware of the exchange requirements and knows how to specify a model view, and (4) *the end user* – who works on the BIM data in the industry.

The objective of this effort is to provide an illustration or proof of concept of the notion of SEMs and implementing a dynamic model view for a particular data exchange requirement in the AEC/FM industry on run-time by the *BIM expert*. A precast concrete detailed design model is chosen as the use case for this study. There is a need for seamless data exchange between the Architect and Engineer on one side to the Precast Detailer and Fabricator on the other side (*the end users*). The ideal scenario is that at the start of a project, the workflow exchanges would be planned and the model views to support them identified by the *BIM expert*. These could be executed by agreeing on a pre-defined exchange. Alternatively, the exchange parties could define dynamically one or more new desired exchanges, and these could be implemented automatically. Model views are defined on the basis of SEMs. Automatic generation of an instance file in native schema is still under development and we have restricted the scope to specifying a model view in EXPRESS schema at this stage. Future research will include generation of the model views in native data structures with the help of *software developers*. The idea is to show the feasibility of modularizing the structure of model views into composable units. This necessitates precisely defining how precast concrete building model objects are to be exchanged

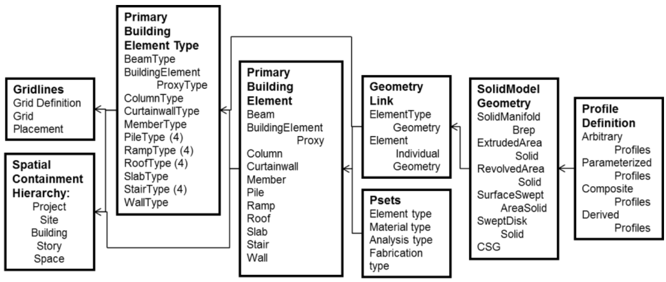

Figure 2. SEM library structure

using IFC files. For example: *What combinations of IFC entities should be used to represent which precast objects? What property values may be?* And, *what IFC relationships are required between entities?*

Consider the case of a floor slab in a parking garage. The precast detailed design model is used for design intent validation by architect, for structural design review by the engineer, for coordination and clash detection by the general contractor and for production and fabrication sequencing by the plant manager. There are different ways to represent this slab entity using a product model schema such as IFC, depending upon the context and also the level of detail required. An IFC data model is at the center of all these exchanges and there needs to be semantic clarity about the exchange information content while the level of detail increases. Five different views required of the same model can be as listed below:

1. For purposes of clash detection among different disciplines such as MEP, or electrical, a simple boundary representation of the entire floor slab might be sufficient.

2. For structural analysis purposes the building components will have to be represented in the form of nodes and axes in a stick (analytical) model. There is no requirement for 3D geometry, however connections and loads (static and live) are important. The SEM library is extensible and a structural analysis SEM family will be included as part of future work.

3. For precast fabrication purposes the slab would need to be represented in the form of individual hollow core planks with detailed geometry, relative layout, connection details and topping information.

4. A fourth case is where there is a need for the parent slab as well as the individual hollow core planks, its topping, washes, and all components aggregated into the parent slab. In this case the geometry of the parent slab will be derived from the union of the individual components (and possibly stored).

5. For production and delivery sequencing, there is no need for geometry information. However, the piece count and other information such as erection sequencing and project schedule are of highest importance.

All five of the above cases can be represented in IFC and can coexist. This shows the richness of IFC as well as the redundancy it is driven to incorporate due to the fact that it caters to a wide spectrum of the AEC/FM domain. Hence, effective exchanges require providing a layer of specificity over the top of an IFC (or any

other) exchange schema. The purpose of the SEMs is to provide precisely such a layer. Therefore, it enables users to select and specify the appropriate information entities from a schema, their attributes, and rules that govern their possible values for particular uses based on SEMs without worrying about the underlying IFC schema.

Process. The process of generating a model view exchange is illustrated in Figure 3. The process begins by the user entering the needs for a model exchange in terms of SEMs. We assume that the SEMs already defined are sufficient at this stage to satisfy the requirements, which means the scope of the model view is restricted to the scope defined in this research. The user selects the required SEMs, for example, in the scenario shown in Figure 3, a precast double tee is to be exchanged represented with extruded geometry. The collection of SEMs selected has a mapping to the IFC schema, based on which an EXPRESS schema file is generated manually. EXPRESS syntax checkers are available as open source modules. The EXPRESS Engine developed by NIST is used in this research.

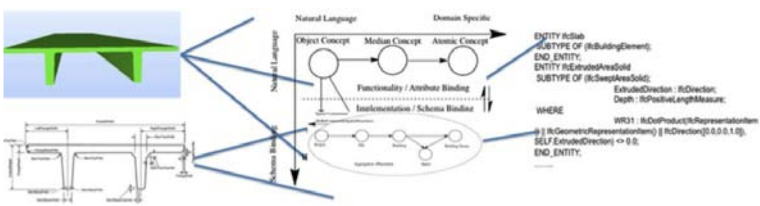

Figure 3. Model view generation based on SEMs

The process of verification involves the following steps, (i) the EXPRESS schema file is parsed using the *EXPRESS Engine*, (ii) the errors are reported based on missing IFC entities, relations, and attributes, (iii) the EXPRESS schema file is modified for correct mapping, and (iv) steps 1 to 3 are repeated until all the errors are resolved. The developers use this resulting EXPRESS file, which is a valid subset of the overall IFC schema, as the model view. This completes the syntactic verification of the model view generated from SEMs. At this stage, the model view generation is done by manually compiling the EXPRESS schema and checking it using parsers for completeness. This step of generating the schema based on user requirements can be automated by writing a schema generator. An automated model exchange protocol based on SEMs is the intended future capability.

Test Cases: Defining a model exchange for clash detection purposes requires a simple boundary representation of the floor slab. The SEM library provides the menu structure for specifying the model view. Let us assume the user selects the slab as a high level entity with B-Rep geometry and precast as material. The sample menu selection is shown in Figure 4. It should be noted that *geometry, placement, material,* and *spatial containment* are modular SEMs that are inherited by this slab (*building element*) SEM. The system will generate the model view in EXPRESS schema for

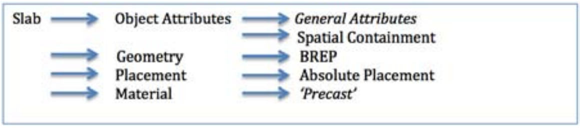

Figure 4. SEM based menu selection for exchange of monolithic precast slab

this particular case based on the mapping of SEMs to IFC. This view can be exported to the IFC schema in two different representation formats, namely B-rep and extruded geometry. B-rep and extruded geometry have different uses. B-rep is a simple face representation and is useful for volume calculations and clash detection. However, for more complicated tasks such as editing and parametric model progression there is a need for extruded geometry.

In terms of model progression and level of detail, the detailed precast model should include all discrete elements when compared to the monolithic elements in the design model. Hence, the idealized monolithic floor slabs are replaced with individual precast planks, connections, topping, and with provision for camber in-place. The detailed model is needed for the precaster to generate general arrangement drawings, assembly drawings, production drawings and the bill of material. There are two exchanges where the detailed model is passed back to the architect and structural engineer for design intent validation and structural review. Architects review the detailed model with corrections as required in terms of the joints and alignments of the precast panels, materials, topping and visible surface finishes. Structural engineers review the model for structural integrity. Let us assume the model view requires the individual components such as the precast hollowcore planks, connection components, and topping. The user can define these on the basis of the SEM structure. An example is shown in Figure 5.

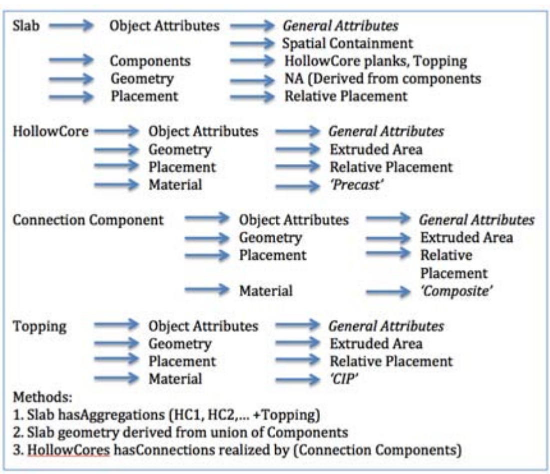

Figure 5. SEM based menu selection for exchange of discrete precast elements

According to a McGraw Hill survey (Young et al. 2009), the BIM-based coordination activities are contributing significant benefit to the industry. In practice the general contractor brings together the models from different subcontractors and checks spatial coordination between systems to avoid clashes before actual construction begins. B-rep geometry is sufficient for this task. At this time or earlier, the contractor decides the construction sequencing and schedule. The final case is one such use of the detailed/fabrication model. The detailed precast model is passed to the plant management system to coordinate the fabrication and delivery of the precast pieces with other project elements being produced at the same time. Project sequencing is applied throughout these steps, so pieces are produced in the order they will be erected. These systems allow allocating parts to the fabrication beds based on the plant schedule and also orchestrate a delivery schedule. Part management systems can be integrated with enterprise resource planning (ERP) systems to pass quantities of material and schedule information back to the general contractor. Production planning requires the delivery schedule of all necessary components and detailed product information including the layout, shape, material types, identification and product information, reinforcement specifications, assemblies and connections, concrete mixes and finish types, and lifting hardware. Therefore, the information about hollow core planks is passed on in a flat format without geometric representation. Dimensions, quantity information, concrete mix, etc. are the main attributes as shown in Figure 6. Further details about the test implementation of interoperability standards for the precast/prestressed concrete industry can be found in (PCI NBIMS 2012).

Future Scope: Implementing a mapping of the SEMs proposed here to the native data structures is a work in progress. This task involves the development of interfaces such that BIM software developers can implement the SEM classes. A successful implementation of SEM methodology can support applications in different stages of interoperability research. We identify some of the applications here:

1. **Tool for documenting exchange requirements:** New exchange requirements can be directly defined using SEMs as the building blocks.
2. **Dynamic model exchanges:** Use of SEM libraries and classes are expected to partially automate the current task of manually defining the IFC mapping for individual model views, thereby making the creation of new model views and exchanges a run-time task.
3. **Querying of exchange data:** SEM objects can facilitate querying of building object model data for exchanges. This is a new initiative and yet to be verified.
4. **Testing and Certification:** The use of predefined and tested SEMs will ease the strain on the testing and certification programs for model exchanges. The set of rules, constraints, and methods are packaged along with the SEM modules.

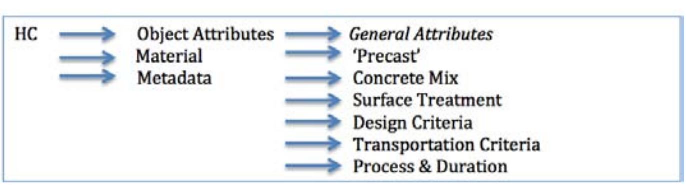

Figure 6. SEM based menu selection for exchange of precast fabrication details

CONCLUSION

This research introduced a new approach for developing model views based on Semantic Exchange Modules (SEMs). Once fully implemented, the SEM based approach can reduce the model view generation-implementation from the current two to three year period to eventually that of a day's run time. Model views are implemented in EXPRESS schema using a SEM library and work is in progress to automatically generate export/import instances using SEMs on run-time. The SEM based approach has resulted in the static and domain specific model views to be converted into better configurable and modular, industry wide workflow specifications, thereby improving the re-use of export and import translations. A new framework based on well defined and unit tested SEMs, thereby following a modular approach, is the future direction for creating exchange specifications and implementing them in a standardized and reusable manner.

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Guidelines for Using Building Information Modeling (BIM) for Environmental Analysis of High-performance Buildings

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ABSTRACT

Building Information Modeling (BIM) efficiently integrates environmental analysis into the design and delivery of high-performance buildings. Building *Energy* Modeling (BEM), a subset of BIM, employs various simulation tools for predicting the environmental performance of buildings. As the demand for high-performance buildings has increased, BEM has facilitated the delivery of buildings that meet expected performance requirements. The research objectives were to: 1) evaluate various BEM tools, and 2) develop guidelines for using BEM tools in design and delivery of high-performance buildings. Twelve BEM tools were evaluated using four criteria: interoperability, user-friendliness, available inputs, and available outputs. The top three programs (Autodesk Ecotect, Autodesk Green Building Studio, and IES <VE>) were selected based on this evaluation. Each of these selected BEM tools was used in the case study to simulate energy consumption, daylighting performance, and natural ventilation for two buildings, one LEED certified and one non-LEED certified. The results of the case study were used to compare the environmental performance of the two buildings and to develop guidelines for using BEM tools to analyze building environmental performance.

INTRODUCTION

As sustainability increasingly becomes a standard practice in the building industry, the demand for high-performance buildings increases. Goals related to sustainability are being set ever higher, demanding greater levels of energy and resource efficiency (Bringezu, 2002). With the demand for high performance buildings and the resulting challenges posed to designers and builders, the integration of building performance analyses into the design and construction process becomes crucial. Building information modeling (BIM) in conjunction with building *energy* modeling (BEM) seeks to make this integration seamless throughout the design process (GSA, 2005).

BEM allows design professionals to predict how well a building will perform upon completion and provides greater insurance that designs will meet or exceed intended performance requirements (Krygiel & Nies, 2008). By allowing design

professionals to simulate building performance in a virtual environment, BEM tools provide feedback related to environmental responsiveness throughout the design process (Schlueter & Thesseling, 2009). The integration of BEM tools into design not only provides greater certainty to designers and owners of a building's performance, but also aids in the design and construction of increasingly *greener* buildings. There are currently several existing BEM tools available for use in the AEC industry, and there is a need to evaluate how these various tools can be employed.

Attia et al. (2009) conducted a survey of BEM users to compare 10 major BEM tools using two criteria: 1) usability and information management interface, and 2) integration of intelligent design knowledge-base. Based on the responses from 249 BEM users (primarily architects and green building consultants), Attia et al. (2009) showed that IES<VE>, eQuest, and HEED were the most "architect friendly" BEM tools. Azhar et al. (2009) conducted a case study to compare the capabilities, advantages, and disadvantages of three BEM tools – Ecotect, Green Building Studio, and IES<VE>. Azhar et al. (2009) concluded that IES<VE> was the strongest of the three BEM tools based on its range of analyses types.

This research aimed to develop guidelines and recommendations for using BEM for the analysis of high performance buildings. In particular, the study focused on whole building energy use, daylighting, and natural ventilation potential. Intended users of the guidelines are building designers and green building consultants. The research objectives were to:

1) Conduct a literature review to evaluate 12 major BEM software tools.
2) Conduct a case study using the top three software tools out of the 12 tools identified in objective 1 to assess the performance of two buildings: one LEED certified and one non-LEED certified.
3) Re-evaluate the top three BEM tools based on the results of the case study and develop a set of guidelines to help potential BEM users select the most appropriate BEM tool.

RESEARCH METHODS

Initial evaluation of the BEM software tools. Twelve major BEM tools were selected for the initial evaluation: Graphisoft EcoDesigner, Bentley Tas Simulator V8i, Bentley Hevacomp Simulator V8i, Autodesk Ecotect, Autodesk Green Building Studio, IES <VE>, DesignBuilder, Visual DOE 4.0, Energy10, EnergyPlus, E-Quest and HEED. These programs were assessed using four criteria: interoperability, user-friendliness, available inputs, and available outputs. There were a number of subcriteria within each criterion (see Figure 1). The scoring system placed an even weight of 1 point maximum for each criterion with a score based on the percentage of subcriteria supported by the BEM tool.

Case study. The top three BEM tools identified in the initial evaluation were used to conduct a case study and compare the performance of two buildings located on the University of Florida campus in Gainesville, Florida: Rinker Hall (a LEED gold certified building) and Gerson Hall (a non-LEED certified building). BIM models were prepared for each building using the software Revit Architecture 2012. Each

model was exported as a gbXML file from Revit to the three BEM software. Specifications pertinent to each building's performance were input into the BEM tools (See Table 1). Each BEM tool was used to simulate the buildings' performance in annual energy usage, daylighting, and natural ventilation.

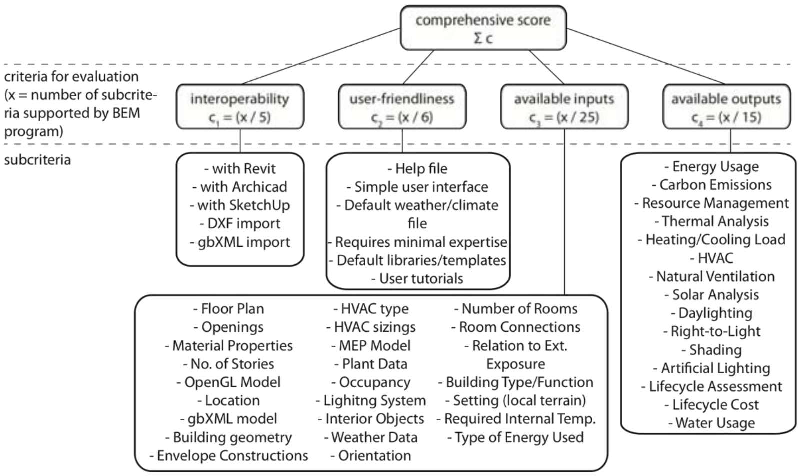

Figure 1. Initial evaluation scoring system with criteria and subcriteria.

Table 1. Specifications of buildings used in the case study.

Building Characteristics	Rinker Hall	Gerson Hall
Area of conditioned space (sqft)	42,719	38,632
HVAC system	Variable Air Volume with Energy Recovery Ventilation	Variable Air Volume with Terminal Reheat
Exterior wall construction (from exterior to interior)	¾" metal panel, 5.5" R20 cellulose insulation, 2" rigid insulation, ½" gypsum board	4" brick veneer, 2" air gap / damproofing, 12" CMU, 5/8" GWB on 1-1/2" studs with rigid insulation
Exterior wall U-Value	0.033	0.097
Glazing type	Low-E, double-glazed, insulated	Low-E, double-glazed
Glazing U-Value	0.53	0.66
Window to Wall Area Ratio	0.22	0.20
Albedo (Roof Reflectance)	0.80	0.41

Development of guidelines for using BEM tools. Upon completing the case study, a re-evaluation was performed on the top three BEM programs using a set of criteria similar to those used during the initial evaluation. Adjustments and additions were applied to the criteria and subcriteria based on information gathered during the case study. The four criteria used in the re-evaluation were interoperability, user-friendliness, versatility (of inputs and outputs), and calculation speed. The best BEM tool was selected by evenly weighting each of the four criteria. Then a matrix was

developed applying different weights to criteria based on order of importance for the potential user. In this way, a user could use the matrix after first identifying the order of importance of the four criteria, allowing the most appropriate BEM tool to be selected.

RESULTS

Initial evaluation of the BEM software tools. The top three BEM tools identified by the initial evaluation were IES <VE> (score 3.38 out of 4 possible points), Ecotect (score 3.14) and Green Building Studio (score 3.06). The major factors that distinguished these three tools from the other tools were high interoperability and available outputs scores (Figure 2). EQuest placed fourth, but did not perform well in regard to interoperability and user-friendliness as compared to the top three BEM tools.

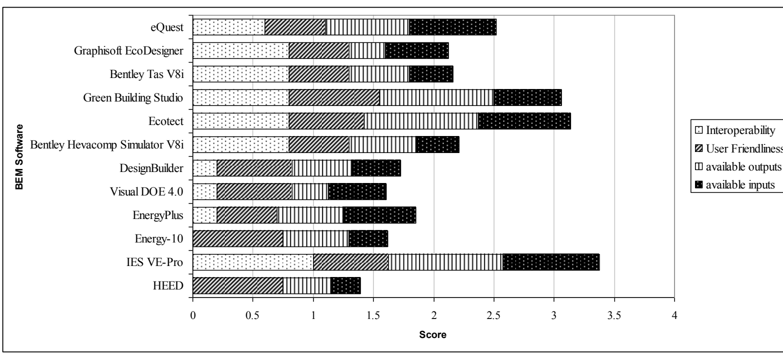

Figure 2. Initial evaluation scores

Case study. The top three BEM software tools were used in the case study. Simulations for each building were performed by each BEM tool assessing energy usage, daylighting, and natural ventilation.

Regarding energy usage, Rinker Hall, the LEED-certified building, performed better than Gerson Hall in both total annual energy usage and in energy use intensity (EUI). This was true in all three BEM programs (See Figure 3).

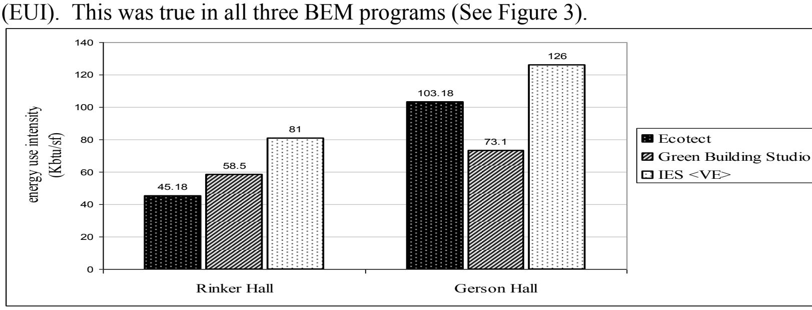

Figure 3. Energy use intensity (EUI) comparison by building and by BEM tool

Ecotect simulations showed that Rinker Hall would save more energy than Gerson Hall (56% difference between EUIs). Green Building Studio calculations showed that Rinker Hall would save more energy than Gerson Hall (20% difference between EUIs). Similarly, IES <VE> simulations estimated that Rinker Hall would save more energy than Gerson Hall (36% difference between EUIs).

To compare the daylighting performance, four rooms from each building were selected (Table 2). Similar rooms based on room function, area, and glazing orientation in the two buildings were compared using daylight factor as the common parameter. Ideally, the study would have compared daylighting based on daylight autonomy, but this was not feasible due to limitations of the software.

Table 2. Characteristics of the rooms used in daylighting analysis

Rinker Hall			Gerson Hall		
Room Function	Area (sq. ft.)	Glazing Orientation	Room Function	Area (sq. ft.)	Glazing Orientation
303 Main Conference	589	North	327 Large Conference	768	North
322 Faculty Office	139	West	324 Office	146	North
240 Est./Dwg./Sch.	1334	East	122 Medium Classroom	1162	East
340 CCE	527	East	329 PhD Office	274	North

Performances of each building could be compared within each program, but results could not be compared between the three BEM programs due to the fact that daylight factor was not calculated in a consistent manner. Only Ecotect and IES <VE> allow the user to specify the placement of sensor points at which the daylight level is measured. None of the three tools allows the user to specify the date and time at which the daylight factor is calculated.

The rooms in Rinker Hall had higher daylight factors than their counterparts in Gerson Hall, but with some exceptions (Table 3). Within each BEM tool, Rinker Hall's conference room, classroom, and graduate student office suite performed better than those in Gerson Hall's. The faculty office had mixed results with Ecotect and Green Building Studio predicting higher daylight factors for the office in Gerson Hall, and IES <VE> estimating the faculty office in Rinker Hall to perform better.

Table 3. Comparison of daylight factors (for the selected rooms and the three BEM programs). Highlighted values are greater than the minimum required daylight factor (2%) for adequate daylighting.

Room Function	Building	Ecotect	Green Building Studio	IES<VE>
Conference Room	Rinker Hall	11.48%	6.30%	13.70%
	Gerson Hall	3.37%	0.70%	4.80%
Faculty Office	Rinker Hall	2.74%	0.30%	6.40%
	Gerson Hall	3.22%	1.00%	5.00%
Classroom	Rinker Hall	3.98%	0.80%	3.80%
	Gerson Hall	3.00%	0.20%	1.10%
Graduate studio	Rinker Hall	3.89%	0.90%	2.60%
	Gerson Hall	1.79%	0.50%	3.10%

Each of the three BEM software tools assessed natural ventilation in different ways. Green Building Studio provided outputs related to how much energy could be

saved through the use of natural ventilation. Green Building Studio simulations showed that Gerson Hall (potential annual energy savings of 57,883 kWh) could possibly save more energy (44% difference) through natural ventilation than Rinker Hall (potential annual energy savings of 32,254 kWh). Potential energy savings from natural ventilation were calculated in Ecotect by subtracting the overall energy use of the models with natural ventilation activated from energy use values of the benchmark models. Ecotect simulations also showed that Gerson Hall (potential savings of 142,043 kWh) could possibly save more energy (35% difference) than Rinker Hall (potential savings of 92,516 kWh). IES<VE> was able to assess natural ventilation by providing average annual infiltration rates (cfm) for each zone. Gerson Hall had an average natural ventilation rate of 0.033 CFM per square foot averaged over the entire inhabitable building floor area compared to Rinker's average natural ventilation rate of 0.022 CFM per square foot. Thus Gerson Hall seemed to provide a 33% higher ventilaton rate than Rinker Hall.

Guidelines for using BEM tools. The breakdown of the subcriteria used in the re-evaluation of the BEM tools is shown in Figure 4. This is a variation on the criteria breakdown used in the initial

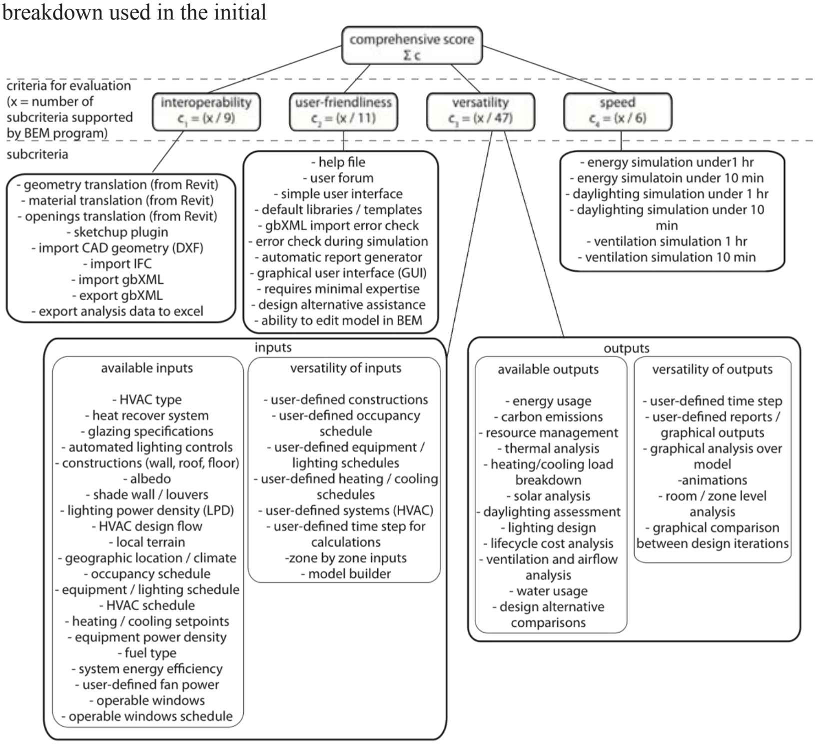

Figure 4. Re-evaluation scoring system with criteria and subcriteria.

evaluation. Available inputs and available outputs (along with versatility of inputs and outputs) were lumped together into one category called "versatility." The additional criterion of speed was evaluated based on the performance of each BEM tool during the case study.

Based on the re-evaluation, IES <VE> had the highest comprehensive score when criteria were weighted equally. This was largely due to IES <VE> receiving high marks in user-friendliness and versatility categories (See Figure 5). A matrix was developed applying various weights to the criteria based on the user's order of importance. The criterion first in importance was multiplied by a factor of four, second by a factor of three, third by a factor of two, and fourth by a factor of one. This matrix yielded 24 possible combinations. Among the 24 possible weightings, IES <VE> held the highest score of 21. Based on the research findings Green Building Studio is recommended when speed is the highest priority for the user, and interoperability the second highest; and when the order of importance is speed, user-friendliness, interoperability, and versatility. The study recommends IES <VE> for any other combination of the criteria.

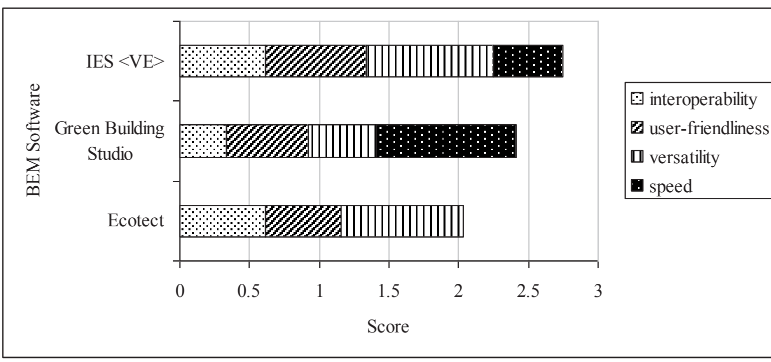

Figure 5: Re-evaluation scores (un-weighted).

CONCLUSIONS

The various building energy modeling (BEM) tools available today present a wide range of capabilities and applications. Based on the criteria used to evaluate BEM tools in this study, IES <VE> was selected as the most appropriate BEM software when criteria were weighted evenly. However, the selection of a BEM tool is dependent on how the user intends to apply BEM and how BEM is incorporated into a design workflow. For example, Green Building Studio may be a more appropriate selection for users requiring a faster output to compare numerous design iterations related to building specifications. As observed in the case study, there are also numerous BEM methodologies that can be adopted for various applications. As design tool, BEM is perhaps most helpful in comparing design iterations; that is,

identifying a number and values of design variables and testing how they affect the simulated energy usage or other building performance parameters. These variables, otherwise known as energy efficiency measures (EEMs), may then be combined in any number of variations to optimize the building energy model.

While BEM is useful as a design tool to aid designers in developing increasingly greener design iterations, many BEM tools are yet to be validated by comparing simulated data in various building performance parameters against measured data from actual building operation. Further research should be performed in order to measure the accuracy of these tools in regards to energy usage, daylighting, and natural ventilation potential. The major difficulty in doing so is predicting the behavior of the building occupants. For the two buildings investigated in the case study, the occupancy schedules are certain to change with each passing semester, and the behavior of occupants in regards to lighting, equipment usage, and operable window usage is never going to be consistent. Therefore, while it is possible to calibrate a building energy model during its occupancy and operation phase, it is impossible to do so during the design phase. This makes it very difficult to simulate building performance accurately. Further research could focus on developing more accurate ways to model these unpredictable variables. Until then, BEM remains a valuable design tool to aid designers in developing increasingly greener design iterations.

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The Challenge of Computerizing Building Codes in BIM Environment

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ABSTRACT

Computerization of building codes and standards in connection with Building Information Modeling (BIM) represents a real challenge for the AEC industry. On one hand, building rules and regulations are written by professionals to be read and applied by people since the reasoning and interpretation ability of the human brain is unlike anything implemented in computer systems. On the other hand, a smart phone app can outperform any engineer on solving a set of linear equations. However, many tasks that are easy for engineers or human in general are surprisingly difficult for computers. Examples include interpretation and expression of code and standard provisions that are characterized by subjective and descriptive rules. The perceptual abilities of engineers certainly surpass the fastest supercomputers. This gave motivation to many researches investing the efforts in creating computable representation of the building codes and standards and their link to Building Information Modeling (BIM). This paper provides critical review of the development of computable building codes rules that can be implemented into BIM-based automated rule-checking systems. It also addresses the complexity of these knowledge systems, the problems they pose for engineers and designers, and the methods for managing and advancing them.

INTRODUCTION

Computerizing the rules and provisions checking of building codes and standard has interested many researcher and practioner since the mid-sixties. For example, in 1966 Fenv investigated application of decision tables to represents AISC standard specifications. He made the observation that decision tables, an if-then-novel programming and program documentation technique, could be used to represent design standard provisions in a precise and unambiguous form. The concept was put to use when the 1969 AISC Specification (AISC 1969) was represented as a set of interrelated decision tables. Subsequently, Lopez et al. implemented the SICAD (Standards Interface for Computer Aided Design) system (Lopez and Wright 1985; Elam and Lopez 1988; Lopez et al. 1989). The SICAD system was a software prototype developed to demonstrate the checking of designed components as described in application program databases for conformance with design standards. Garrett developed the Standards Processing Expert (SPEX) system (Garrett and

Fenves 1987) using a standard-independent approach for sizing and proportioning structural member cross-sections. The system reasoned with the model of a design standard, represented using SICAD system representation, to generate a set of constraints on a set of basic data items that represent the attributes of a design to be determined.

Then further research effort was led by Singapore building officials, who started considering code checking on 2D drawings in 1995. In its next development, it switched and started the CORENET System working with IFC (Industry Foundation Classes) building models in 1998 (Khemlani,, 2005). In the United States similar works have been initiated under the Smart Code initiative. There are also other several research implementations of automated rule-checking to assess accessibility for special populations (SMC, 2009) and for fire codes (Delis, 1995). The GSA and US Courts has recently supported development of design rules checking of federal courthouses, which is an early example of rule checking applied for automating design guides (GSA, 2007) .

More focused research efforts on frameworks for the representation and processing of design standards for automated code conformance began two decades ago (Yabuki and Law 1992). During that time, building models and the methods for rule checking have been developed, but effective Smart Codes systems are just beginning to emerge. In the 1990s, the introduction of the Industry Foundation Classes (IFC) led to early research for using this building model schema for building code checking. Han and others laid out schema for a client–server approach (Han et.al, 1998 and Vassileva,, 2000). They later developed a simulation approach of American Disability Act (ADA) wheelchair accessibility checking (Han et. al, 1999, 2002). (Han et.al. 2009).These efforts set the stage for larger, more industrial-based efforts. A comprehensive survey on the topic was reported by Fenves et al. (1995) and Eastman et al. (2009).

Building rules and regulations are written by professionals to be read and applied by people since the reasoning and interpretation ability of the human brain is unlike anything implemented in computer systems, the computerization of this process poses a real challenge to the AEC industry. Fortunately, the recent advancement in the Artificial Intelligence research and Building Information Modeling (BIM) can provide key solutions. The next sections will review some of the AI fundamentals that have relevance to the AEC knowledge domain.

Nature of human languages. Human languages are easy to learn by children, they can express any thought that any adult might ever conceive, and they are adapted to the limitations of human breathing rates and short-term memory (Sowa, 2007). This indicates that with a finite vocabulary, they possess infinite extensibility of expressions and an upper bound on the length of phrases. Together, they imply that most words in a natural language will have an open-ended number of senses, and thus vagueness and ambiguity is inevitable. Throughout history many philosophers (e.g. Charles Sanders Peirce and Ludwig Wittgenstein) understood that vagueness and ambiguity and concluded that these are not defects in language, but essential characteristics that permit it to express variety of things and all aspects of objects that human need to describe. For example, Peirce noted the difficulty of stating any

general principle with absolute precision (Sowa, 2007): “It is easy to speak with precision upon a general theme. Only, one must commonly surrender all ambition to be certain. It is equally easy to be certain. One has only to be sufficiently vague. It is not so difficult to be pretty precise and fairly certain at once about a very narrow subject”. This quotation summarizes the futility of any attempt to develop a precisely defined ontology of everything, but it offers two useful alternatives: an informal classification, such as a thesaurus or terminology, and an open-ended collection of formal theories about narrowly delimited subjects. It also raises the questions of how and whether these resources might be used as a bridge between informal natural language and formally defined logics and programming languages.

Modeling languages. During the second half of the 20th century, various models of language understanding were proposed and implemented in computer programs. All of them have been useful for processing some aspects of language, but none of them have been adequate for all aspects of language or even for full coverage of just a single aspect.

Statistics.: In the 1950s, Shannon’s information theory and other statistical methods were popular in both linguistics and psychology, but the speed and storage capacity of the early computers were not adequate to process the volumes of data required. By the end of the century, the vastly increased computer power made them competitive with other methods for many purposes. Their strength is in pattern-discovery methods, but their weakness is in the lack of a semantic interpretation that can be mapped to the real world or to other computational methods.

Syntactics: Chomsky’s transformational grammar and related methods dominated linguistic studies in the second half of the 20th century, they stimulated a great deal of theoretical and computational research, and the resulting syntactic structures can be adapted to other paradigms, including those that compete with Chomsky and others. But today, Chomsky’s argument (Chomsky, 1957) that syntax is best studied independently of semantics is at best unproven and at worsts a distraction from a more integrated approach to language modeling. In the construction industry ISO STEP is a good example of such modeling. The main issues with STEP is that the models have been proven to be to complex and difficult to implement and currently can be more efficiently replaced with web-based technologies.

Logic: By the 1970s, the philosophical studies from Carnap and Tarski among others led to formal logics with better semantic foundations and reasoning methods than any competing approach. However, those methods can only interpret sentences that have been deliberately written in a notation that looks like a natural language, but is actually a syntactic variant of the underlying logic.

Lexical Semantics: Instead of forcing language into the mold of formal logic, lexical semantics deals with all features of syntax, vocabulary, and context that can cause sentences to differ in meaning. The strength of lexical semantics is a greater descriptive adequacy and sensitivity to more aspects of meaning than other methods. Its weakness is a lack of

an agreed definition of the meaning of ‘meaning’ that can be related to the world and to computer knowledge representation systems.

W3C Semantic Web (SW): Web technologies provide modeling alternatives such as eXtensible Markup Language (XML) and eXtensible Schema Definition language (XSD) that more effectively replaced SPFF and EXPRESS language. However, the problem of the languages is that it is not extensible and limited to structure only and not really providing instruments to add actual semantics in the form of concepts, properties and rules. These limitations have let to the development of Ontology Web Language (OWL) and RDF(Resource Description Framework)-XML as syntax for the content according to OWL-expressed ontologies. It is in essence a fully generic, freely reusable data structure with knowledge specified in OWL. OWL is a fully web-based and distributed variant of the traditional ISO STEP technologies like EXPRESS and SPFF. Semantic Web technology like OWL and RDF-XML provide promising new modeling languages in the construction However, their applications in representing building codes and standards are limited.

Neural Network: Many researchers believe that neurophysiology may someday contribute to better theories of how humans generate and interpret natural language. Certainly, that can be true, but the little that is currently known about how the brain works can hardly contribute anything to linguistic theory and knowledge representation. *Neural networks* are statistical methods that have the same strengths and weaknesses as other statistical methods, however, they have little resemblance to the way actual brain neurons work.

Each of these approaches is based on a particular technology: mathematical statistics, grammar rules, dictionary formats, or networks of neurons. Each of them ignores those aspects of language for which the technology is ill adapted. For humans, however, language is seamlessly integrated with every aspect of life, and they don’t stumble over boundaries between different technologies. The greatest strength of natural language is its flexibility and power to express any sublanguage ranging from cooking recipes to stock-market reports and mathematical formulas.

BUILDING CODES COMPUTABLE MODEL

Building codes generally have a natural aim to organize, classify, label, and define the rules, events, and patterns of the build environment to achieve safety, efficiency and economy. However, their best-laid plans are overwhelmed by the inevitable change, growth, innovation, progress, evolution, diversity, and entropy. These rapid changes, which create difficulties for both young engineers and experienced professionals, are far more disruptive for the fragile traditional knowledge bases in computer systems. Although precise definitions and specifications are essential for solving problems in building design, many code provisions are not well defined and highly subjective in nature. Furthermore, code provisions are characterized by continuous gradations and open-ended range of exceptions make it impossible to give complete, precise definitions for any concepts that are learned through experience.

For over two thousand years, efforts were made to create intelligent classification systems as depicted in Aristotle's categories and his system of syllogisms for reasoning about the categories were the most highly developed system of logic and ontology (Sowa. 2004). The syllogisms are rules of reasoning based on four sentence patterns, each of which relates one class in the subject to another category in the predicate: (i) *Universal affirmative*. Every truss is a frame. (ii) *Particular affirmative*. Some trusses are space frames. (iii) *Universal negative*. No truss is a deep foundation. (iv)*Particular negative*. Some space frames are not trusses.

Fascinating enough is the effort by Leibniz in 1666 when he tried to automate Aristotle's syllogisms by creating a computable model: “The only way to rectify our reasonings is to make them as tangible as those of the Mathematicians, so that we can find our error at a glance, and when there are disputes among persons, we can simply say: Let us calculate, without further argument, in order to see who is right.”

At the same time, it is crucial to realize the limitations of any computerization systems by clearly indicating which part of the codes and standards can’t be computerized.

The introduction of SmartCodes will greatly improve the current design practice by simplifying the access to code provisions and complaints checks. Representing building codes and standards in a computable and flexible model that accommodate and make sense of the specific nature of this knowledge domain play a key role and as Leibniz stated “let us calculate without further ado”. By breaking through the precincts of Code and Standard provisions, design software, and the Building Information Modeling a solution to insurmountable hurdle can be achieved.

SmartCode is referred to as the computable digital format of the building codes that allow automated rule and regulation checking without modifying a building design, but rather assesses a design on the basis of the configuration of parametric objects, their relations or attributes. Smart Codes employ rule-based systems to a proposed design, and give results in format such as “PASS”, “FAIL” or “WARNING”, or ‘UNKNOWN’’ for conditions where the required information is incomplete or missing.

Recently, a number of researchers investigated the application of ontology-based approach (Yurchyshyna et al. 2009) and the semantic web information as a possible computable framework (Pauwels et. al. 2009) for computerizing building codes rules. The first research approach works on formalizing conformance requirements conducted under the following methods (Yurchyshyna et al. 2009): (i) knowledge extraction from the texts of conformance requirements into formal languages (e.g. XML, RDF); (ii) formalization of conformance requirements by capitalizing the domain knowledge. (ii) semantic mapping of regulations to industry specific ontologies; and (iv) formalization of conformance requirements in the context of the compliance checking problem. On the other hand the semantic web approach focuses on enhancing the IFC model by using description language based on a logic theory such as the one found in semantic web domain.

The computable representation of building codes and standards requires special purpose ontology that is consistent with the general-purpose ontology set forth by the National BIM Standard (NBIMS). This special purpose ontology must have the ability to handle exceptions and uncertainties presents in various building

code provisions. The organization of building elements into categories and subcategories in a taxonomic hierarchy is a vital part of these ontologies. Although most of the code checking activities takes place at the level of individual structural elements, much rule checking and reasoning begins at the level of categories. Also, Categories serve to assist in making prediction about building objects once they are classified. Furthermore categories serve to organize and simplify the knowledge base through inheritance. Thus, a system for mapping of terms, definitions and code provisions to existing classification tables will provide key solutions. The OmniClass represents a good example of general purpose (upper) ontology for the construction industry. Figure 1 below illustrates the classification of some building elements using the categories and subcategories concept mentioned earlier.

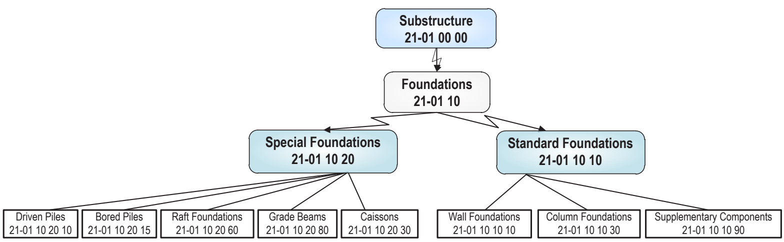

Figure 1. Part of OmniClass Table 21 – upper ontology

The current Omniclass that will be adopted by the NBIMS version2 include a limited number of tables (namely, Table 13, 21, 22, 23, 32, and 36). However, the transformation of codes and standards require the inclusion of all tables to establish general-purpose ontology for the computable model of the building codes. Hopefully, this will be addressed in the subsequent versions of the NBIMS.

In addition to the general purpose ontology, special-purpose ontology needs to be developed to cover the level of details for the computable models of the SmartCodes. This special-purpose ontology will play a similar role as the UniFormat II (ASTM E1557) classification did for cost estimate and project management domains.

In the United State, the International Codes Council (ICC) will be available in some form of XML. The ontology used in this model is based on the Omniclass classification system and the International Framework for Dictionaries (IFD). The dictionary is being developed as part of the IFD effort and, in the US, is being managed by the Construction Specifications Institute (CSI) in cooperation with ICC.

BIM-MODEL CONTENT

With the introduction of Building Information Modeling, the production and dissemination of information was accelerated, but ironically, communication became more difficult. When construction documents were printed on paper, an engineer could compare details from different consultants, even though they used different formats and terminology. But when everything is model driven, designer, contractor, client and vendor systems cannot interoperate unless their formats are identical.

The primary requirement in application of SmartCodes is that object-based building models (BIM) must have the necessary information to allow for complete

code checking. BIM objects being created normally have a family, type and properties. For example, an object that represents a structural column possesses type and properties such as steel, wood or concrete, and sizes etc. Thus the requirements of a building model adequate for code conformance checking are stricter than normal drafting requirements. Architects and Engineers creating building models that will be used for code conformance checking must prepare them so that the models provide the information needed in well-defined agreed upon structures.

The GSA BIM Guides (GSA, 2009) provide initial examples of modeling requirements for simple rule checking. This information must then be properly encoded in IFC by the software developers to allow proper translation and testing of the design program or the rule checking software. IFC is currently considered one of the most appropriate schemas for improving information exchange and interoperability in the construction industry. These software applications have mainly concentrated on deriving additional information concerning specialized domains of interest. In order to automatically verify the information in an exchange process it is required to detail the information further than the general level of the IFC standard. The code conformance domain represents a new level of details and requirements on IFC model. This should be achieved by developing the appropriate Information Delivery Manuals (IDMs) and Model View Definitions (MVDs) for the Automated Code Conformance Checking (AC3) domain (Nawari 2011).

CONCLUSIONS

Building rules and regulations are written by professionals to be read and applied by people since the reasoning and interpretation ability of the human brain is unlike anything implemented in computer systems, the computerization of this process poses a real challenge to the AEC industry. The computable model for code representation must possess enough elasticity and expressiveness to capture most of the provisions similar to how a child grow from a simple stage to a more sophisticated stage without relearning everything from scratch: each stage from infancy to adulthood adds new skills by extending, refining, and building on the earlier representations and operations.

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BIM Standardization and Wood Structures

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ABSTRACT

With the rapid acceptance and increasing interest in Building Information Modeling (BIM) in the AEC industry, the issues of level of details and interoperability as means to communicate and integrate various model-based application into a high productive workflow has emerged to the forefront of the professional attention. The ultimate success of BIM will in part depend on the ability to capture all relevant data in the BIM model, and to successfully exchange data between the various applications. BIM tools that have matured to some extent for structural steel and concrete construction are not yet satisfactory for modeling wood structures. This study reviews the current state of BIM tools in modeling wood structures and formulates the functional requirements for development of successful BIM models for designing wood structures. This paper focuses on advancing standardization of BIM model for designing and analyzing wood structures. In particular the paper addresses the Information Delivery Manual (IDM) and Model View Definitions (MVDs) as they aim to provide the integrated reference for process and data required by identifying the discrete processes undertaken to design wood structures and to create an efficient method for seamless, reproducible exchange of reliable information that is routinely acknowledged by the industry.

INTRODUCTION

The concept of the Building Information Modeling (BIM), which is an object oriented technology, is revolutionizing the way projects are designed and built. This is due to fact that the building project can be gradually assembled digitally and visualized in 3D before it is actually built. In addition, BIM offers a wealth of information that is generated automatically as the model is created. In turn this information can be used for structural analysis and design, cost estimating, project planning and control, and eventually for management of the operation and maintenance of the building. BIM will truly allow a new model based process to occur, however, a new form of contract is required, one where the two parties to construction—designers and contractors—work together from the early stages to build a combined model that captures the needs of both parties.

The eventual success of this process will in part depend on the ability to capture all relevant data in the BIM model, and to successfully exchange data between the various project participants. One of the means of doing this information exchange is through a standardized data exchange format. Standards are critical when communication between different trades and disciplines. All the different entities

utilizing BIM technology in the construction and building industry including architects, engineers, contractors, facility owners and operators, and software developers, have diverse nomenclatures, diverse vocabularies, geometries, computing paradigms, data formats, data schemas, scales and fundamental world-views. To solve these problems nationally and internationally, advancing standardization is becoming a key factor in BIM adoption across industries.

The National BIM Standard (NBIMS) is established to provide the digital schema and requirements for efficient BIM application in the AEC industry. The vision for NBIMS is "an improved planning, design, construction, operation, and maintenance process using a standardized machine-readable information model for each facility, new or old, which contains all appropriate information, created or gathered, about that facility in a format useable throughout its lifecycle by all" (NBIMS, 2007).

Many of the aspects of this overarching goal will be accomplished by a large conglomerate of players. The area that BIM Standard is focused on is the design of the theory and structure for a new way of thinking about facilities and structures as information models. Specifically, the BIM Standard recognizes that a BIM requires a disciplined and transparent data structure which supports the following:

- A specific business case that includes an exchange of building information.
- The users' view of data that is necessary to support the business case.
- The digital exchange mechanism for the required information interchanges.

This combination of content selected to support user need and described to support open digital exchange are the basis of information exchanges in the NBIM Standard. All these levels must be coordinated for interoperability and this is the focus of the NBIMS Initiative. Therefore, in nutshell the primary drivers for defining requirements for the BIM Standard are industry standard processes and associated information exchange requirements (Nawari, 2011). In addition, even as the BIM Standard is focused on open and interoperable information exchanges, the BIM Standard Initiative addresses all related business functioning aspects of the facility lifecycle.

Research in wood construction has promoted important innovations on new wood engineered products, structural analysis methods and more efficient construction processes. However there is still a perception that the limits of wood design are not being challenged by the architects and engineers. Current technical innovations are not being extensively transferred into architectural design practice and in most cases new wood buildings continue to adopt conventional and rather conservative solutions. BIM for wood structures should offer a great opportunity for architects and engineers to change their perception and drive wood to the edge as they explore wood structures in many innovative and exciting ways.

Wood construction represents a significant portion of the construction market and a great deal of historical buildings and non-building structures. Wood offers abundant advantages via building information models, to the owner, architect, engineer and contractor if executed correctly. Use of BIM in wood and timber construction can reduce the required material on-site and assist the engineer in providing additional and clearer details for typical and non-typical wood construction, offer an appreciable sustainability advantages, improve the design and construction

processes by supporting the creation, testing and evaluation of a higher number of design alternatives before the actual construction begins.

WOOD STRUCTURES AND BIM

In addition to low cost benefit of using wood structures, wood remains a top choice in terms of green building materials. Many research studies have shown time and again that using wood products from sustainably managed forests rather than non-wood building products, results in a reduction of Green House Gases (GHG) emissions that fuel global warming, and provides high performance buildings. In comparison to other common building materials such as steel and concrete, wood has by far the least environmental footprint at several stages of the life cycle process, including raw resource extraction, manufacturing, and transportation (FPInnovations, 2011).

Further advantages of wood include that it allows a wide and rich range of shape and form possibilities, whether in load-bearing mode or as shell structures. For instance, to a name few: the Olympic Oval in Vancouver for the Olympic Winter Games 2010 (Canada) and Centre Pompidou-Metz in France display wood competency and abilities in larger building projects. Thermal and sound resistance, and light weight are intrinsic wood properties that give wood structures leading position. Aesthetics, of course, are subjective, but wood's natural beauty and warmth have a positive effect in any application and have been proven to generate improved productivity and performance in schools, offices and better patient outcomes in hospitals. These features can be intensively explored using BIM, making the evaluation of structural functions, complex patterns, colors and shapes an easier and more efficient process.

These characteristics can be provided as parametric information, which allows changes made to the project to be reflected in all locations in the design. This greatly reduces change orders, omissions and errors, which could become costly and time consuming, possibly delaying construction for months. Much of the information included on a particular product is centered on construction specifications, but the advantage of BIM model is that it continues to provide information even after construction has finished and the project is in service. Many owners/operators find themselves using BIM also to facilitate the maintenance, operations and efficiency of the structure for its lifecycle.

By the use of building information models architects and engineers can provide significantly greater drawing details, potentially reduce material required for construction, and minimize conflicts between disciplines. Furthermore, use of BIM allows the engineer to take more control of wood building details as wood products come in many forms, from dimension lumber, laminated strand lumber (LSL), to glulam members with varied shapes. Via BIM, each and every wood and wood products and other types of modular elements can be modeled in its intended location, with a higher level of dimensional control leading to potential resources and time savings. Moreover, BIM for wood structures would furnish a great opportunity for young architects and engineers to gain wood experience in accelerated fashion. Also construction of complex or unusual configurations is naturally considered risky and

complicated using wood structures; however, with the aid of wood BIM these can be achievable tasks.

Notwithstanding these benefits, current BIM tools are not mature enough to model wood structures efficiently to higher levels similar to steel or concrete structures. The main objective of this research is to explore the current BIM tool capabilities and maturity when used to model wood structures and formulates the functional requirements for development of a successful BIM model for designing and analyzing wood structures. This research is a part of the project UF-DCP-002 which is a seed funded research by the College of Design and Construction, University of Florida to investigate the development of IDM & MVD for Wood Structures. The project team includes architects, engineers and also other organizations are promised to participate such as Autodesk, and RISA Technology. Some of the results of this study are presented in the next sections.

BIM MODEL REQUIREMENTS FOR WOOD STRUCTURES

The problems of interoperability between engineering software systems have existed since the introduction of computer-aided design (CAD) in the 1970s. The same issues have become critical in the architecture, engineering, and construction (AEC) industries with the widespread adoption of building information modeling (BIM) in the early 2000s (Eastman et al. 2008). While parametric modeling of buildings has existed for as long as it existed in manufacturing, efforts to develop a building product model exchange schema based on ISO-STEP technology only began in the mid-1990s and are an ongoing effort. These efforts resulted in the industry foundation classes IFCs (IAI 2007), promoted by buildingSMART previously called the International Alliance for Interoperability (IAI).

The real success of applying Building Information Modeling will in part depend on the ability to capture all relevant data in the BIM model, and to successfully exchange data between the various project participants. One of the means of doing this information exchange is through a standardized data exchange format (Nawari et.al. 2010 and Nawari 2011). One of the primary roles of BIM Standard is to set the ontology and associated common language that will allow information to be efficiently exchanged between disciplines.

The National BIM Standard (NBIMS) is established to provide the digital schema and requirements for efficient BIM application in the AEC industry. The objective of this standard is to improve productivity in the design and construction industry by developing a basis for incorporating and integrating structural design, codes, and analysis tools and methods. The data model commonly used in this capacity is the IFC standard. This work covers the challenges related to advancing standardization of BIM model for designing and analyzing wood structures. In particular the paper addresses The Information Delivery Manual (IDM), Model View Definitions (MVDs) and IFC.

The technology for exchanging information using Industry Foundation Classes has now been established, but many areas require additional development before comprehensive interoperability solutions are reached. These areas include: extending the scope to include a broader range of project information, for more types of

projects, and more types of information; developing the exchange mechanisms layer below the data standards and the formalized transactions layer above; developing the range of software applications that implement model-based interoperability; and re-examining project management practices based on new integration technologies. It provides an extensive set of generic building object types such as beam, column, wall, slab, etc. with associated attributes and other properties. It offers numerous shape definition methods and means to depict relations between objects.

The core components of NBIMS include the Information Delivery Manual (IDM), and Model View Definition (MVD). The information delivery manual (IDM**)** is adapted from international practices, to facilitate identification and documentation of information exchange processes and requirements. IDM is the user-facing phase of NBIMS exchange standard development with results typically expressed in human-readable form.

The Model View Definition **(**MVD**)** is generated based on the exchange requirements specified in the Information Delivery Manual (IDM). MVD is conceptually the process which integrates Exchange Requirements (ER) coming from many IDM processes to the most logical Model Views that will be supported by software applications. The required BIM model for wood structures must encapsulate, organize, relate, and deliver information for both users and machine in accordance to the IDM and MVD.

Wood IDM. Essentially, the IDM provides a list of information that must appear in the IFC schema and the MVD provides the guideline specifying how the information must appear in the IFC schema. The IDM has two main components: one is the process map detailing the end user processes and information exchange between end users. The other component is the list of exchange requirements. The main categories of exchange requirements for wood IDM can be identified as: data exchanges required between architect and engineer, engineer and supplier, architect and contractor, contractor and wood framers. The development of IDM begins with definitions of the data exchange functional requirements and workflow scenarios for exchanges between these parties utilizing the 'use case' concept. A use case defines an exchange scenario between two well defined roles for a specific purpose, within a specified phase of a building's life cycle (Eastman et. al, 2010 and Venugopal et.al. 2010).

Figure 1 illustrates the general process map for wood BIM construction. The main objectives of the process map include: define the processes within the wood structural design project lifecycle for which engineers require information exchange, describe the results of process execution that can be used in subsequent processes, and identify the actors sending and receiving information within the process.

This process map (Figure1) shows the main tasks only and the exchange requirements needed between them. Each of these tasks includes many subprocesses, functions, and exchange requirements that need to be defined. This research focuses on task number 2.0, i.e. (OminiClass 31-20 10 00 and 31-20-20 00) exchanges between architect and engineer.

To establish an IDM for wood structural design, a process map illustrating the

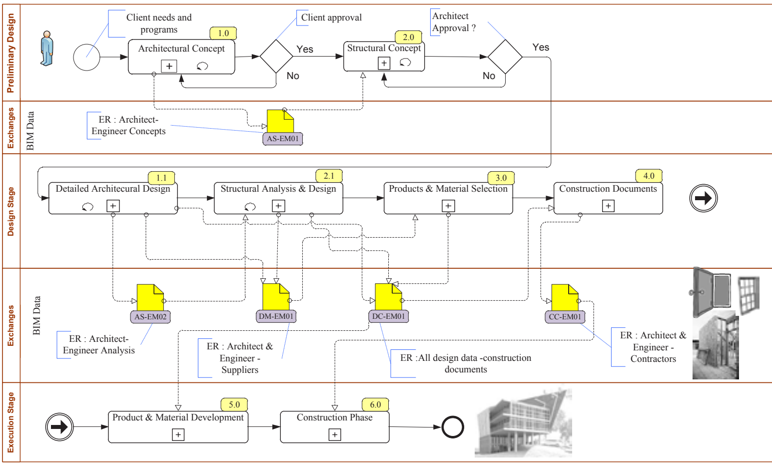

Figure 1. Process map for wood construction

details of information exchange requirements has been developed and shown in Figure 2. It covers primarily exchanges between architects and engineers (task No. 2 in Figure 1). The exchange model requirement presents a link between process and data. It applies the relevant information defined within an information model to fulfill the requirements of an information exchange between two processes at a particular stage of the project. Each exchange model is uniquely identified across all use cases and besides its name caries abbreviated designation of the use case it belongs to.

The scope of the exchange requirement is the exchange of information about structural elements and systems. Each of the exchange models described above contains a wide range of exchange requirements to support the coordination of wood structural analysis and design requirements with general architectural form and spacing requirements. For instance the exchange mode AS_EM01 represents , data exchange requirement between architect and engineer during the preliminary design and could include the following data: (a) Type, color and geometrical properties of structural wood elements: dimension lumber, timber, laminated strand lumber (LSL), parallel strand lumber (PSL), structural composite lumber (SCL), laminated veneer lumber (LVL), cross-laminated timber (CLT), glulam members …etc. (b) Type of connection and connectors properties, (c) grade (d) wood treatment, (e) temperature and moisture conditions (f) Structural usage, (g) Exterior and interior finish. Other exchange models shown in Figure 2 include: AS_EM01 - Architectural, Structural Concepts use case exchange models; DD_EM01 - Structural concepts, Loads, boundary conditions, & connections; DD_EM02 - Structural concepts, detailed structural analysis use case exchange models.

Information about wood data associated with structural wood components of the building that are required to run analysis and design according to the NDS 2005 Code (NDS 2005); DD_EM03- Superstructure, substructure Design use case exchange models.

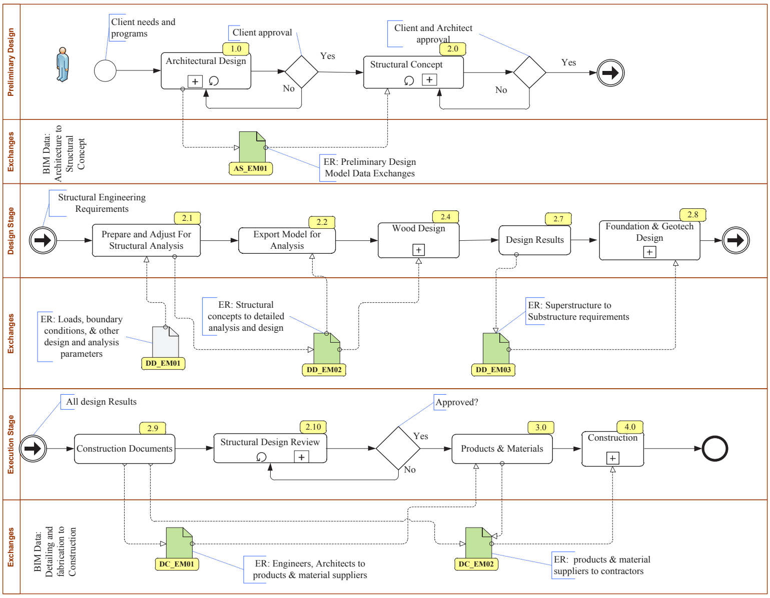

Figure 2. Process map for wood IDM.

Wood MVD. The process of developing the MVDs begins with defining the information exchange requirements (ERs) how they will be used, both in terms for the users and software developers. These definitions are then captured in the Information Delivery Manual or IDM. From this information the MVD is defined for each attribute and describes very specifically how it is to be handled in the IFC exchange. For instance, figure 3 shows a portion of the model view (structural concepts to structural analysis, DD-EM02) illustrating structural analysis of wood beam.

CONCLUSIONS

Wood structure is another area giving opportunity for engineers and architects to utilize BIM to improve upon design, analysis, documentation, and coordination between the architectural design and structural engineering teams. In wood construction, BIM offers the additional opportunity to assist in enhancing interoperability and productivity. To fully realize these goals, clear modeling requirements in standardized format to leverage a BIM model to carry out wood structural analysis and design are required. Currently, BIM platforms are lacking such requirements for designing wood structures. This study focused on advancing wood BIM and its relationship to design and analysis of wood structures as well as formulating the functional requirements for development of a successful BIM model for designing wood structures.

This research has taken a first-step in developing IDM and MVD for the wood structural systems. Notwithstanding that this effort only begins to touch on model exchange requirements, it will provide foundation for a standardized BIM in the structural wood domain.

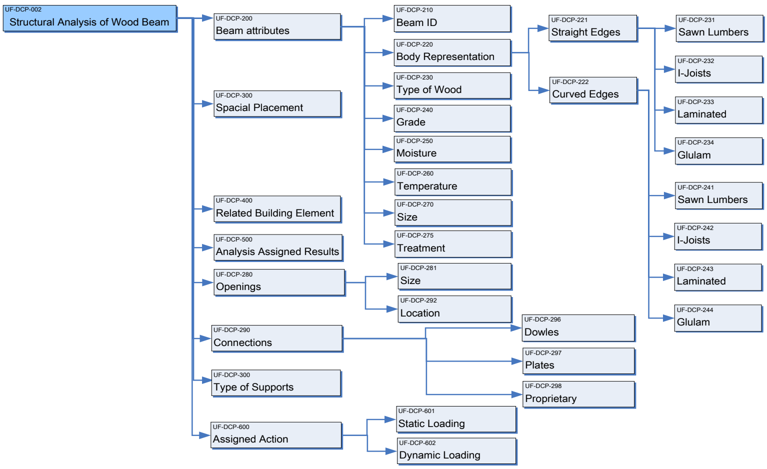

Figure 3. Part of the Wood MVD

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An Experimental Platform for Building Information Research

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ABSTRACT

The authors' efforts to improve the quality of Industry Foundation Class (IFC) building information exchanges has highlighted needed for defensible verification methods. The tools and techniques needed to meet these efforts requirements would also improve research that requires building information. This paper announces the open publication of a series of models and tools produced and used by the authors for their research. Widespread use of common models and shared tools are expected to improve the quality of research that requires building information.

INTRODUCTION

The process used to certify software for Industry Foundation Class Coordination Model View compliance was that software vendors would provide partial building model files that would be consumed and replicated by other software (Groome 2007). Since automated methods for testing software are not yet publically available, the subjective evaluation of software company representatives present at "certification" meetings has been the criteria for IFC software certification (Lipman 2011a). Lipman reports that the majority of all IFC model testing, eight cases in all, relied on manual review. The Lipman critique of IFC model testing results parallels a recent study on validation of research methodology (Lucko 2010). Such subjective testing is insufficient for designers and builders who rely on such certifications because the results obtained behind closed doors cannot be replicated by actual software users. In the worst case, known directly to the first author of this paper, software tested was never intended for commercial distribution; but that fact was never made clear during the testing. In the best case, software users who have been provided product version-specific configuration templates and who fastidiously follow software vendor guides will be able to export a data file that meets the formatting of the specified Model View.

Another difficultly in the application of buildingSMART certified software is that the detailed technical specifications of these views are easily misunderstood by designers and builders. For example, expectation that Coordination View data is intended for re-importation is misplaced since there is not a specific mandatory semantic relationship demanded for geometric representations mappings. As a result, the exportation of Coordination View information, for the purposes of geometric coordination, is valid but that information cannot be successfully re-imported. The lack of specification of precise geometric semantics was documented in the 32

missing beams example reported in Ma et. al. (Ma 2006). Misunderstanding by practitioners that the Coordination View contains all the BIM information a practitioner would ever need is reinforced by the fact that the Coordination View is the only model view that has been the subject of buildingSMART international testing regimes.

In addition to the problem of inappropriately overloading a model view for purposes other than the scope of that specific model view, buildingSMART certification testing to date considers the format, but not the quality, of the information provided. Thus a native door object in a software authoring tool may be exported as an ifcDoor or an ifcProxyElement with either representation being given equal validity from the perspective of the Coordination View. Given that real projects have Door schedules, not ifcProxyElement schedules, the establishment of mandatory quality standards reflecting the actual needs of users who wish to use the model views produced by buildingSMART is essential to practitioners.

Public, automated testing of format and content quality of IFC-based building information accomplished, not cited in the Lipman study, began in 2008 in support of the adoption of the Construction-Operations Building information exchange (COBie) project. The rules for the precise format, constraints on data in that format, and quality of data content have been established prior to the start of each COBie-related event. In 2009, standard building models and test files were added to ensure that the building information from different systems could be more precisely tested and compared. In 2013 a set of contract drawings for a real facility, described later in this paper, form the basis for testing the quality of the software output.

A critical evolution in the authors' process was that the test files were specifically designed to reflect differences in workflows that would normally be encountered when meeting generic design and construction contract deliverables. To distinguish the testing requirements of actual designers and builders, from those of data modelers and software companies alone, COBie testing established the buildingSMART alliance "Challenge" nomenclature. Further pressing the point that bench-tested solutions may not meet real project needs, a blind panel of design and construction practitioners will be asked to repeat the results demonstrated by the software company's engineers starting in 2013.

Increased discussions and even national workshops in the United States related to the verification and validation of academic research follows closely the progression of thought found in IFC certification and challenge critique. Without the identification of an authoritative set of standard building information models, researchers are required to spend a significant portion of their time creating their own experimental tools and procedures. The frustration with this stage of research and the inability of the resulting research platform to be re-used has been a common theme in discussions by many researchers with the authors. Those funding research also expect that building information research results should be repeatable in more general contexts including constraints commonly found in practice. The creation of proprietary tools and models is unsustainable given the lack resources, post-grant and post-graduation, to maintain these site-specific artifacts.

The authors' argue that insistence on open standard building models using improved "Challenge" methods with freely available, open tools will be required to

instill the confidence in designers and builders to use both building information model standards and research resulting from the use of such information. This platform is also expected to reduce the cost of software development and testing, and also accelerate the pace of research that uses building information.

PLATFORM REQUIREMENTS

The recommendations for improved interoperability testing (Lipman 2011a) and validity of research (Lucko 2010) results lead directly to the identification of requirements for an experimental BIM Platform. First, there must be an ability to generate test models that conform to the specific set of requirements to be tested. An example of such a generator is used in the Operations Research community for scheduling problems (Kolisch 2001). This generator must also provide compliant and non-compliant, format, semantics and constraints based on the requirements of the exchanges to be tested. Second, there must be standard methods to evaluate the test files and the products produced by the software companies and researchers. There must also be a test to determine the extent to which the information in the file covers the entire range of information and constraints imposed by the data model specification. With notable exceptions, the two most widely cited contributions to such a platform to date have been the Open IFC Model Repository (Amor 2010) and the IFC File Analyzer (Lipman 2011b). The Open IFC Model Repository has been developed as a collection of building models used for "unit testing" of IFC model components as well as full example models. The IFC File Analyzer provides useful statistics about the contents of any IFC models.

COMMON EXPERIMENTAL MODELS

This paper announces the public release of data sets on three buildings that simulate contractually required information exchanges regarding building asset information (spaces, products, and equipment). The three buildings are: a small duplex apartment building, a small office building, and a medical clinic. The duplex apartment project was originally created as part of a German design competition and was first used in the Dec 2009 COBie Challenge. The two-story office building was developed based on published template floor plans for a typical United States office building. The medical clinic project was developed from a medical/dental clinic built in the South-West United States. The clinic information includes a complete set of redacted design drawings. Operations and maintenance manuals from the clinic are also expected to be published in January 2013 following redaction of project and company information.

To reflect the evolving nature of building asset information through a projects' life-cycle, example deliverables were developed for every typical exchange of asset information during a project. In the context of the Life-Cycle information exchange (LCie) specification (East 2009), the files produced represent full, batch exchanges, of building asset information models that could be expected if contract documents required performance-based delivery of building asset information using the COBie specification. The table below summarizes the files provided and illustrates the differences in file size for the native, Coordination View, and FM

Handover MVD (known by its “marketing name” of COBie) files. The “Optimized” files were produced through the shareware Solibri IFC optimizer.

Table 1. Size of Architectural Models (in MB)

	Native Model (.rvt)	Native Coordination View (IFC)	Optimized Coordination View (IFC)	FM Handover MVD, COBie (.xls)
Duplex Apartment	6.7	2.4	1.6	1.4
Office	9.0	4.0	4.0	2.9
Clinic	10.4	17.7	12.9	6.3

Table 2. Size of MEP Models (in MB)

	Native Model (.rvt)	Native Coordination View (IFC)	Optimized Coordination View (IFC)	FM Handover MVD, COBie (.xls)
Duplex Apartment	17.2	17.8	10.9	2.4
Office	22.5	64.3	40.1	16.8
Clinic	33.2	202.5	122.8	36.9

While an extensive common object library and configuration guide were developed and have been published with these data sets, problems found in these model have become clear upon additional review. An essential value of repeated trials and documentation of the use of these models was that the software vendor in question could no longer support claims that apparent problems in their files were the result of inexpert use or configuration of their software product. The required manual transformation of the raw design models into models that simulated the final required construction handover resulted in the estimate of 120 hours required to bring the design models up to compliance with the expected content of owners’ specifications (Love 2010). While only one software product was benchmarked in this particular study, the authors are confident, based on prior evaluation of COBie Challenge results and other unpublished benchmark and case studies, that such problems exist with other vendors’ data exports as well.

As we have discovered through testing, the polite framing of problems stemming from a lack of BIM software internal representational power as “implementer’s agreements” has hidden the impolite impact of such problems - - the need for manual correction of data by experienced data integrators. To help move from bench tests to reality the authors developed the explicit mapping table needed by the native software users to ensure that information can be correctly found in the information provided from the vendors. The mapping table for the FM Handover Model View Definition is called the COBie Responsibility Matrix. All software vendors participating in COBie Challenge events are now be required to publically identify the required work-arounds (i.e. implementer’s agreements) resulting from inability to export IFC FM Handover MVD compliant models. The publication of all of these blemishes will promote the development of tools, such as the one described below, that allow practitioners to use the information that is available despite violations of the data schema specification. It is the authors’ hope that the

documentation of work-arounds will be a temporary fix that allows the hundreds of thousands users to make the most out of the data produced from the product versions they currently have installed until all upgraded to future, fully compliant software products.

COMMON MODEL SERVER PLATFORM

The first building information verification tools were web-based checking tools to verify compliance of building information model files against what would become the FM Handover MVD specification. Today, an example of a tool like this is freely available (Onuma 2012). An additional tool, bimServices, developed for automated transformation, compliance checking, filtering, model merging, and reporting was released publically (East 2009) but has subsequently found not to meet performance requirements on realistically sized building models. Subsequent commercial versions of bimServices, not tested by the authors of this paper, may have resolved such performance bottlenecks. Concurrent with the development of the public bimServices tool was the initiation of the open source model server project BimServer (BimServer 2011). BimServer is an open-source (GNU GPLv3 license) IFC model server that provides an inexpensive, scalable, and extensible platform for IFC information exchanges (import and export) via Web application front-end or remote back-end interfaces such as SOAP, REST, or a Java Client API. BimServer also provides a model merge engine that can combine disparate model views using simple pre-defined priority rules.

The authors have contributed several BimServer plug-ins to support our research and software testing efforts. The first are routines that incorporate the work-arounds found in imperfect commercial implementations of the IFC Coordination View needed to produce FM Handover Model View Definition (i.e. COBie) data files. The second is a series of report writers that provide room and equipment schedules directly from the model that allow practitioners to evaluate the quality of content of the model when compared against other deliverables. The third is a flattened COBieXML schema developed for auto-generation of Java Document Object Model (DOM) classes that include code for reading from and writing to XML documents. A COBieXML export provides the superclass, or foundation, of all subsequent exports such as Spreadsheet XML, PDF, and html – this superclass/subclass relationship is a convenient way to separate the data transformation logic from the data presentation logic. While this COBieXML schema is a key architectural component of the BimServer plug-ins for COBie, it is not intended to be introduced as approved format for the NBIMS-US COBie standard. Rather, it is an example of how COBie common data models may be used by software without the inefficiencies of binding to Spreadsheet XML. Additionally, the authors have successfully demonstrated extensions of this technology at international BIM workshops where mini-model views may be exported to Portable Document Format or small spreadsheets, updated as part of a simulated construction process, and merged back into the building model (Bogen 2011). These demonstrations provide an example of the implementation of “transactional” BIM model exchanges as described in the LCie project.

COMMON MODEL CHECKING ENGINE

The authors have also developed a model checking engine using Schematron (ISO 2006) validation rules and the BimServer export plug-in architecture. Schematron is a free ISO-standard XML-based language for defining assertions that extend beyond those typically implemented in XSD (XML schema definition) constraints. Schematron supports XSLT 2.0 functions and XPATH 2.0 expressions to define complex tests on relationships between XML document elements and attributes. In addition to the programmatic definition of rules, Schematron provides human readable representations of rules: e.g. the sum of Space floor area on a floor may not be greater than the net area of a floor. Advanced features of Schematron also allow the modeler to define phases of validation that may be run independently or may be skipped if previous phases fail. In addition to a standard representation for rules, the Schematron standard also includes a standard XML validation report format, the Schematron Validation Report Language (SVRL).

The authors have developed Schematron rules for project independent validation of COBie data on the life-cycle phases defined in the LCie project. At an implementation level, the authors developed an SVRL export for BimServer that validates the target model based on a specific rule-set. A tabular HTML export of the SVRL document is also provided. The validation report is produced after three transformations occur: (1) The target IFC model is loaded into an in-memory COBieXML object. (2) Schematron rules are transformed into an in-memory XSLT document. (3) The XSLT document produced in Step 2 is used to produce an SVRL document with the results of the rule checking from the COBieXML object produced in Step1.

The automated generation of coverage analysis from the specification of the Model View, one of the requirements for a complete test bed (Lipman 2011b) is not directly addressed by the authors' rule checking tool. Hand crafted rule sets are required based on the well-defined model constraints identified in the new MVD format. The full specification for this rule checking engine and associated release information will be provided during the presentation of this paper at the ASCE 2012 Conference.

CONCLUSIONS AND RECOMMENDATIONS

Those developing new standards, theories and techniques who cannot compare their results directly with the results of others run a serious risk of having their work go unused. The work described in this paper provides the starting point for a new set of tools upon which the next generation of building informatics research can be benchmarked. Two specific requirements: a test set generator and automated coverage analysis (Lipman 2011b) remain. The work described in this paper is the prerequisite for such developments. Without a precise and constrained specification of models to be created, a building model generator is not practical. The widespread use of the computable MVD specification containing explicit definitions of constraints and common business-rules, is also a pre-requisite for the development of a complete set of coverage rules.

The authors propose that the three models and tools identified in this publication be used as a starting point for the development of an international test bed for building informatics. Two universities in the United States have included the common models released in this paper in their course work. As a starting point for the use of these tools within the United States, the authors' have formally proposed that all future submission to the US National BIM Standard be required to demonstrate their results with these standard models and evaluated using the methods and tools described in this paper.

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Testing of Depth-Encoded Hough Voting for Infrastructure Object Detection

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ABSTRACT

The lack of viable methods to map and label existing infrastructure is one of the engineering grand challenges for the 21st century. For instance, over two thirds of the effort needed to geometrically model even simple infrastructure is spent on manually converting a cloud of points to a 3D model. The result is that few facilities today have a complete record of as-built information and that as-built models are not produced for the vast majority of new construction and retrofit projects. This leads to rework and design changes that can cost up to 10% of the installed costs. Automatically detecting building components could address this challenge. However, existing methods for detecting building components are not view and scale-invariant, or have only been validated in restricted scenarios that require a priori knowledge without considering occlusions. This leads to their constrained applicability in complex civil infrastructure scenes. In this paper, we test a pose-invariant method of labeling existing infrastructure. This method simultaneously detects objects and estimates their poses. It takes advantage of a recent novel formulation for object detection and customizes it to generic civil infrastructure scenes. Our preliminary experiments demonstrate that this method achieves convincing recognition results.

INTRODUCTION

As-built geometric modeling is the creation of a 3D model of an existing facility. As part of the modeling process, modelers spend a considerable amount of time in manually detecting and classifying objects from 3D point clouds. As a result, the labor cost of modeling an existing facility is prohibitive for small to medium sized infrastructure projects, and the results are prone to human error. In order to address this issue, recent research efforts have focused on automating this procedure. Several methods that use spatial data, visual data, or a combination of both have been proposed. However, they all have limitations that restrict them from being successful when applied to complex civil infrastructure scenes. For example, each object requires special encoding; some methods are computationally expensive and sensitive to topological changes, while others are incapable of accounting the 3D position of the parts of the object in relation with each other and are therefore limited of working only when the data is acquired from specific angles.

The Depth-Encoded Hough Voting method applied in this paper is a view and pose-invariant method that has the potential of automating the procedure of detecting commonly seen infrastructure objects. Images or a point cloud of the object, which are collected using laser scanning or photogrammetry, may be used as input. The method detects objects as a collection of parts and along with the registered topologies the category models of the objects are formulated (learning process) and stored in a database. The models can then be used to detect the object's type, position and orientation in other images. Nonetheless, this method hasn't been tested in the civil infrastructure scene. To fill the gap, preliminary experiments were conducted in which pictures of columns, doorframes and windows were collected to test this method. The results are quite promising.

STATE OF PRACTICE IN AS-BUILT 3D MODELING

The collection, organization and integration of as-built data of construction facilities into single data structures is achieved with the use of building information modeling (BIM) tools (Eastman et al, 2008). Such tools generate logical building objects along with their parametric relationships. The process of as-built modeling can be divided into three stages. In the first one, spatial and visual data is collected on site using laser scanning (LIDAR) or photo/videogrammetric techniques. The resulting products of this stage are images and a high-resolution point cloud. In the second stage, the 3D point cloud is used to detect objects and assign object relationships. This step is performed manually by an operator who observes the data to identify each object type. He then searches for it in a database of standardized objects, tries to fit it in the point cloud using fitting algorithms for optimal fitting and finally assigns the relationship of the object with the others in the scene. In the third stage, which is also manual, non-spatial as-built attributes (e.g. material, schedule and cost) are assigned to every object.

The first stage of as-built modeling is automated (Agarwal et al., 2010), whereas the other two are heavily human dependent, thus time-consuming, error prone and costly. Some attempts have been made towards automating them. For example, researchers have proposed methods for matching the point cloud with as-designed CAD objects (Son and Kim, 2010). Others proposed methods that classify and label components (e.g., walls, floor, window) of a room on a point cloud by assuming that the objects are related with each other in either an orthogonal, parallel, adjacent or coplanar way (Xiong and Huber, 2010; Huber et al., 2011; Oliver et al., 2011).

STATE OF RESEARCH IN OBJECT DETECTION

Object detection is the process of detecting the location of an object in a data set, and classifying it into a predefined object category. There are several methods that can be categorized according to the type of input data used, which are spatial, visual or a combination of both.

Point clouds include spatial measurement information, so the aim of object detection using spatial data is to recognize objects in 3D according to their shape (Schnabel et al., 2008) and/or spatial context (Huber et al., 2011). Techniques that are

based on shape similarity start with searching the point cloud for primitive shapes (such as line, plane, sphere etc.). While searching the image for primitive shapes, a topology graph representing the relationships between shapes is created. Then, the primitive shapes are matched in order to identify objects. However, these methods are not able to recognize objects that are noisy, partially occluded or not completely scanned (Mahmoudi and Sapiro, 2009), and also they are not computationally efficient (Atmosukarto et al., 2010). Spatial context methods (Huber et al., 2011) explore a priori knowledge in relation to object semantics (such as point clouds which is known to contain walls, floors etc.), geometrical constraints and spatial relationships (such as walls are orthogonally connected with the floor and the ceiling) of objects. The positive aspect of those methods is their ability of detecting objects, which have similar geometries (such as walls and floors) (Oliver et al., 2011). Recent efforts have focused on applying spatial context methods on infrastructure object detection (Xiong and Huber, 2010; Huber et al., 2011), since those objects are easily decomposed into parts that can be matched to geometric primitives and also have strong spatial relationships. Unfortunately, since each object type needs unique encoding (Pu, 2008), those methods can identify a small number of objects in restricted scenarios.

Visual data include different features (e.g. color, texture, shape, etc.) and can be used to extract spatial and temporal information that can be translated into machine language for object detection. Methods using visual data are usually model based. The model required is a list of spatially correlated characteristics of an object. Several researchers have created such models (Fei-Fei and Perona, 2005; Felzenszwalb et al., 2008). These methods are able to model an object using its shape variability viewed from specific angles (Fei-Fei et al., 2007) or a combination of angles (Zhang, 2004) and their resulting product is a list of class labels (e.g. chair or desk) along with their rough 2D location and scale. Recent efforts have focused on producing methods that perform object detection using a multi-view setting (Savarese and Fei-Fei, 2007; 2008). These methods utilize coherent models for the object type detected, in which the elements of the object are connected across the different views. The disadvantage of those methods is their inability of accounting the 3D position of the parts of the object in relation with each other and to the viewer. The work by Savarese and Fei-Fei does encounter it; however it is still in its early stage of research.

In civil engineering, Brilakis et al. (2011) proposed a framework of creating visual pattern recognition models for infrastructure element detection. This framework identifies the visual characteristics of element types, uses analysis tools to numerically represent them, and form the models using the derived representations and their topology. However, the existing method of Visual Pattern Recognition models is not view or scale-invariant and is restricted to view/scale invariant objects or planar pattern, unless models for each view are created.

Several researchers have attempted to combine spatial and visual data in order to detect objects (Sun et al. 2010), and reconstruct the 3D structure of the scene (Li et al., 2009, Bao et al., 2010). Hoiem et al (2006; 2005) enhance the detection of objects in complex scenes by using the geometrical contextual information of the scene's layout. Bao et al (2010) use one image to analyze the interaction of objects and their surfaces, whereas Bao and Savarese (2011) use multiple. Sun et al. (2010) created a

novel Depth-Encoded Hough Voting (DEHV) detector that simultaneously detects objects and estimates their poses. The advantage of using this method is its ability to handle severe occlusions due to its representation with a large set of parts (similar to the implicit shape model (Leibe et al. 2004)). Moreover, it has the ability of incorporating depth information during recognition if while training this dimension is also included and this may increase the detection accuracy. DEHV jointly detects objects, infers their categories, estimates their pose, and infers/decodes objects' depth maps from either a single image (when no depth maps are available in testing) or a single image augmented with the depth map (when this is available in testing). This method holds great potential of being accurate for detecting commonly encountered civil infrastructure objects. Moreover, the depth values inferred are valuable for mapping the detected objects' image regions with their counterparts on the 3D point cloud. This is an essential step towards the automation of generating as-built building information models of civil infrastructure.

PROBLEM STATEMENT AND OBJECTIVES

Object recognition and reconstruction methods have been successfully devised and/or adapted for small or linear objects (e.g. columns), or restricted building scenarios that require a priori knowledge without considering occlusions. However, many infrastructure objects are large and/or planar without significant and distinctive affine invariant features, such as walls, floor slabs, and bridge decks. Based on the literature review, the Depth-Encoded Hough Voting detector is very promising when used to recover both object category and its 3D structure. However, this technique has not been tested on civil infrastructure objects. As a result, the overall objective of the work presented in this paper is to test the applicability of the Depth-Encoded Hough Voting method for detecting commonly seen infrastructure elements. The final goals are to pave ways of creating element category models for different infrastructure objects, detecting such objects in images, and matching the detected objects between images and the corresponding 3D point cloud.

EXPERIMENTAL DESIGN

A Canon VIXIA HF S100 camera is used to collect the data and three different datasets under natural light are chosen to perform the experiments. Each set represents a typical civil infrastructure object and those selected are columns, doorframes and windows. The collected sample size both for training the machine and testing the method is determined using the following equation (Eng, J, 2003). This equation was chosen after assuming that the population is normally distributed and also since this study focuses on parameter estimation.

$$N = \frac{4z_{crit}^2 p(1-p)}{D^2} \tag{1}$$

In this equation, z_{crit} is the standard normal deviation and is equal to 1.645 considering a significance level of 90%, p is an estimate of the accuracy of the test (meaning that we desire at least 50% of our test to be accurate) and is equal to 0.5,

which is considered the worst case scenario for sample size determination, and D is the total width of expected confidence intervals and is equal to 0.2 since the significance level is set to 90%.

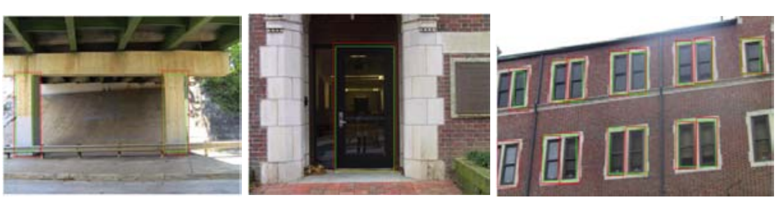
The collected data is pre-processed by manually drawing a bounding box around the object of interest; the co-ordinates of its upper left and lower right corner are noted. The training of the machine for the formulation of the object's model follows. In the experiments presented below, the information regarding depth has not been applied, since this part constitutes ongoing research. Finally, the algorithm is tested for evaluation. New bounding boxes around the detected objects are automatically drawn and the corresponding coordinates of the upper left and lower right corner are saved.

The indicators used to measure the performance of the algorithm are precision and recall. Precision, which measures the detection exactness, is the number of objects correctly detected (TP, True Positive) over the total number of objects correctly and incorrectly detected (TP+FP, True Positive + False Positive). The higher the precision, the more detected objects are actually corresponding to the object of interest. Recall, which measures the detection completeness, is the number of objects correctly detected (TP) over the total number of correctly detected objects and not detected at all (TP+FN, True Positive + False Negative). The higher the recall, the more detected objects are correctly identified. The detection is assumed to be correct when the intersection of two bounding boxes is bigger than a threshold (usually it is equal to 0.5; other thresholds were also used tested).

IMPLEMENTATION AND RESULTS

According to the settings of the experimental design, the result of Eq. (1) is 68, thus meaning that 68 pictures are needed for training and testing in order to come to statistically significant conclusions.

Figure 2(a-c) shows an example from each dataset. The red bounding box is manually drawn during the training stage, and the green bounding box is the detection result that specifies the object local boundary.



(a) Columns **(b) Door** **(c) Windows**

Figure 2. Visual examples from each dataset

Table 1 shows the results of the experiments. The threshold rates (measured in percentages) that were tested were 0.4 and 0.5. It seems that as the threshold increases, the average precision decreases. For the cases of doors and windows, the best result (higher avg. precision) is when the threshold is equal to 0.4 (average precision is 0.704 and 0.299 accordingly). Overall, the best outcome is in the case of columns, where for a threshold of 0.5, the average precision is 0.785.

The algorithm of object category (OC) seems to outperform the VPR models of Zhu and Brilakis (2010) when applied to columns. At precision 84.4%, the recall of OC is 79%, whereas with VPR it is 74.5%. Keeping the recall constant at 74.5%, the precision of OC is 91.5%, whereas for VPR is 84.4%. For doors, the results aren't as high. An explanation to this is probably the repeating edges and corners of the door itself and the door frames, which might confuse each other. Finally, the application on windows seems unsuccessful, since the average precision is quite small, especially compared to the other objects. Two are our observations and possible explanation to this. First, in most of our data, a large number of windows are included in the image and their relative size is much smaller than that of the image, in contradiction to the cases of columns and doors. Second, our dataset includes images of windows formed from smaller ones. Sometimes the OC detects the small windows and some other times it detects the big ones. We conclude that our definition of a window should be changed.

Table 1. Experimental results.

Object	Threshold	Average Precision
Columns	0.5	0.785
Doors	0.4	0.704
	0.5	0.606
Windows	0.4	0.299
	0.5	0.142

CONCLUSION AND FUTURE WORK

Because of the lack of automation in the process currently applied for as-built modeling and the negative consequences it leads, our research has focused towards improving it. This paper initially evaluates a pose-invariant, depth-encoded method for automating the object detection procedure by creating a model for an object category. Images and point clouds are used as input in order to create the model and then detect the object and calculate its distance from the viewer. This paper has explored the potential of the algorithm regarding the creation of the model and its detection capabilities. The results are both promising and satisfactory. Future work includes the registration of 3D point clouds and calculation of the distance between the object and the viewer for training. In addition, more common civil infrastructure objects are going to be modeled and tested.

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A Sparsity-Inducing Optimization Algorithm for the Extraction of Planar Structures in Noisy Point-Cloud Data

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ABSTRACT

Most of the manual labor needed to create the geometric building information model (BIM) of an existing facility is spent converting raw point cloud data (PCD) to a BIM description. Automating this process would drastically reduce the modeling cost. Surface extraction from PCD is a fundamental step in this process. Compact modeling of redundant points in PCD as a set of planes leads to smaller file size and fast interactive visualization on cheap hardware. Traditional approaches for smooth surface reconstruction do not explicitly model the sparse scene structure or significantly exploit the redundancy. This paper proposes a method based on sparsity-inducing optimization to address the planar surface extraction problem. Through sparse optimization, points in PCD are segmented according to their embedded linear subspaces. Within each segmented part, plane models can be estimated. Experimental results on a typical noisy PCD demonstrate the effectiveness of the algorithm.

INTRODUCTION

Traditional Building Information Models (BIMs) represent the conditions under which the building was *designed*. However, the reality of the building's construction can differ from the nominal design; furthermore, changes in building conditions may happen during the entire life cycle of the building. This discrepancy between design and as-built BIMs has recently been a topic of interest in the literature (Huber, D., et al, 2011). Greater use of as-built BIMs is hampered because generating them currently requires manual work and is very time-consuming. Hence, automatic generation of as-built BIMs is of great interest.

Recent developments in laser scanning technology which generate PCDs have led to increased interest in generation of as-built BIMs (Tang, P., et al, 2010). Raw PCD contains the 3D coordinates of discretely measured points. High-level geometric information, such as the presence of embedded planar surfaces, must be extracted from the PCD. As-built BIMs can subsequently be generated using the results of the processed point-cloud data. This work addresses a sub-problem in the extraction of high-level information from PCD: detection of planar surfaces along with an associated parametric description. Robustness in the presence of noise in PCD is handled by posing the problem as a minimization of a sparsity-inducing cost function.

Recently, many practical problems have been modeled as formal optimization problems with sparsity-inducing costs; see refs. (Karasev, P. et al., 2011). The proposed algorithm for surface extraction uses *sparse subspace clustering,* which was designed for segmenting data using embedded lower-dimensional subspace models (Elhamifar, E. et al., 2009). Since the underlying data in point-clouds of interest contain sparsely embedded surface subspaces, sparse subspace clustering can be used to segment PCDs. After which, robust estimation algorithms such as "RANdom Sample Consensus" (RANSAC) can estimate the parametric models of the planar surfaces. From the segmentation step and the estimation step, planar surfaces embedded in the PCD can be extracted with their parametric models.

RELATED WORKS

Techniques for 3D Surface modeling from point cloud data have been widely investigated in the domain of computer graphics. Most of the algorithms are based on building meshes from the point clouds with different explicit representations of surfaces. The problem of representing surfaces was partially addressed by Farin, G., et al., who proposed triangular meshes (Farin, G., et al, 1992) and splines (Farin, G., et al.1996). Although 3D modeling through surfaces meshes gives an explicit description of object's surfaces, it fails to give information of the surfaces' parametric models. Since these modeling techniques lose information of the surface models, they are not suitable to be used in building as-built BIMs.

Different from mesh-based 3D surface reconstruction, model-based surface reconstruction requires the detection and extraction of embedded surface models in point cloud data. Schnabel, R, et al (Schnabel, R, et al 2007) proposed using RANSAC to perform shape model detection. The basic idea behind shape detection using RANSAC is that, given the type of shape to be extracted, estimates of the model parameters are found by sampling the data randomly and checking the ratio of inliers; if the ratio of inliers to outliers is satisfactory, the best-fit parametric model is extracted. Using RANSAC, Yang (Yang, M.Y, et al, 2010) proposed an algorithm for detecting planes as well as estimate model parameters from point cloud data; Tarsha-Kurdi (Tarsha-Kurdi, F, 2008) applied RANSAC in building roof detection. However, the method is limited by the high computational complexity when applying RANSAC to a whole PCD dataset. Also, RANSAC extracts only one model at a time.

Another approach to addressing the problem of planar model extraction from PCD uses the Hough transform. Okorn (Okorn, B.et al, 2010) proposed an algorithm for automatic modeling of floor plans, in which 3D point clouds are projected onto a 2D ground plane to generate a point density histogram, from which walls are detected through the Hough transform. The algorithm requires that the vertical direction be known. Landes (Landes, T., et al, 2007) made a comparison between 3D Hough transforms and RANSAC for automatic detection of planes from point clouds, and found that RANSAC is better than the 3D Hough-transform in speed and percentage of successful detections. Ioannis (Stamos, I., et al, 2000) proposed a planar surface extraction algorithm by fitting local planar surfaces and clustering with co-normality and co-planarity metrics.

This paper focuses on solving the problem of extracting the planar surfaces from PCD, the goal of which includes detecting the embedded planar surfaces and

estimating the model parameters simultaneously. Compared to the existing algorithms above, the work of this paper addresses the problem in a new theoretical framework based on sparse optimization.

PROPOSED ALGORITHM

The proposed algorithm is novel in two aspects: 1) the extraction of planar surfaces is based on a new procedure that first segments the PCD after which parametric models of the planar surfaces are estimated using RANSAC to find a consensus-set in each segmented region. PCD segmentation is achieved by posing sparse subspace clustering as an optimization problem; 2) the sparse subspace clustering step is improved with the mean-shift non-parametric robust clustering technique, which does not require prior knowledge of the number of subspaces.

Performing segmentation on the point cloud before estimation using RANSAC greatly lowers the computation cost of RANSAC and increases the success rate of plane detection. Reciprocally, RANSAC estimates the plane models robustly even with possible misclassifications in the segmentation step, thereby increasing the robustness of the whole algorithm.

Sparse Representations in Subspaces. Sparsity-inducing optimization algorithms are based on sparse representations. Consider a vector $x \in \mathbb{R}^D$ representable in a basis $\psi_i \in \mathbb{R}^D, i = 1,2 \dots, D$, where x can be written as $x = \sum_{i=1}^{D} f_i \; \psi_i$. Often x cannot be measured directly but only its k combination y can be measured,

$$y = \sum_{j=1}^{k}[\varphi_j \cdot (\sum_{i=1}^{D} f_i \; \psi_i)] = \varphi\psi \cdot f = \Phi f,$$

where $\varphi = [\varphi_1, \varphi_2, \dots, \varphi_k]^{\mathrm{T}} \in \mathbb{R}^{k \times D}, \psi = [\psi_1, \psi_2, \dots, \psi_N]^{\mathrm{T}}, f = [f_1, f_2, \dots, f_N]^{\mathrm{T}}$. In many cases, x has a sparse representation in the proper basis Ψ. When formulated correctly, the sparse representation of x is recovered by solving the optimization problem (Cand´es,et al,2005; Baraniuk ,et al,2008):

$$\min \;\; \|f\|_0 \quad s.t. \, y = \Phi f; \text{ where } \|f\|_0 \text{ is the L0-norm of } f.$$

The work of Donoho (Donoho, D. L.,2006) showed that the solution to the above problem is obtained by solving the following convex optimization problem:

$$\min \;\; \|f\|_1 \quad s.t. \, y = \Phi f; \text{ where } \|f\|_1 \text{ is the L1-norm of } f.$$

For the case that the signal lies in a union of m disjoint low-dimensional linear subspaces with dimensions of d_i, i=1,2…, m, then

$$y = [\Phi_1, \Phi_2, \dots, \Phi_m] \cdot [f_1^{\mathrm{T}}, f_2^{\mathrm{T}}, \dots, f_m^{\mathrm{T}}]^{\mathrm{T}} = \Phi \cdot f.$$

PCD Segmentation via Sparse Subspace Clustering with Mean-Shift. Based on the sparse representation theories stated in Section 3.1, an algorithm was proposed (Elhamifar, E. et al., 2009) for clustering the sparse subspaces embedded in a higher dimensional space. Let $\{ S_i \}_{i=1}^{m}$ be a union of m independent linear subspaces of dimensions $\{ d_i \}_{i=1}^{m}$ embedded in a k dimensional space, and $\{ y_i \}_{i=1}^{N}$ be a collection of N observations from the k dimensional space, $y_i \in \mathbb{R}^k$. If y_i belongs to subspace S_j, then y_i can be represented as a linear combination of all the other data points in $\{ S_i \}_{i=1}^{m}$. When y_i is written as a linear combination of points in its own

subspace, the representation is the sparsest. This sparse representation can be obtained by using L1 minimization:

$$\min \|f_i\|_1, s.t. y_i = \Phi_i \cdot f_i, \text{for every data point } y_i \text{ in } \{ y_i \}_{i=1}^N$$

where $\Phi_i = [y_1, y_2, \dots, y_{i-1}, y_{i+1}, \dots, y_N]$. This is the Basis-Pursuit formulation of L1 minimization for the linear subspace case. Taking noise into consideration and using the Lasso Optimization algorithm (Tibshirani, R., 1996), the optimization problem can be formulated as a Basis-Pursuit denoising problem.:

$$\min \|f_i\|_1 + \gamma \|y_i - \Phi_i \cdot f_i\|_2, \text{for every data point } y_i \text{ in } \{ y_i \}_{i=1}^N$$

where γ is a positive constant.

After getting the sparse representation of every data point y_i, the matrix of coefficients $\Phi = [\Phi_1, \Phi_2, \dots, \Phi_N] \in \mathbb{R}^{N \times N}$ can be obtained. Let ϕ_{ij} be the element in matrix Φ, then a similarity graph can be formed with N nodes each representing a data point in $\{ y_i \}_{i=1}^N$, and form the edges between each two nodes with the weight of $w_{ij} = |\phi_{ij}| + |\phi_{ji}|$ for the edge connecting node *i* and node *j*.

To cluster the data, spectral clustering is applied to the similarity graph. First form the Laplacian matrix L of the graph, $L \in \mathbb{R}^{N \times N}$, then use clustering algorithm to cluster the data from eigenvectors of L. In (Elhamifar, E. et al., 2009), the *k*-means clustering algorithm is used in this step. However, *k*-means requires the number of clusters to be known before performing the clustering. Also, *k*-means makes the assumption that the clusters are shaped spherically in the space of the distance defined. Unlike *k*-means, mean-shift (Cheng, Y., 1995) clustering is a non-parametric algorithm which iteratively computes the mean shift vector by translating density estimation windows until convergence. Mean-shift clustering makes no assumptions about number of clusters. Also, it can handle arbitrarily shaped clusters because it is based on density estimation. Mean-shift with sparse subspace clustering method is thus more suitable to the current surface-extraction application.

Estimate Plane Models using RANSAC. After segmenting the PCD, RANSAC is applied to extract plane models in each segmented area. The RANSAC algorithm for planes extraction is as follows: Given a segmented part of the PCD, repeatedly sample randomly 3 points from the PCD to get an estimated plane model M_{p_i} from a least-squares fit. With the estimated plane model, points in the PCD will be classified as inlier if their Euclidean distance to the estimated plane is smaller than a threshold. Next, the percent of inlier points in the whole segmented area is computed. After sampling a certain number of iterations, the estimated M_{p_k} with the largest inlier rate is extracted.

The boundary of each extracted plane model can be obtained by finding the convex hull of the set of inlier points. A robust and efficient algorithm of finding convex hull from a given point set was presented by Kirkpatrick, D. (Kirkpatrick, D., et al, 1986), with which the supporting point set $\{P_{Sj}\}_{j=1}^J$ forming the convex hull can be extracted. The convex hull found from the inlier set of an extracted plane model forms the support domain of that plane. The collection of $\{M_{p_k}\}_{k=1}^K$ and the

supporting point set $\{P_{Sj}\}_{j=1}^{J}$ from each segmented area is the final output, which is the collection of the planes extracted from the whole input PCD.

Final Steps of the Proposed Algorithm. The final steps of the complete algorithm are as follows:

Algorithm: Planes Extraction from PCD via Sparsity Optimization

Input: A point cloud dataset $\{y_i\}_{i=1}^{N}$ with m linear subspace $\{S_i\}_{i=1}^{M}$

1. Solve the basis-pursuit denoising optimization problem: $\min \|f_i\|_1 + \gamma \, \|y_i - \Phi_i \cdot f_i\|_2$, for every data point y_i in $\{\, y_i \,\}_{i=1}^{N}$;
2. Use the coefficient matrix Φ to form a similarity graph $\widetilde{\boldsymbol{G}}$ with N nodes representing $\{y_i\}_{i=1}^{N}$ and edge weights of $w_{ij} = |\phi_{ij}| + |\phi_{ji}|$; then compute the Laplacian matrix L of $\widetilde{\boldsymbol{G}}$;
3. Perform Mean-shift Clustering in the eigenvectors space in Laplacian matrix L and get the segmentation result of the PCD;
4. Apply RANSAC in each segmented part to extract the embedded planes and estimate the plane model M_{p_k}; determine the boundary of the support domains of each extracted planes using convex hull;

Output: The collection of extracted plane models $\{M_{p_k}\}$ the supporting point set $\{P_{Sj}\}_{j=1}^{J}$ forming the support domain of each extracted planes.

EXPERIMENTAL RESULTS AND DISCUSSION

This section presents experiment results of the proposed plane extraction algorithm. Based on the experimental results, comprehensive evaluation of the algorithm will be made, including three aspects: (1) extracted surface parameters error; (2) point cloud segmentation correct rate; (3) visualization complexity.

First we use a synthetic PCD consisting of 1180 noisy points for experiment. In the experimented PCD, there are four embedded planes with intersecting parts between some the planes. Moreover, there are some clutter points in the PCD.

Figure 1 depicts the experimental results using the proposed algorithm. In the top-right, even though there are some intersecting parts between the embedded planes and clutter in the PCD, the segmentation result has high accuracy. The error rate of the segmentation is 3.88% with 46 of the 1180 points wrongly segmented. The errors in the final extracted planes shown in **Figure 1** (bottom left) is evaluated as follows: Given the plane model $\mathrm{ax} + \mathrm{by} + \mathrm{cz} + \mathrm{d} = 0$, the coefficients of the extracted plane models are found in **Table 1**. The coefficients of each plane model in **Table 1** are normalized, for improved comparison, so that the largest absolute value among $\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}$ is equal to 1. **Table 1** shows that the proposed algorithm achieves a small absolute error between the resulted plane models and the ground truth plane models. The result of supporting domains in **Figure 1** (bottom right) depicts the final sparse representation of the original point cloud. If any prior knowledge is known about the shape of the planar patches, the support domain boundary can be improved.

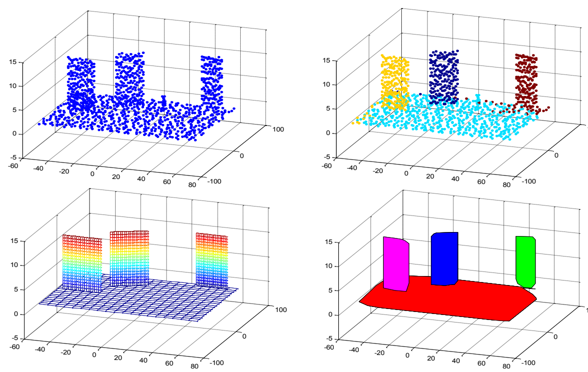

Figure 1: **Results of proposed algorithm. Clockwise from top left: original PCD, segmentation result, planar surfaces extracted; final extracted planar patches.**

Table 1. **Errors between ground truth and the extracted models (Plane 1 and 2).**

		Coefficients of extracted plane models			
		a	*b*	*c*	*d*
Plane 1	Ground Truth	-6.6667e-1	1	0	-43.3333
	Results	-6.6607e-1	1	- 1.3369e-3	-43.3306
	Error	-6 e-4	0	- 1.3369e-3	-0.0027
Plane 2	Ground Truth	0	0	-1	0
	Results	3.8624e-5	-1.3676e-4	-1	-4.0352e-3
	Error	3.8624e-5	-1.3676e-4	0	-4.0352e-3

Figure 2 depicts the approach of building Delaunay triangular meshes on the inlier set of each segmented area (without projection to the planar surfaces). The model surfaces are not planar and have a less compact surface description. To validate the hypothesis of reduced model description size, the resulting models are ouput to 8-digit ASCII data files. With the extracted results, the final representation is significantly smaller than the original representation. The size of the original PCD is of 59,250 bytes, while the size of the final representationis 3,186 bytes. The compression rate of the data is 94.6228%, which demonstrates that the proposed algorithm results in smaller file sizes. Building a Delaunay triangular mesh results in an output data size of 161,300 bytes, which is larger in size than the original PCD file.

To evaluate the interactive visualization speed between different representations, renderings with the representations of different algorithms are performed on a PC with a 2.80GHz Intel Core i5 CPU and 8GB RAM, using MATLAB R2010B Version. The average rendering time is provided in Table 2. Table 2 demonstrates that the representation of the proposed algorithm achieves the least rendering time and faster interactive visualization speed on cheap hardware.

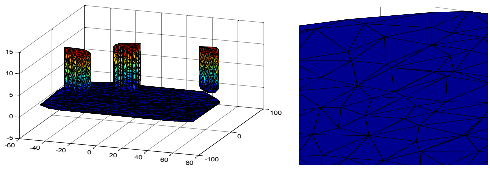

Figure 2. Left: the Delaunay triangular meshes built on the inlier set of each segmented area; Right: the detailed triangular meshes built on the floor plane.

Table 2. Rendering time of different representations.

Representation	Point clouds	Triangular meshes	Proposed algorithm
Rendering Time (sec)	0.037065	0.016738	0.006355

Note that the proposed algorithm is able to support civil engineering by extracting the embedded planar models in the scanned data of infrastructures and help build the Building information models. Following is an experiment that proposed algorithm is applied to a real bridge scanned data, as shown in **Figure 3 (Left)**.

In this PCD, there are 61217 points. The whole PCD was first partitioned into smaller parts with the dimensional size 30x30x30. Then the proposed algorithm was applied to each partitioned PCD. Finally the extracted planar surfaces with the difference of parameter models lower than a certain threshold are merged into one common plane. **Figure 3 (Right)** is the middle part of the bridge PCD with the planar surface of the road of the bridge detected and extracted by the algorithm. The estimated parametric model is: $-0.0234145x+0.0489097y-0.998529z=17.004$, while the ground truth is $0.0234x+0.05y-z=17$. Because the algorithm employs the robust statistical estimation method RANSAC in one of the step, the algorithm result is robust PCD noise. For instance, in the result above, although with the PCD noise from the tree on the bridge, the extracted plane model is still of high accuracy.

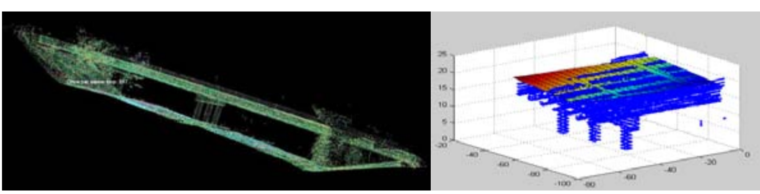

Figure 3. Left: Bridge PCD; Right: the extracted plane of the road of the bridge.

CONCLUSION

This paper presents a novel algorithm for extracting embedded planes from point cloud data (PCD). Given noisy PCD with embedded planar surfaces, the final output of the proposed algorithm is a set of parametric models of the planar surfaces. The PCD is clustered and segmented by finding the embedded planar subspaces, via a sparsity-inducing optimization. The sparse subspace clustering method is improved by using mean-shift, so that number of the embedded planar surfaces is not required before performing clustering. After segmentation, parametric models of the planar surfaces are estimated using RANSAC to find a consensus-set in each segmented

region. Experimental validation of the approach demonstrated that the planar models are well estimated, and the final surface representation is compact.

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Projection-Recognition-Projection (PRP) Method for Rapid Object Recognition and Registration from a 3D Point Cloud

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ABSTRACT

This paper introduces a model-based automated object recognition and registration method, Projection-Recognition-Projection (PRP), to assist heavy equipment operators in rapidly perceiving 3D working environment at dynamic construction sites. It has been a challenging subject to recognize target objects from a scattered work environment because large and complex 3D site data obtained by a laser scanner makes it difficult to process itself in real or near real time. In this study, a CCD camera and a hybrid laser scanner were used to rapidly recognize and register dynamic target objects in a 3D space by separating target object's point cloud data from other background point cloud data for quick process. The experimental results were promising in terms of modeling speed and accuracy. If successful, as an on-going project, the proposed PRP method can significantly improve heavy construction equipment operations and automated equipment control by rapidly modeling dynamic target objects in a 3D view.

INTRODUCTION

Safe construction and operation of heavy construction equipment such as cranes, excavators, concrete pump trucks has been considered a very important subject in construction fields. It would be helpful for the operators if the accurate 3D position of the target objects and surroundings are readily available. Besides using stereo vision, one of the common methods to obtain the precise 3D position of the objects is based on 3D laser scans (Tang, et al. 2010; Huber, et al. 2010), which,

however, has several obvious disadvantage, such as low speed and low object recognition rates (Kim et al. 2011). Also, it has been a challenging subject to recognize specific objects from a 3D laser point cloud in unstructured construction environments. This is because the 3D point cloud data set obtained by a laser scanner is quite large and complex so that it is difficult to separate the target objects from other interferences in a short period of time. In addition, the surrounding objects like trees, people, and common stuffs, cause interferences to the recognition process, so it is necessary to develop a specific method to exclude such interferences and to keep only the scenes needed for the target object recognition and registration process.

Currently, many researchers are working on the similar topic, and proposed several methods, such as context-based modeling (Antonio et al. 2011; Xiong and Huber 2010), which is able to automatically model and identify the main structural components in an indoor environment. Kim (2011) proposed a method to register a 3D CAD model to point clouds using photogrammetry approach. However, most of the studies emphasize on the components with primitive shapes, such as a rectangle and a circle; few works have been done on the recognition of objects with irregular shapes, such as heavy equipment. Meanwhile, the registration process is time-consuming and manual (Shih and Wang 2004; Bosche 2010; Son and Kim 2010). Also, there were some studies proposing a method projecting models to images. Lowe (1992) projected a model into a image plane. Correspondences were determined by analyzing image features that were close to a projected visible model entity. A probabilistic approach was used to select the best match in his research. Once correspondences have been established, numerical minimization was used to determine object's rotation and translation values. However, when computing the perspective projection of a three dimensional model, occlusions have to be taken into account. In the method proposed by Wunsch (1996), a CAD model was registered into images by iterative inverse perspective matching. However, there was not distance metric relating 3-D point coordinates to 2-D image coordinates, so Wunsch could not apply the closest point principle to the registration of a 3-D model to a perspective image.

In this study, a new method was developed in order to automatically recognize complex objects from a 3D laser point cloud scene. In this study, a CCD camera was used to initially recognize a target object and an area containing the target object. To rapidly process recognition and registration of target object in a 3D space, a point cloud in the target area was separated from other background point clouds. Then, the separated point cloud of target object was projected onto different 2D planes from multiple different views. By finding matching views from the previously built 3D model library, the position and orientation of the target was determined and the target's CAD model was registered to the point cloud data. The whole process can be summarized in the three steps, projection, recognition and projection (PRP).

METHODS

The framework of the proposed PRP method is illustrated in Figure 1.

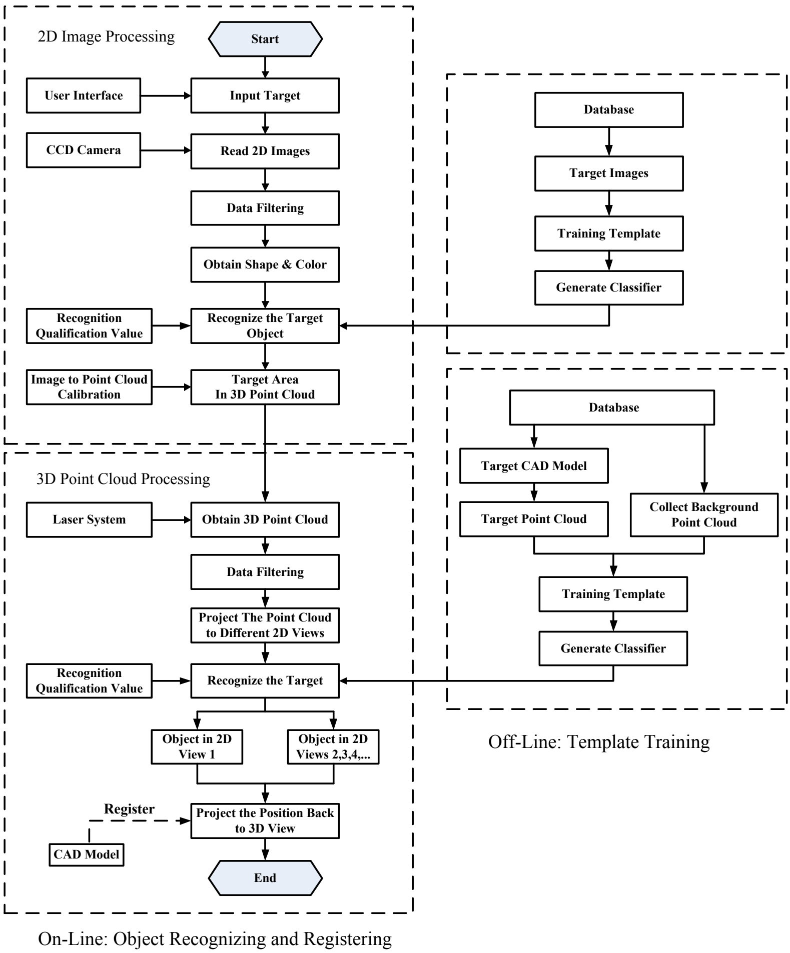
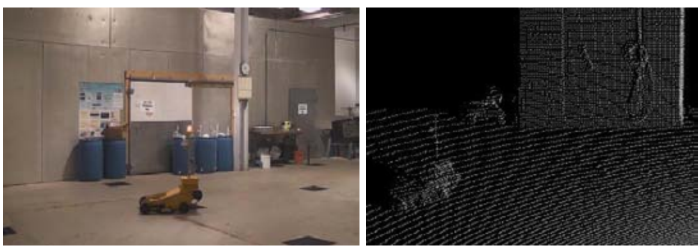


Figure 1. The framework of the proposed PRP method

The PRP process is as follows: (1) a target is selected by users through a user interface; (2) 2D images are obtained from a CCD camera; (3) these 2D images are filtered through removing noises, of which shape and color feature is fetched from the results; (4) the target object is recognized automatically from the 2D images, while

the position area is also obtained with corresponding values in Cartesian coordinates; (5) the target's area obtained above is transferred into a 3D point cloud view, where the target is further recognized and the prepared CAD model from a model library is registered (6) 3D point-cloud data in Cartesian coordinates is obtained by a 3D laser scanner; (7) 3D point-cloud data is filtered according to the distance information; (8) filtered point cloud data in the area obtained above is projected into different 2D planes from several different views; (9) the object is recognized automatically from the 2D planes, while the positions are also obtained with corresponding values in Cartesian coordinates; (10) the values obtained from 2D planes are projected back to the corresponding ones in the 3D view; (11) the object is recognized and an existing CAD model is registered to the point cloud data based on the recognition results. In the experiment, a mobile robot was used as a target object as shown in Figure 2.



(a) **(b)**

Figure 2. Mobile robot (a) and a single scan point cloud scene (b)

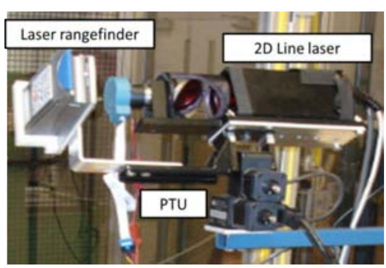


Figure 3. The hybrid 3D laser system developed by the research team

Data Filtering. A CCD camera obtains 2D images of target object and the area (x-y plane) containing the target. The scan depth can be optionally measured by the laser rangefinder of hybrid laser scanner system (Figure 3) in the obtained area around the target (z-axis direction). Then, the laser scanner automatically scans around the bounding box by excluding other unimportant features. Or, pre-scanned data can be filtered later based on the measured area volume information (Figure 4). The proposed data filtering method is useful when it is necessary to exclude unimportant background surroundings from the scanning process, thus increasing a scanning speed and reducing a scanned data size and data processing time.

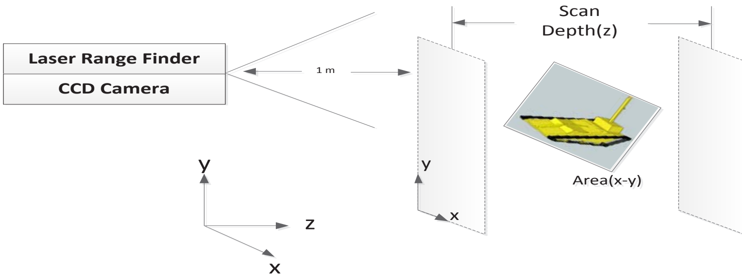


Figure 4. Illustration of filtering a data acquisition zone

3D to 2D Projections. After obtaining the point cloud data, the 3D point cloud is projected into different 2D planes from different views. The principle of the projection process is shown in Figure 5. A 3D object, mobile robot, is in the center, and different projection angles can be randomly selected from the laser scanning direction (e.g., 90 degree or 45 degree). Here, a distance value is also obtained from the 3D point cloud to the 2D projection plane, based on which 2D image data are collected and displayed. The projection results are shown in Figure 6, including the 3D point cloud data and the 2D projection planes of the mobile robot.

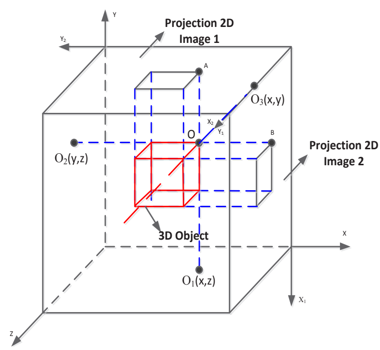


Figure 5. 3D to 2D projection process

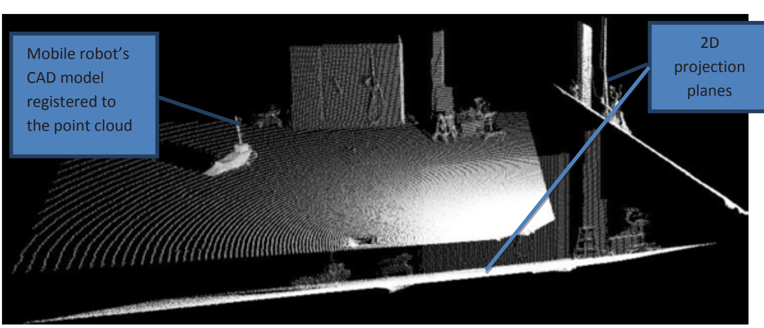


Figure 6. Randomly created 2D projection views of a point cloud

Target Object Recognition. The following steps mainly focus on illustrating how to recognize a target object from 2D images. The steps include: (1) collecting the templates of the object mobile robot in 2D images, and training the classifiers based on Haar-features (Viola and Jones 2001); (2) reading the 2D images and the trained classifiers (Viola and Jones 2001); (3) using the classifiers to localize the positions of the objects in images, here a threshold rate value is set in order to guarantee a high recognition rate (Lienhart and Maydt 2002). Figure 7 shows the initial recognition results of a mobile robot by a CCD camera.

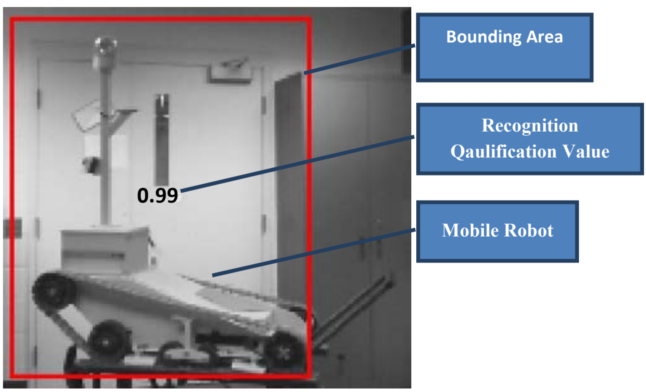


Figure 7. Initial recognition of a mobile robot from a CCD camera

Register a 3D CAD model to a Point Cloud. After localizing the object mobile robot in 2D images, the position of the object in a 3D view is calculated according to the principle discussed in Figure 5. In this process, assuming the projection point of the object's left corner point O in image 1 is point A, in image 2 is point B, while the point A is corresponding to point O1(x,z) in X-Y plane and point B is corresponding to point O2(y,z) in Y-Z plane. Therefore, the coordinate value of point O in 3D view system is (x, y, z), which is the combination of point O1 (x, z) and O2 (y, z). After obtaining the coordinate value of each corner of the object, an existing CAD model from a database, which has same dimension with the real model, is registered according to the coordinate values of the object in a 3D view. An example of registered model result is shown in Figure 8.

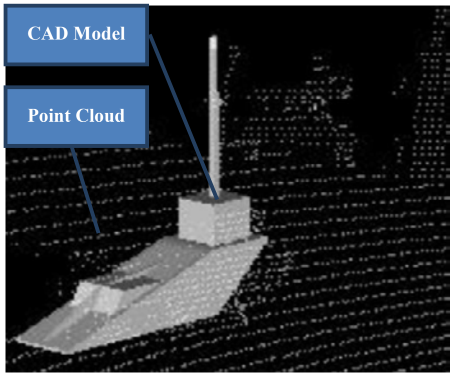


Figure 8. Results of registering a 3D CAD model to a single scan point cloud

CONCLUSIONS

In this paper, a new automated object recognition and registration method, Projection-Recognition-Projection (PRP), was introduced to assist the heavy equipment operators in rapidly perceiving 3D working environment at construction sites. The test results showed that the proposed method was theoretically sound, and the overall target object recognition and registration results were promising in terms of speed and accuracy. If successful, the proposed method can significantly improve the operations of heavy construction equipment or automated equipment by rapidly recognizing and registering target objects in a 3D space from a scanned point cloud scene. As an on-going project, this research plans to conduct outdoor tests in heavy equipment construction sites to validate the proposed PRP method in real world situations.

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Utilizing BIM to Improve the Concrete Reinforcement Supply Chain

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ABSTRACT

Using Building Information Modeling (BIM) for design, detailing, fabrication and erection of concrete reinforcement and automating information exchange throughout AEC projects potentially improves productivity of the reinforcement supply chain. This study first develops an information flow process map documenting the reinforcement supply chain activities, and identifying the contents of the reinforcement models, created and exchanged by different disciplines during various phases of a concrete project. Then the identified information items are used as a basis to assess the functionality of BIM tools for reinforcement. BIM tools are evaluated in four areas: design and modeling, editing, project and construction management, and interoperability. The IFC schema is chosen as the preferred medium to examine the interoperability capabilities of the evaluated BIM tools. Our study identified significant enhancements in 3D parametric modeling and information interoperability of concrete reinforcement. Despite these improvements, notable modeling and interoperability deficiencies in the reviewed BIM tools remain unsolved. These shortcomings impact the modeling outcome and hinder effective use of BIM reinforcing models generated in design during fabrication and construction management. Recommendations to improve the identified shortcomings in all the four reviewed areas are provided.

INTRODUCTION

The Architectural, Engineering and Construction (AEC) industry has realized continuous progress in the productivity of the concrete reinforcement supply chain over the last two decades. Among improvements in the design and detailing stages, Building Information Modeling (BIM) has facilitated major advances as an enabling tool to provide interoperable and reusable information throughout the life cycles of the AEC projects (Barak et al. 2009). However, there is a lack of research to assess capabilities of the available BIM tools for concrete reinforcement, and to identify the areas that need further improvement.

This study documents the information flow throughout the reinforcement supply chain based on best practices identifying information exchange items for

reinforcement provided by different disciplines and in various phases of projects. In light of the identified design and detailing models' contents, the capabilities of BIM tools are evaluated in four areas: design and modeling, editing, project and construction management and interoperability. Our study identified numerous enhancements in the reviewed BIM tools in all the four reviewed areas. Despite the significant improvements in parametric modeling of reinforced concrete and implementing IFC import and export interfaces in the recent years, notable technical shortcomings remain unsolved. Examples of the important shortcomings are: lack of modeling capability for prestressing elements in most of the reviewed tools, inadequate capabilities to model custom-designed meshes and cages in some of the reviewed tools, difficulty of modeling reinforcement for complex geometries, lack of features to optimize design based on the production process, and insufficient interface with production planning and management, and project management tools.

These shortcomings hinder error-free and effective use of the models to coordinate with parallel design and detailing efforts. Furthermore, reusing model information in downstream activities like on- and off-site reinforcement production and management activities is inhibited. Thus, recommendations are provided to improve BIM tools' performance in reinforcement design and detailing, to better coordinate BIM-enabled design with other disciplines in the project and to reuse the information in the created models throughout project lifecycle.

BIM IMPLEMENTATION IN REINFORCED CONCRETE

In the design and detailing stages of AEC projects, BIM processes have quickly been adopted (Eastman et al. 2011), replacing non-parametric 2D and 3D CAD. Adopting parametric modeling is a critical requirement to implement BIM (Eastman et al. 2011).Without implementing parametric modeling mechanisms (Lee et al. 2006) most benefits of BIM like automatic propagation of changes in the objects related by defined design constraints, automatic update of the design views based on changes in associated views, and managing and reporting attributes can't be obtained.

Several software packages are now available for 3D parametric design and detailing of precast and/or cast-in-place reinforced concrete. However, a recent survey by the Concrete Industry's Strategic Development Council (SDC) shows that most firms still don't use BIM in design, detailing and manufacturing of the reinforced concrete. Among disciplines involved in the concrete projects, contractors and reinforcement manufacturers represent a lower rate of BIM adoption compared to architects and engineers (SDC 2009). The SDC survey indicates that BIM capabilities for clash detection, code compliance checking, estimation, scheduling, and project coordination are not utilized by most BIM adopters.

Software interoperability enables the cost-effective information exchange among various domain-specific BIM tools without requiring IT technical expertise for users (ISO 1993). Industry Foundation Classes (IFC) (Liebich et al. 2011) and CIS/2 (Crowley and Watson 2000), are the main neutral and open data model standards developed to facilitate AEC interoperability. In a survey of the areas of desired improvement to enhance the value of BIM, the top two were identified as improved functionality of and improved interoperability between BIM software applications, by 80% of surveyed BIM users (McGraw Hill 2009). Thus, it is important to identify the

potential areas where future improvements can optimize the supply chain by streamlining the information exchange and removing non-value adding activities.

REINFORCEMENT SUPPLY CHAIN: THE INFORMATION CREATION AND EXCHANGE PROCESS MODEL

The process maps developed for the Precast Concrete Institute (PCI) National BIM Standard (NBIMS) project (developed by the authors in coordination with PCI members [PCI 2009]), served as the starting point for development of the high-level process map for the reinforcement information process. Then the detailed information flow model for the concrete reinforcement was developed and coordinated with industry experts. Some members of the American Concrete Institute (ACI) technical committee on BIM were asked to review and validate the process model. We have used the Business Process Modeling Notation (BPMN) (Ouyang et al. 2009) to represent the process map of business operations used in the concrete reinforcement supply chain. Part of the developed process map is shown in Figure 1. Process map design principles and BPMN are explained in (Aram et al. 2010).

The EM-series depicted in Figure 1 represent BIM model information exchanges while the B-series represent non-model information exchanges. Most of the information exchanges are round trip in nature as the recipient provides review comments and might request changes in the original model. Currently, review comments are primarily sent in the non-model formats.

Creating reinforcement related information in models usually starts during the design development stage with the structural engineer designing the initial reinforcement types using the architectural design model for design intent and geometric information. The model shown as EM.2 is passed to the reinforcement detailer for initial layout design. EM.3 represents the transfer of rebar details to the fabricator for review and/or estimating at this stage. The structural design and reinforcement detailing models are then elaborated and completed during the next phases of the project, providing EM.5, 6, 7, and 8.

The structural engineer determines reinforcement design, including rebar shape, size, spacing, and splicing type and requirements, defined based on different standards. The reinforcement detailer models and locates reinforcement elements and assemblies in the elements making up the physical model as well as the details needed to fabricate and place reinforcement like hooks, hoops and ties.

BIM tools should enable utilizing the models in various project and construction management activities. For instance, information provided in the detailing models should be adequate so that modelers can directly extract accurate reports like bar bending schedules and shop or placing drawings. Bar bending schedules and material take-off reports are used to manage ordering, production planning and control, and fabrication of reinforcement. The bending schedules should contain the shape, grade, size, length, weight, and mark properties for all the reinforcement types used in the model. Material take-off reports also include total weight of different designed reinforcement grades.

Detailing models in cast-in-place concrete are called placing drawings as they facilitate on-site installation of reinforcement. Placing drawings should represent layout and requirements of bar supports and form accessories, and preferably the

placing sequence. The design and detailing models must be coordinated with the other parties involved in the project like reinforcement fabricator, concrete subcontractor, and general contractor.

The coordination can be for different purposes including but not limited to rule checking, clash and conflict checking, and constructability review. Other important applications of BIM in construction management are to provide erection sequences and 4D schedules that help the construction team better understand the structure and identify possible constructability issues and schedule conflicts. 4D schedules can also be used for production, delivery and erection planning.

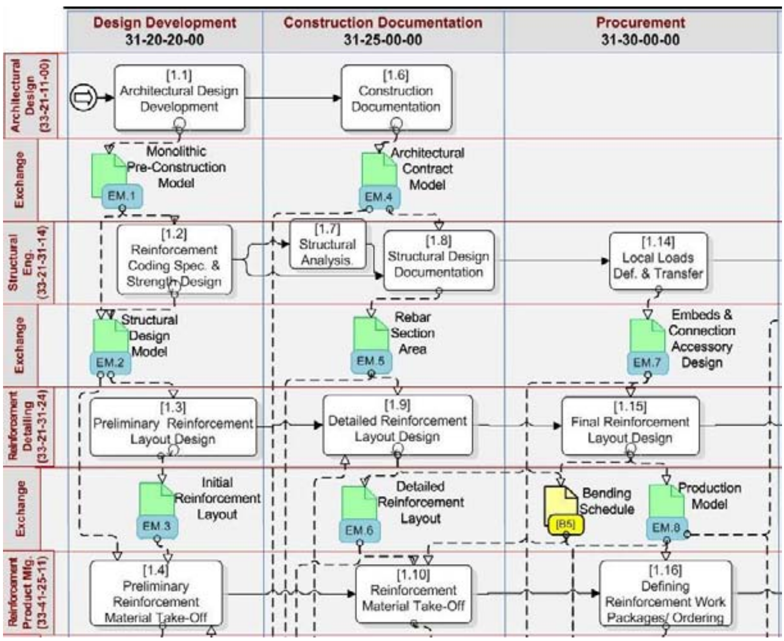

Figure 1. Part of the concrete reinforcement information creation and exchange

MODELING REINFORCEMENT WITH BIM AUTHORING TOOLS

A detailed evaluation of current capabilities of BIM tools identifies BIM development trends for reinforcement, finding gaps in using BIM during reinforcement supply, and also supports providing product recommendations.

Based on the authors' review, currently there are five major software packages that provide 3D parametric modeling capabilities for concrete reinforcement. They include Autodesk Revit Structure (including Revit Precast Tools extension) for structural modeling, Scia Engineer for structural modeling and analysis, and the three detailing packages of Bentley ProConcrete (including Applied Systems Associates (aSa) built-in features), Allplan Engineering (including Allplan Precast extension)

and Tekla Structures (including Precast Concrete and Reinforced Concrete configurations).

We reviewed these tools to evaluate their capabilities in the concrete reinforcement area, in four categories of modeling: design and modeling, editing, project and construction management, and IFC-enabled interoperability. The reviewed software versions were as follows: Autodesk Revit Structure 2012 and Scia Engineer 2011, Bentley ProConcrete V8i, Allplan Engineering 2012, and Tekla Structures 18.0. Component representational completeness, design-customizing options, supported standards, options for creating reports and 4D schedules, and IFC exported reinforcement elements and their attributes were among the important evaluated areas.

Design and Modeling. All five products model rebar with standard rebar bent shapes, rebar stirrups and tie hooks, and standard mesh. In addition to 3D geometric representation of reinforcement elements users can define rebar properties like bar type, size and grade. Concrete covering and rebar spacing parameters can also be determined by users. These design properties are defined based on the implemented standards in the software packages such as ASTM specification and national standards like ACI-318.

However, features for modeling custom-designed rebar bent shapes, cages, and meshes are mainly available in the three detailing software tools. Engineered-mesh is custom-designed mesh that optimizes the reinforcement design by using project-specific sheet geometry and reducing on-site cutting and fixing work. Designing reinforcement mesh to reinforce polygonal or circular elements and using bent rebars in the mesh are enabled in the three detailing packages. Furthermore, custom-pattern mesh can be created in Allplan Engineer and Tekla Structures, applying multiple bar diameters and variable spacing.

Pre- and post-tensioned concrete components can be designed and analyzed only in Scia Engineer and detailed only in Tekla Structures. Both software packages provide modules to define tendon (strand) properties like size, grade, and debonding length as well as most profiles and spacing information for tendon patterns.

Modeling reinforcement for building elements of various forms is continuously being improved. Multi-planar bent rebars used in concrete elements such as stairs and corbels can be modeled not only in the detailing tools but also using Revit Structure (Figure 2a). Further, modules for easier reinforcement of curved elements are provided in Allplan Engineer and Tekla Structures. Allplan Engineer supports enhanced capabilities to reinforce polygonal and free-form curve building elements (Figure 2b & 2c). Scia Engineer provides tools for modeling and analyzing free-form structural elements. The three detailing packages provide automatic splicing of reinforcing bar using a catalog of standard bars to cut rebars to the correct length. While ProConcrete currently only supports lap splices, the other two detailing tools support both predefined mechanical splices and lap splices.

Editing. All the reviewed software packages enable propagation of changes in model objects to all 2D and 3D views, using parametric modeling and associating objects through geometric relations. In Revit Structure, Tekla Structures, and ProConcrete, associating the designed reinforcement to the building elements like slabs, beams and columns, facilitates automatic update of reinforcement according to

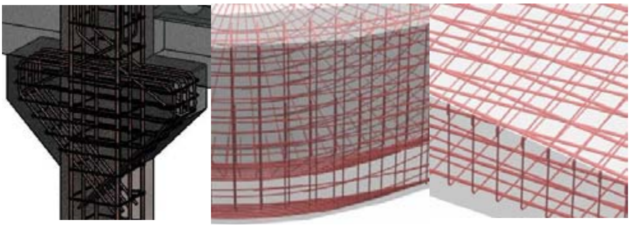

Figure 2. From left to right (a) Corbel reinforcement design in Revit Structure, (b) Allplan Engineer reinforcement modeling in circular (c) sloped polygonal element

changes made in building element geometry. Some level of reinforcement grouping capabilities, based on similarities in rebar properties like size or grade is available in all reviewed software. This capability simplifies modification of big numbers of rebar. Further, in Revit Structure, Tekla Structures, and Allplan Engineer levels of assembly hierarchies can be created to distinguish groups of reinforcement with common functionality.

Project and Construction Management. Users of Revit Structure and the three detailing packages can directly provide customized bar bending schedules and material take-off reports. Properties in the bending schedules can be customized by adding categories like grade, size, total length of rebars with particular shape, and type mark.

One of the capabilities that the three detailing packages and Revit Structure embrace is filtering reinforcement based on different properties. The filtering feature helps manage production and transportation of reinforcement components. For instance, rebars exceeding a certain length might need a specific transportation arrangement and can be easily identified. Revit Structure and Allplan Engineering provide limited 4D scheduling capabilities through assigning project phasing to reinforcement elements. Tekla Structures takes this to the next level by providing various time-related properties for tasks and a task management tool.

Interoperability. To leverage the value of 3D parametric models created in the reviewed packages, BIM models must be exchanged seamlessly with other platforms used in the reinforcement supply chain. For cross-disciplinary coordination, information exchange with other design, analysis and detailing platforms, and also with downstream programs used in project management, production planning and management, and CNC machines is necessary. All the reviewed software packages have developed several methods to exchange model data with other platforms that perform in different levels of success.

The IFC schema's capabilities in providing neutral and comprehensive product modeling information throughout the AEC/FM project lifecycle (Liebich et al. 2011) has made it the preferred interoperability solution. Despite efforts of software vendors to improve the IFC interface of their products, IFC import and export capabilities for reinforcement remain inadequate, making IFC-based interoperability the weakest of all the four evaluated categories. Currently, Allplan Engineer, ProConcrete and Tekla Structures export some level of the reinforcement

information through IFC standard. Rebar exported by Allplan Engineer are represented as IFCFacetedBrep entities. The Brep method represents geometry as a set of faces and lacks geometric parameters such as diameter and length, not allowing parametric editing. Tekla Structures and ProConcrete export single rebars using extruded solid geometry representation and map them to the IfcReinforcingBar. Allplan Engineer hasn't developed a reinforcement object converter to recognize and map reinforcement elements with the corresponding IFC entities. As a result reinforcement elements are listed as IFCBuildingElementProxy; hence, the exported models must be manually interpreted.

In the examined test files, identification attributes including name, type, geometry type, IFC GUID and the BIM tool's ID, as well as location attributes and quantity attributes of bottom area and volume are exported by the three detailing software tools. Some engineering attributes of reinforcement elements are now exported as well. Main attributes common in the Allplan Engineer, and Tekla Structures' reviewed test files include length, grade, and size of the rebar (Figure 3).

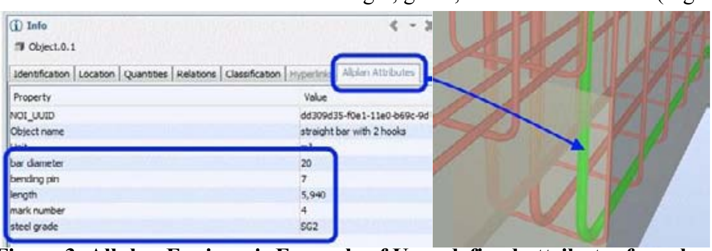

Figure 3. Allplan Engineer's Example of User-defined attributes for rebar

RECOMMENDATIONS AND CONCLUSION

Expanding deployment of BIM tools requires improving flexibility, speed and ease of modeling. Limitations specially in modeling custom-designed meshes and cages need to be overcome. Improvement in the automated production of prefabricated reinforcement assemblies should be embraced by BIM tools by providing libraries of advanced reinforcement systems with customization options.

Structural design, analysis and detailing modules for pre-and post-tensioned concrete should be accommodated in more BIM tools. BIM modeling should take a bigger role in optimizing design of the concrete members and their reinforcement based on user-defined parameters that reflect project constraints. Automatic update of reinforcement with changes in the associated elements, providing a variety of options for grouping and filtering rebar as well as creating reinforcement assembly hierarchies based on different attributes can greatly improve editing efforts.

Many models and reports created by BIM tools don't have the complete set of required information so that reinforcement fabricators can directly use them for production. Technical reasons include lack of flexibility in providing user-designed reports, lack of interface with CNC machines and finally lack of features to embed all the needed details to create shop drawings for precast and placing drawings for cast-in-place (CIP) concrete. Further, improving 4D scheduling and erection sequencing

capabilities is very important especially for CIP projects in which simulation can help examine the feasibility of placing designed reinforcement in congested areas.

Improving the value of BIM for reinforced concrete depends to a large extent on interdisciplinary collaboration in creating, updating, and exchanging models throughout the project lifecycle. Implementing and enhancing the IFC interface to import and export model information is the cornerstone of project-wide streamlined communication and requires greater efforts from BIM vendors.

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3D Visualization of Sub-surface Pipelines in Connection with the Building Utilities: Integrating GIS and BIM for Facility Management

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ABSTRACT

Buildings cannot be used for their intended purpose without utilities. Maintenance workflows require work to be performed from the inside and outside of the buildings. The inside information can be extracted from a fully built building information model, and the outside information can be extracted from a Geographical Information System (GIS) map. GIS is the platform that integrates maintenance workflows for mechanical, electrical and plumbing systems for facility infrastructure. In order to perform efficient maintenance work, it is necessary to get the related information of the pipe network in advance. The purpose of this paper is to investigate how to use GIS and BIM information to get the detailed information for facility operation and maintenance. Field workers, without strong GIS and CAD background, need to visualize and analyze the subsurface pipelines. This study proposes a method to use data from BIM and GIS for 3D visualization.

INTRODUCTION

As Facility Management requires building information including mechanical, electrical and plumbing (MEP) from both insides the building and the pipeline network information outside the building, besides the 3D building model, it is necessary to for the facility management staff to have access for the 3D model of the underground pipe systems and the data behind the model before performing any maintenance work because it may cause disasters digging in the ground without clear understanding of the location and size of the underground conditions such as incognizant gas lines. However, current best practice is still divided by the building exterior walls. In the best scenario, the information inside the building is saved in the Building Information Modeling (BIM) model while the pipe network information underground outside the building is saved in Geospatial Information System (GIS) map. For some maintenance work that need to perform on the subsurface pipelines, a common damage source is the workers' accidental cutting as they do not have the precise underground location and size information of the pipelines. There has been an increasing interest in the area of integrating (BIM) and Geospatial Information System (GIS) (Isikdag et al. 2008). But until now, the two worlds are still not integrated (Berlo and Laat 2011). This paper, which proposes a method to use data

from BIM and GIS data for 3D visualization, is part of the ongoing research on the subject matters.

LITERATURE REVIEW

The technology and standards behind BIM and GIS are quite different as they are designed for different purpose with their own specialized functions (Zlatanova et al. 2002). Platforms that can have seamless integration of BIM and GIS are not expected to be developed soon. A more feasible approach is to achieve the integration on the data level (Wu and Hsieh 2007). Industry Foundation Classes (IFC) and BIM typically model buildings above the ground (Berlo and Laat 2011). BIM models focus on constructive solid geometry, decomposition and specialization of objects and the relation between objects (Liebich 2009). In addition, BIM or even CAD has a long history in managing 3D visualization data. At the same time, GIS strongly focus on the geo-location using the real world coordinate system. GIS technology focus more on database management (Balogun et al. 2011) and the relations between objects is calculated based on the coordinates sitting in the database.

In the field such as petroleum pipeline sector, misinterpretations of 2D maps by the field labors or even non professionals lead to pipe broken and busted as the construction workers mistakenly strike the pipes underground (Abdul-Rahman et al. 2006). Major accidents including blind-cutting off of water supply, natural gas etc. have been caused by such kinds of misinterpretations (Smith and Friedman 2004) and lives are lost due to the deadly explosions accompanying such accidents(Balogun et al. 2011). 3D visualization of the pipelines underneath the ground is paramount and been considered as an essential approach to fix the recurring problems with 2D GIS (Pubellier 2003). However, 3D maps became increasing popular due to their ability to overcome the limitation. It is a top-level challenge for the geospatial industry to have proper 3D visualization of pipelines (Balogun et al. 2011). Most of the existing pipelines are still viewed and managed in 2D (Hu et al. 2005). GIS, although strong in 2D geometry, just start to experiment 3D (Kolbe 2007).

When BIM and GIS users have to deal with the other part of the world, they all try to solve the problems by their own technology (Berlo and Laat 2011). GIS users integrate BIM data or CAD data into the GIS system. For example, Benner *et al*. (2005) built the QUASY (Quartierdaten-Management system) model, which transformed CAD data into a GIS based model, designed as 3D semantic building models for urban development. Isikdag and Underwood (2008) designed, developed, and validated three software components to transfer BIM data into GIS environment. They demonstrated that transferring information from BIM into geospatial environment is possible. Isikdag and Zlatanova defined a framework for automatic generation of buildings in CityGML semantic models (Isikdag and Zlatanova 2009). On the other side, BIM users tried to communicate geo-data from GIS platform to BIM or CAD system. For example, the IFC for GIS project, called IFG, aimed to provide geographic information from GIS into CAD system(BuildingSmartAlliance 2011).

METHODOLOGY

Three different software platforms will be used for this purpose: ArcGIS 10, Revit and AutoCAD Civil 3D (C3D). ArcMap 10 and ArcCatalog 10 are used to view and modify the shapefile datasets i.e. the location of the building, the road around it and the subsurface pipeline networks. Revit Architecture and Revit MEP are used to model the building structure and the building MEP systems in the building. C3D is used to import both the BIM model from Revit and the GIS dataset from ArcMap, modify the integrated model and view the result for the visualization of the pipeline network outside the building, the MEP systems and the connections between the two systems. The workflow for the integration is shown in Figure 1.

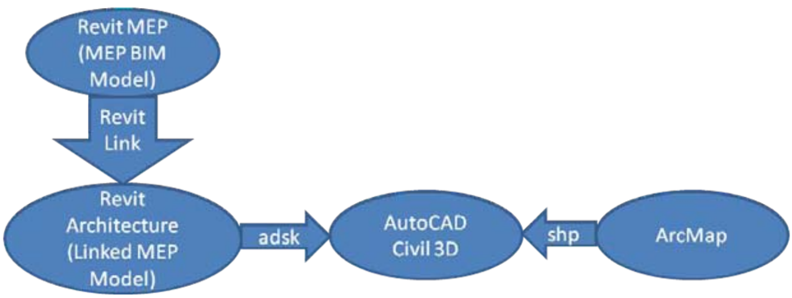

Figure 1. BIM and GIS Integration Workflow

ENSEMBLE APPROACH TO 3D VISUALIZATION

The research procedure can be divided into stages, and these stages are accomplished in sequence to achieve the research goal.

- Stage 1: Data collection

Collect building CAD drawings and GIS datasets from corresponding departments.

- Stage 2: Data processing and model building

Based on the CAD drawings, check the accuracy of the as-build drawings and rebuild the BIM model in Revit (Figure 2). Clean up the Shape files in ArcMap and ArcCatalog, check corresponding attribute fields and export the data related to the interested building (Figure 3). As the datasets always cover a much bigger area, for the performance of the next step, only the information nearby the interested building is selected and exported for the export to C3D. For demonstration purpose, this paper only imports and models the chilled water pipelines from ArcMap to C3D.

- Stage 3: Different platform integration

Export the Revit Model in adsk format which can be imported into C3D, import the adsk file and the shp file into C3D. Before exporting and importing, set and check the

geographic coordinate system in Revit and ArcMap to make sure the datasets share the same coordinate system.

- Stage 4: Clean up final visualization result

As the GIS data use 2 lines for each pipe, after importing to C3D, C3D recognize each line as one pipe, as a result, there are two pipelines for each corresponding pipeline in ArcMap (as shown on the top left of Figure 4). Delete the redundant pipeline and structures in C3D.

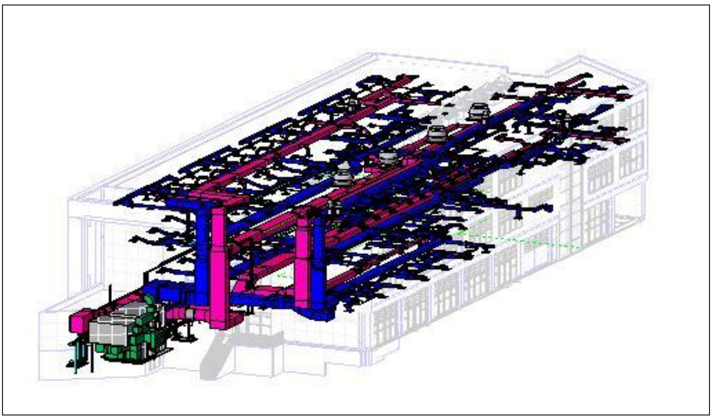

Figure 2. MEP model with Architecture Model as Underlay

Figure 3. Subsurface Pipeline Network Around the Interested Building

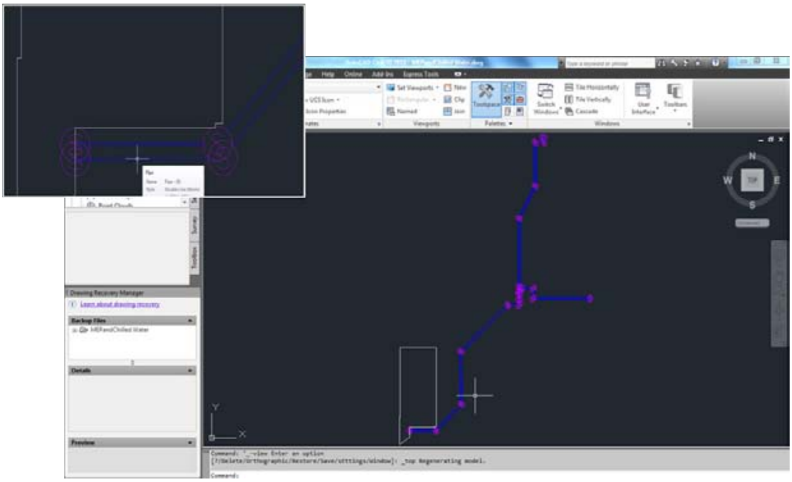

Figure 4. 2D View after Import the MEP Model and the Chilled Water Pipelines

DEMONSTRATION

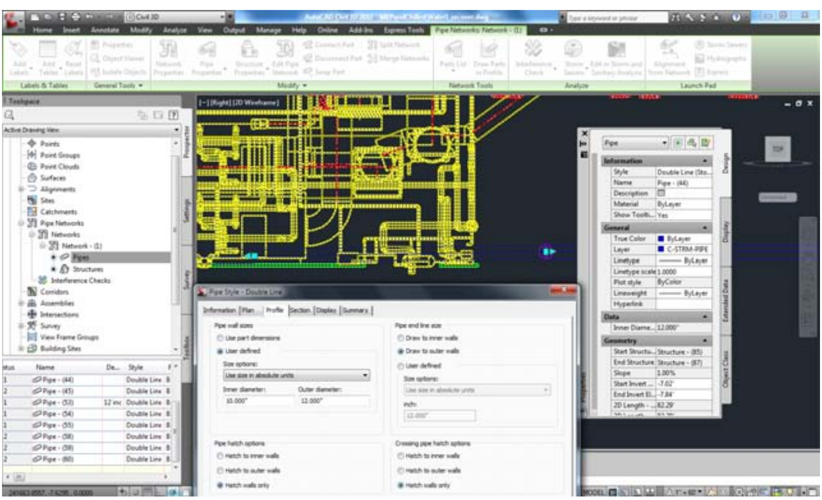

Figure 5. Pipe Properties View in C3D

Figure 5 shows the pipe properties and pipe style window of the selected pipeline. As the shapefile may not carry the material and size information of the pipelines, it is easy to add such information to the pipe properties and structure

properties. After all the necessary information is input into the model, it is convenient to query the model about the location and elevation of each pipe and structure that requires excavation. Figure 6 shows the visualization of the conncetion between the inside and outside pipes.

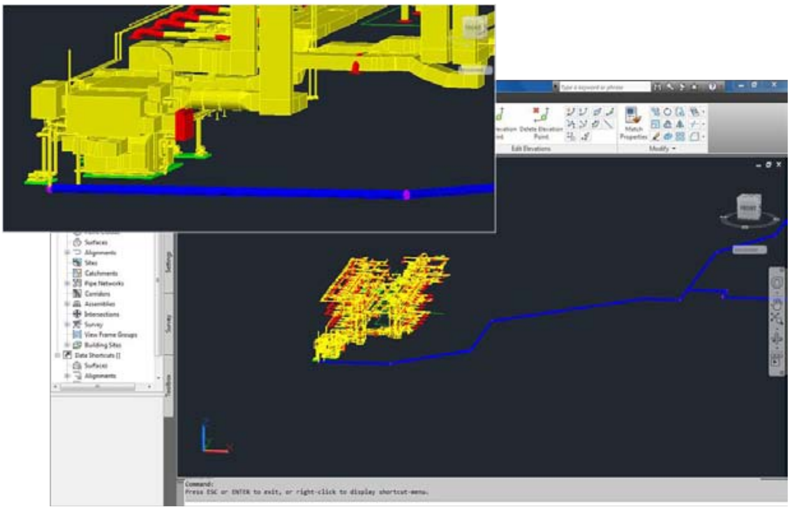

Figure 6. Final Visualization of the System

DISCUSSION

The elevation and position of the pipeline network would be more evident if the building site surface information were available. Since sometimes the utility provider digs a hole there is risk other utility's underground products get damaged. So it is necessary to have accurate GIS datasets that hold all the underground product information including, the location, the size, and the elevation before performing any underground work, especially when the pipelines underground may have noxious gas or combustible products.

The adsk format is designed for site information transfer between Revit and C3D. When the MEP models are exported as adsk format, they cannot be modified in the C3D environment as the imported shapefile. When changes needed for the MEP components insides the building, what the users have to do is to go back to the Revit platform to make changes and import it again to C3D. On the other hand, the importing from a shapefile to C3D is time consuming, for a shapefile of 260K, it took about 20 minutes, and the size of the resulting file increased dramatically from 260KB to 16M. Partial reason for this is that C3D builds redundant pipes and structures when it cannot recognize the polyline from the GIS.

The major advantage of the 3D visualization is that it offers a clearer view of the pipelines than presenting them in the 2D format. Excavation and other workers will understand the underground environment much better in this format.

CONCLUSIONS AND FUTURE RESEARCH

This study investigates the integration of BIM and GIS using the available tools on the market. An approach has been proposed for integrating the 3D BIM data and 2D GIS data. An example using a campus building was used to validate the feasibility of integration of the BIM and GIS data. However, to further validate this approach, it is necessary to include larger datasets with more information such as site, other underground pipelines and gas lines, electrical cables etc. While this paper only focuses on the chilled water pipeline network for demonstration purpose, a continuous study with other types of pipes and cables will be done as a follow up work. From this study, it is clear that all the underground pipe systems can be shown in 3D view accurately with the depth, location, size or even the materials of the pipes. As a result, before the underground work such as digging for a specific infrastructure pipe, the field worker can have a better understanding of the work environment and reduce the chance of damaging other networks or doing inefficient work. Furthermore, after the 3D visualization database is completely built, effort will be made to use the model to determine the optimized route for maintenance or excavation activities.

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BIM Use and Requirements Among Building Owners

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ABSTRACT

Driven by the knowledge that Building Information Modeling (BIM) may result in fewer conflicts and improved coordination, many owners are now mandating that it be utilized on new construction projects. However, they are often unsure of what BIM deliverables and processes to demand and how proficient the stakeholders they choose to contract with are in using such technologies. This research aims to assist facility owners in the adoption and mature implementation of BIM processes by assessing their current state of BIM execution. Using a survey of building owners, it identifies the proportion of owners currently requiring BIM, what requirements are being set forth for BIM deliverables and whether those deliverables are being used post-construction for operations and maintenance.

INTRODUCTION

Fueled by the understanding that BIM may result in more successful project outcomes, many owners are now requiring that BIM be utilized on their construction projects. However, as the development of BIM processes and technology continue to evolve, the quality of implementation among stakeholders varies dramatically across organizations. Thus, it is critical that owners be informed and aware of BIM's capabilities so they can adequately select and manage the stakeholders they choose to contract with. Since they will play a vital role in achieving a mature BIM standard in the future, this research seeks to analyze the level of BIM implementation among building owners and determine what improvements can be made to encourage the life-cycle use of BIMs.

LITERATURE REVIEW

BIM adoption by building owners. FMI, the largest provider of management, consulting and investment banking for the AECO industry, in partnership with the Construction Management Association of America (CMAA) has conducted an annual survey of building owners since the year 2000. In 2007, 35% of the owners surveyed

indicated having used BIM on one or more projects and 12% had implemented it for a period of five years or more. At that time, owners surveyed felt that their lack of expertise seemed to be the greatest hurdle preventing owners' adoption of BIM (FMI Corporation 2007).

In a national survey of industry professionals conducted by McGraw-Hill Construction (2008), 46% of owners surveyed indicated having used BIM on more than 30% of their projects and considered themselves to be very heavy users of the technology and 41% reported that BIM had a positive impact on their projects (McGraw Hill Construction 2008). In a similar survey on the perceived value of BIM conducted in 2009, 38% of respondents felt that having a BIM knowledgeable client was a top-rated factor influencing a project's value. However, when asked which phases of a project's life reaped the greatest value from utilizing BIM, industry respondents noted closeout/commissioning and O&M to be of the least value; suggesting that owners have yet to realize the potential benefits of using the model post-construction (McGraw Hill Construction 2009).

Therefore although BIM adoption by building owners is on the rise, the utilization of BIM for O&M is falling behind design and construction applications; despite the fact that there is much more to gain from the outcome (Akcamete et al. 2010). More specifically, in the university facility segment of owners, the adoption of BIM is currently dependent upon efforts to understand not only the software applications, but also the contract and what to outline in terms of deliverables. Although owners understand that they are driving this request, many lack expertise and knowledge of BIM applications and must rely somewhat on consulting partners (Reilly 2010).

Potential benefits of BIM to owners. Owners will potentially benefit the most through the use of the facility model and its embedded knowledge of the facility's life cycle (GSA 2006). Often, the same information is viewed at the time of specification, purchase, installation, and lastly when creating a handover file. There is potential for a more collaborative process, allowing for the information to be captured and documented once in the model; thus, reducing the redundancy and effort required throughout the design, construction and handover process. One major goal of using BIM for facility management is the automatic creation of equipment inventory lists which can populate the owner's computerized maintenance management system (CMMS). Therefore, the reduction in efforts can be found not only throughout the design process but is also extremely beneficial at handover to reduce the requirement to manually enter the documentation into another platform for facilities use (GSA 2011).

The model also provides an improved means of space asset management and equipment maintenance post construction. This is a significant improvement since space designations establish the platform for all information in the CMMS system. For space managers, BIM provides increased precision in terms of existing condition information since identification and area is automatic as opposed the need in AutoCAD to create manual polylines for each space (GSA 2011).

BIM execution trends among building owners. To ensure that BIM deliverables are useful to facility managers post-construction, a number of owners have begun dictating specific requirements for BIM implementation. Many government agencies as well as private owners have developed BIM requirements guidelines, contractual addendums and standards to improve the quality of information handover.

Perhaps the most noteworthy has been the work of the General Services Administration. In 2003, the GSA's Public Building Services (PBS) office of chief architect established its "National 3D-4D BIM program", setting a goal to require BIM on all new projects undertaken in the 2006 fiscal year as a means for improving design and construction quality and delivery (Hagan et al. 2009). What followed in later years was the publication of eight BIM Guide Series covering a vast array of topics specific to GSA's specific requirements on BIM-assisted projects (Yee et al. 2010).

Similarly, in 2006 the Army Corps of Engineers Engineer Research and Development Center (ERDC) published its own BIM roadmap outlining BIM implementation strategies for military construction and civil works projects (Brucker et al. 2006). Finally, the department of Veterans Affairs followed suite, publishing its VA BIM Guide in April of 2010. The guide includes 45 pages of the organization's life-cycle vision, implementation strategies, roles and responsibilities of different stakeholders, model sharing practices and requirements for using BIM as well as an in depth set of standards for model applications and paper deliverables (Department of Veterans Affairs 2010).

In June of 2008, the AGC and ConsensusDOCS consortium drafted the *Consensus Docs 301: BIM addendum* to help aid in some of the legal ramifications that may result from sharing the model between different stakeholders and the liability related to the model's completeness or accuracy. Shortly after, the AIA released its own *E202 BIM Protocols exhibit* to be used on design or construction contracts in which BIM is employed. One major difference between the two contractual addendums is that the E202 references an extensive model element table which defines the level of detail required for each modeling object; whereas, CD301 references an *external BIM execution plan* allowing project members to customize their contractual requirements to their own specific level of depth (Haynes 2009).

Amidst the increased publication of these master BIM guides, standards and contracts by larger building owner organizations, there have also been two major emerging trends. One has been the increased requirement for the informed use of a *project-specific* BIM execution plan as referenced in CD301 and the other has been the supplemental distribution of model element matrices designed to establish the level of detail required for each BIM object in the model. The VA is one of many owners requiring the use of such documents. In addition to their master guide, they also require the use of project specific-BIM Management Plans (BMPs) for design and construction phases depending on the acquisition strategy used (Department of Veterans Affairs 2009).

Also on the forefront of developing these BIM execution plans have been many higher education institutions. Indiana University published an organizational BIM Guidelines and Standards document in 2009 which was supplemented by three project-specific templates including an execution plan, an IPD methodology plan and

a BIM proficiency matrix (Indiana University 2009). Shortly after IU issued these documents, Pennsylvania State University published its Project Execution Planning Guide in October of 2009. The guide outlines a four step procedure for developing a detailed BIM execution plan to be customized by any project team wishing to implement BIM. Perhaps the most useful content it provided was its synthesis of the different categories of information suggested to be integrated in a BIM Execution Plan (BEP). They include: project goals and BIM objectives, BIM process design, BIM scope definitions, organizational roles and staffing, delivery strategy/contract, communication procedures, technology infrastructure needs, model quality control procedures, and project reference information (CIC Research Group 2009). Finally, Autodesk has also suggested its own Revit-centric version of a BEP, which it has termed the “Project BIM Deployment Plan” developed in 2010. It closely resembles the BIM execution plan template developed by IU.

Perceived difficulties in BIM adoption for owners. According to the International Facility Management Association (IFMA), Facility Management is "a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, places, processes and technology" (Cotts et al. 2010). Therefore, the building owner cannot be defined as one person within the organization. When the term building owner is used, unfortunately, the tendency is to associate the term with one segment of the profession; however, the reality is that the owner can consist of a multitude of individuals, all of whom have a specialized interest in specific job duties as well as different needs from the information provided at handover.

The handover process has always been difficult for owners, in terms of the distribution process of information. The move from hard copies to electronic version was an improvement; however, the owner is still left with a substantial amount of information to be distributed to multiple stakeholders within the organization. Standardization is beginning to occur through the execution of COBie and IFC standards; however, owners continue to maintain information in many different formats including CAD, Word, Excel, PDF and additionally in GIS and BIM. This illustrates the struggles that owners experience when beginning to utilize a new application, because integration and interoperability must flow from the files received to the format of those that need the information. Vendors are working to meet those needs but the adoption of BIM is also dependent upon the support of vendors. Each segment of the industry will follow the focus of the development of the supporting technology. History has shown the first BIM implementation was for design. The construction industry soon followed. Now, the industry is slowly beginning to develop the tools needed to integrate BIM into facilities management (Tardif 2010).

Information needed by the owner, in many cases, can be provided in a non-graphical format which eliminates the need for the owner to immediately become proficient in BIM tools, and obtain its useful benefits. For example, a spreadsheet identifying the building and room number of a pump to be maintained does not necessarily need to be in graphic format (East 2009). However, the space definitions are at the core of managing the facility and owners rely heavily on space management for the organizational uses of almost every aspect of the handover files. To provide this information to facility users, a space manager must often perform some action on the deliverable before disbursement. When using CAD, typically the action included

creating a polyline around each identified space to determine room boundaries, but this is no longer required when utilizing BIM.

For universities, difficulties are compounded by the fact that space must be reported based on specific space standards such as BOMA or the Facilities Inventory Classification Manual (FICM). Owners, with just the need to define space continue to utilize additional steps through third party tools to enable all of the stakeholders to have access to the space files. The transfer of information to CMMS systems creates a challenge as well. The US Army Corps of Engineers, in 2008, developed a 44 page document on the transfer of COBie data into Maximo (Nisbet 2008). The abilities to transfer information are improving; however, unlike the GSA, many owners are at the point of beginning to request models as part of their contract and have not yet identified a trained staff member within the organization to champion this instrumental change for data transfer. Additionally, despite great efforts, owners can also fall into one of the common pitfalls outlined by Cotts et.al. (2010) and may fail to define the needed documentation (type, quantity and format) required at handover.

METHODOLOGY

A survey questionnaire consisting of 29 questions in a variety of formats was distributed to members of the Florida Chapter of the Construction Owner's Association of America (COAA). Questions were organized into four distinct parts including: a section on demographics, a section on BIM Execution requirements, a section on BIM uses and required format of deliverables, and a final section on quality control procedures for those deliverables.

RESULTS

Thus far, the survey has received a total of 20 complete responses. The demographic population consisted of 15 College/University organizations, representing 75% of all respondents. This is likely attributed to the COAA sample that was available to us and our current connections within the state of Florida university system. Although the sample population is somewhat skewed, the different roles played by survey respondents within their organizations were more evenly distributed. Most respondents indicated having multiple responsibilities within their various organizations. The most common roles indicated by respondents included assistance with construction and planning, project team selection, and space management.

When asked whether BIM was currently a requirement of their organization, 40% of respondents indicated to not currently require BIM and only 15% of the sample population indicated BIM to be a requirement on ALL projects; suggesting that the implementation of BIM processes by owner organizations, at least at the University level in Florida, has not quite matured. A breakdown of the proportion of respondents among each BIM use category is shown Figure 1.

When asked what obstacles they were facing in the adoption of BIM, 50% of respondents (on that question) indicated software costs and lack of training or expertise to be the greatest impediments preventing them from executing BIM thus far. When asked what construction delivery method seemed most conducive for using BIM, the most common response was Design/Bid/Build and CM at risk, representing

20% in each category. Thus, despite the notable benefit of using BIM in combination with IPD, Design/Build or Negotiated contracts, a much lower proportion of respondents (10%) indicated using those delivery methods.

Despite the lack of formal BIM mandates among much of the survey population, many respondents still indicated having made certain strides as an organization toward BIM. Table 1 shows the frequency of BIM provisions being made by building owner organizations in the sample population. The greatest proportion of respondents (35%) indicated having implemented education and training to account for new BIM processes.

In addition to the executable provisions being made, they were also asked what types of contractual changes had been implemented as a result of requiring BIM processes. Approximately 24% of respondents had no contracts which addressed BIM yet. However, another 24% also indicated that their contracts referenced some supplemental BIM requirements documentation. Interestingly, no respondents within the survey population indicated having used E202 or CD301.

Table 1. BIM Provisions Made by Survey Respondents

BIM Provision	# of respondents	% of Total
No BIM provisions	6	30.00%
Education and Training	7	35.00%
A trained staff member to manage BIM procedures	4	20.00%
Revised contracts	6	30.00%
Presence of an organizational BIM execution guide	5	25.00%

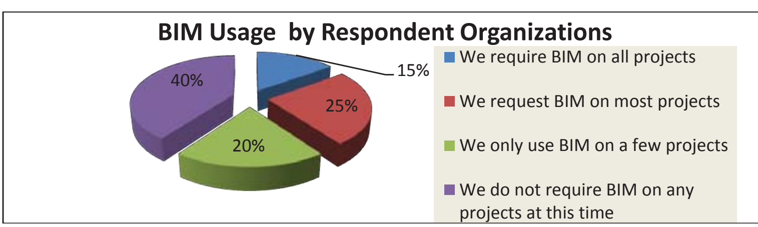

Figure 1. BIM Use by Owner Organizations

Respondents, who indicated requiring BIM, were asked their perceptions of stakeholders' responsiveness to BIM requirements and contractual changes mandated by owner organizations. The sample population indicated architects, engineers and

contractors to be largely supportive of these changes. One respondent did indicate that they felt the contractors to be non-responsive; suggesting that there is still a need for owners to be firm in their requirements guidelines and thoroughly check the deliverables they require.

Responses from owners suggest that the maturity of buildings owners in terms of BIM execution is still very widespread and the demands of owners may depend on the demographics. Although the owners are faced with many challenges, they are not able to begin implementation before investing in the software and training (Tardif 2010). Although two respondents did indicate that they would accept an IFC or COBie compliant model as part of the as-built deliverable, the majority (54%) of respondents who indicated having BIM requirements indicated mandating a federated model in Autodesk's 2011 or 2012 Revit building suite. Thus, the few organizations who have invested the time and money are software-specific in their standards.

Responses indicated that currently, importance of the uses of BIM during design and construction are in the areas of cost estimation, phase planning and structural analysis. In the construction phase, 83% of the respondents rated 3D coordination and clash detection as very important. This perhaps indicates the trend on behalf of owners to begin gradual implementation during design and construction. Many of the owners are not mandating BIM on their projects; however, it appears that they value its use during design and construction.

In the operations phase, where the greatest value can occur for the owner, 61% of owners identified building systems analysis, asset management, and space management as very important BIM uses; however, 56% of owners surveyed do not have BIM requirements in place currently to address their needs for the operations phase. Currently, many owners are transitionally working on implementation plans and are reluctant to request models that they must pay for, but are not yet sure how the models will be used. Lastly, the survey indicated that 71% of owners continue to request hard copy, and CAD files on CD as part of the as-built deliverable, suggesting that despite their requirement for BIM use, they are not currently using the model for Operations and Maintenance (O&M).

CONCLUSIONS

It is clear that BIM adoption by building owners has increased in recent years and though many resources are now available to owners regarding possible methodologies for requiring BIM, an extensive literature review showed great variability in the level detail found in owner's requirements specifications. This in combination with the survey findings suggests that the maturity of building owners in terms of BIM execution is still in its infancy. The survey also confirmed that even owners with BIM experience are not utilizing their BIMs post-construction for facilities management. Respondents indicated similar obstacles outlined by the literature including: lack of interoperability, misunderstanding of information handover requirements, and a general lack of software knowledge required to utilize BIM deliverables.

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Fall Hazard Checking Tool Based on BIMserver

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ABSTRACT

The construction industry has incurred the most fatalities of any U.S. industry in the private sector in recent years. While many factors may contribute to this statistic, one likely cause is due to designers who often lack design for construction safety knowledge, which results in many safety hazards being built into project models. To improve the current situation, a design for construction worker safety tool based on BIMserver was developed. This tool can automatically conduct compliance checking by using the advanced query functions of the BIMserver. Construction safety best practices were complied into computable rules. These rules were written by adopting Java code with the IFC hierarchy. This tool efficiently makes designing for safety suggestions available to designers and constructors. Particular emphasis was placed on fall accidents since falls are the most frequently occurring cause of fatalities on construction sites.

INTRODUCTION

The construction industry has incurred the most worker fatalities of any industry in the private sector in recent years. It is partly because designers cannot access design for construction safety knowledge, which results in many safety hazards being built in the project models/drawings. To improve the current situation, this research study identifies the possible influences of Building Information Modeling (BIM) technology on construction worker safety. After identifying the extent of the positive impact of BIM technology on construction worker safety through a literature review, the researchers describe the development of a design for construction safety tool which can automatically check three-dimensional (3-D) building models and make the designing for construction worker safety suggestions available to the designers and constructors in an efficient way.

Using a software tool to help designers implement design for construction safety knowledge is not a new idea. In the 1990s, after recognizing the lack of designer involvement in construction worker safety due to their minimal education and experience in addressing safety on the construction site, the Construction Industry Institute (CII) funded a research project to develop a software tool to assist designers in recognizing project-specific hazards and in providing them with design suggestions for consideration in the project design (Gambatese 1997). The design for safety suggestions were accumulated through research efforts that included input from designers, traditional construction contractors, and design-build firms. Then these

suggestions were incorporated into the "Design For Construction Safety ToolBox" by Gambatese and Hinze (1997).

Other researchers also have developed a few automated critiquing systems to support designers in making design decisions or to check IFC format building models. The U.K. Health and Safety Executive (HSE) was concerned that safety should be as much a key aspect in design as it is during construction and operation. A prototype was developed which was primarily concerned with the hazards while working at height, and accidents due to falling objects. An object-based CAD system exports design data in the IFC format to an EDM (Express Data Manager) database provided by EPM Technology. Design data are tested against health and safety requirements that are graded according to levels of risk. The checking results are reported through graphic and rule-browsing software (HSE 2003). Another endeavor is the SMARTcodes project. Since 2004, the International Code Council (ICC) started to develop object-based technology to represent their codes and to test submitted construction documents. The key elements are a model checking application and SMARTcodes. A protocol and software program were used to create tagged representations of building codes that use a tagging schema that reflects the logic and requirements of the codes from the text of the codes (Conover 2009).

The application tool adopted in this research study is BIMserver (Beetz 2010). BIMserver is an open source tool that enables users to centralize the information of a construction project (Van Berlo 2011). It uses the model-driven architecture approach, which means IFC data are interpreted by a core-object and stored in an underlying database. The users can query, merge and filter building models through this tool.

METHODOLOGY

An IFC model server is a database management system that centrally stores the building information model and manages all access to it. Various parties involved in a construction project can share information through it. The URL bimserver.org is linked to an open source IFC model server project and plays a role as an information hub that allows users to merge, filter, query, or even conduct clash detection.

From the collected falls prevention best practices, the following provision was selected to locate the method of how to compile a computable rule based on BIMserver: 'Locate the floor/roof opening which has an area value larger than 4 square feet' (Qi et al. 2011). Openings in structures on construction sites are a major causation for falls from elevation. During construction, elevator shafts, skylights and stairs can all appear as openings in the floor slab. Windows and doors are also closely related to openings in that they are normally inserted in to an IfcOpeningElement using the IfcRelFillsElement relationship.

The opening element represents a void within any element that has a physical manifestation. It stands for opening, recess or chase, and can be inserted into walls, slabs, beams, columns, or other elements. The IFC specification provides two entities for opening elements. IfcOpeningStandardCase is used for all openings that have a constant profile along a linear extrusion. Another entity, IfcOpeningElement, is used

for all other occurrences of openings and in particular also for niches or recesses. The second entity, IfcOpeningElement, is used in this research study.

In this research study, two methods were proposed to query an IFC file through the ‘Advanced Queries’ function of BIMserver. The purpose of this direct method was to retrieve the area value using the semantic information already stored in the model. The indirect method searches for the geometric parameters of the opening elements, and obtains the area value through further calculations.

Direct approach. The quantities relating to an IfcOpeningElement are defined by the IfcElementQuantity and are attached to the IfcRelDefinesByProperties. One quantity defined by the IFC specification is the NominalArea, area of an opening as viewed by an elevation view for wall openings or as viewed by a ground floor view for floor openings. First, the NominalArea is used to query the area value of an IfcOpeningElement. The hierarchy graph shown in Figure 1 shows the relationship between an IfcOpeningElement and its area value. Figure 1 shows that the IfcSlab and IfcOpeningElement are two separate entities. These two entities have to be first linked to locate each IfcOpeningElement in the floor slab.

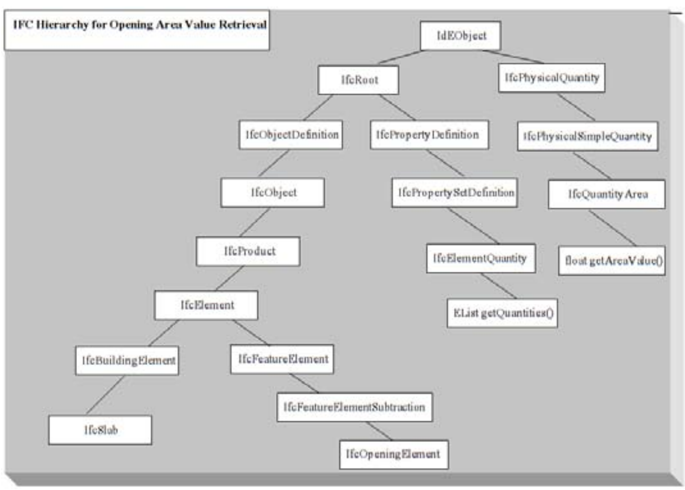

Figure 1. IFC Hierarchy for Opening area Value Retrieval

Then the relationship between IfcOpeningElement and its area value is found. This was one of the most difficult steps because the IfcQuantityArea is separately stored from the IfcOpeningElement. At this point, the specifications of all the IFC 2×3 terms defined by the BIMserver dictionary become critical resources to understand and establish these relationships.

After validating the linkage between an IfcOpeningElement and its area value, the following approach was used to query the area value of openings:

Step 1. Load the building stories.

Step 2. For every storey, get the IfcProduct and check the instance as IfcSlab.

Step 3. Using RelVoidsElement, get the related IfcFeatureElementSubtraction for the IfcSlabs
Step 4. Use the information from step 3 and the IfcRelDefines to obtain the IfcPropertySetDefintion collection.
Step 5. Check for the IfcElementQuantity instance in the collection from Step 4.
Step 6. Using the IfcElementQuantity in step 5, get the IfcPhysicalQuantity.
Step 7. Typecast the IfcPhysicalQuantity to IfcQuanityArea to get the required Area Value for consideration.

Indirect approach. Besides directly accessing the area value by using IfcQuantityArea, the area value of an IfcOpeningElement can be calculated by using its dimension parameters. The second approach was proposed to indirectly get the area value of an IfcOpeningElement. As shown in Figure 2, the IfcRectangleProfileDef contains the YDim and XDim of a rectangular opening. The IfcRectangleProfileDef.YDim is the opening width, and the IfcRectangleProfileDef.XDim is the opening height. IfcAxis2Placement3D is used to locate and originate an object in three dimensional space and to define a placement coordinate system.

```
#82=IFCOPENINGELEMENT('2D3aG1qsX7uv55sjsCYstR',#42,$,$,'Opening',#81,#80,'157488');
 ├── #42=IFCOWNERHISTORY(#41,#2,$,.NOCHANGE.,$,$,$,0);
 ├── #81=IFCLOCALPLACEMENT(#47,#172);
 └── #80=IFCPRODUCTDEFINITIONSHAPE($,$,(#79));
      └── #79=IFCSHAPEREPRESENTATION(#36,'Body','SweptSolid',(#76));
           ├── #36=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,1.E-009,#35,$);
           └── #76=IFCEXTRUDEDAREASOLID(#73,#75,#9,1.);
                ├── #73=IFCRECTANGLEPROFILEDEF(.AREA.,$,#72,9.99999999999998,18.0000000000001);
                ├── #75=IFCAXIS2PLACEMENT3D(#74,#10,#6);
                └── #9=IFCDIRECTION((0.,0.,1.));
```

Figure 2. Dimension Parameters of an Ifcopeningelement

The IFC R2.0 Object Diagram developed by the Building Lifecycle Interoperable Software Project (BLIS Project) was a helpful tool at the beginning stage of this process. It shows that the area value can be obtained by using the geometric dimension of an entity. With the progress of the project, the IFC R2.0 Object Diagram – IfcOpeningElement was found to not represent the correct relationships between an IfcOpeningElement and its IfcRectangleProfileDef because the IFC schema had been updated from the old IFC R2.0 to the new IFC 2×3. A new diagram based on IFC 2×3was then developed to replace the old one. Figure 3 shows a partial hierarchy and attributes of an opening element. The full object diagram was more complicated, so only relationships that were useful for querying purposes are demonstrated here. The geometric relationships between an opening element and its dimension parameters can be derived from this diagram.

In Figure 3, the IfcLocalPlacement defines the local coordinate system, which is referenced by all geometric representations. The relative placement of an opening element to the IfcWall and IfcSlab is recorded through it. The IfcShapeRepresentation represents the concept of a particular geometric representation of a product or a product component within a specific geometric representation context. It has an inherited attribute RepresentationType to define the geometric model used for the

shape representation. The swept area solid is a predefined type of RepresentationType. It can be created through either an extrusion or a revolution. The IfcExtrudedAreaSolid is defined by sweeping a bounded planar surface. It defines the extrusion of a 2D area by using the direction and depth. A 2D area is given by a profile definition. The opening element extrusion segments may have any profile. Three profiles are supported by IFC 2×3. They are IfcRectangleProfileDef, IfcCircleProfileDef and IfcArbitraryClosedProfileDef.

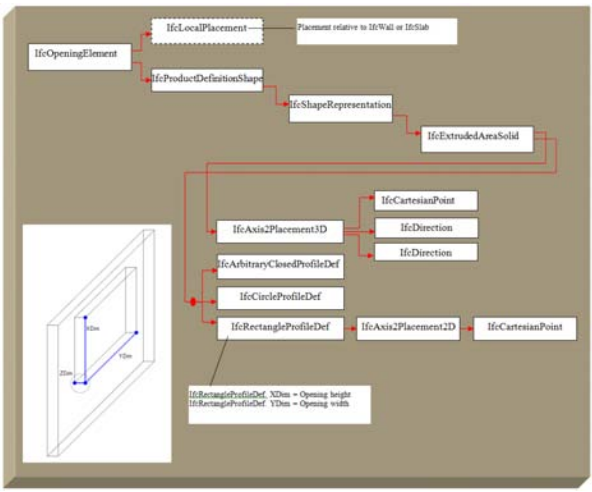

Figure 3. IFC 2×3 Object Diagram – Ifcopeningelement

The IFC rectangle profile is the most common profile of an IfcOpeningElement. It defines a rectangle as the profile definition used by the swept surface geometry or the swept area solid. In IFC 2×3, rectangles are defined centric, which means the placement location has to be set with IfcCartesianPoint (XDim/2, YDim/2).

The indirect approach can be realized through the following steps:

Step 1. Load the building stories.
Step 2. For every storey, get the IfcProduct and check the instance as IfcSlab.
Step 3. If the instance is an IfcSlab, get its generalized parent object IfcElement.
Step 4. Using IfcElement, check to determine if the object has any opening elements using getHasOpenings() which will be a relationship IfcRelVoidsElement.
Step 5. Collect the IfcOpeningElement into a set from the relationship class IfcRelVoidsElement using getRelatedOpeningElement().
Step 6. The IfcOpeningElements searched for are rectangular opening elements along with their respective area values.
Step 7. Iterate the collection of IfcOpeningElements, to get the X Dimension and Y Dimension values to calculate the area as follows.
Step 8. The objective is to find the path: IfcOpeningElement → IfcExtrudedAreaSolid → IfcRectangleProfileDef for the methods getXDim() & getYDim().

Step 9. Get the IfcRepresentation and iterate over them to find the IfcShapeRepresentation which will return the items of IfcExtrudedAreaSolid.
Step 10. IfcExtrudedAreaSolid has the profile definition among which IfcRectangleProfileDef is defined.
Step 11. Check for the instance of IfcRectangleProfileDef to invoke the getXDim() and getYDim().
Step 12. Calculate the area as a product of the return values of the above dimension methods.
Step 13. Filtering the IfcOpeningElement using the search area criteria.

RESULT

BIMserver provides six potential functions which can be executed. The Query function is used for a compliance check. This user interface is shown in Figure 4.

Figure 4. User Interface Of Advance Query Function Of BIM Server

The 'Compile' function automatically checks the validity of the computable rule. It reports the grammar errors if the imported rule is wrong. The 'Compile & Run' function checks errors as 'Compile' function and executes code checking if the imported rule is well written. Here the computable rule is compiled using the direct approach is first imported and executed. The result of the check is shown in Figure 5.

Figure 5 shows that there are a total of four opening elements in project 4351. This matches the number of IFC opening elements in the original building model. The retrieved area values mismatch the true values in the original model. After further validation, it was found that the retrieved values were the 'net area value' of the slabs to which opening elements are attached. The relationship between the net area value, slab area value and opening element area value is represented using the following equation: Slab area value − Opening area value = Net area value of slab

```
Compilation successfull
Executing...

Total Element quantity in the model are 6
Total Opening Element in the model which are associated to slabs are 4
Area for org.bimserver.ifc.emf.Ifc2x3.impl.IfcOpeningElementImpl@1ead544: 2111.8076
Area for org.bimserver.ifc.emf.Ifc2x3.impl.IfcOpeningElementImpl@b05d81: 2111.8076
Area for org.bimserver.ifc.emf.Ifc2x3.impl.IfcOpeningElementImpl@1c722c1: 1767.5867
Area for org.bimserver.ifc.emf.Ifc2x3.impl.IfcOpeningElementImpl@8f4acd: 1767.5867

Execution complete
```

Figure 5. Checking Area Values of Opening Elements with Bimserver by Using Computable Rule Written in Direct Approach

Even though the retrieved values are not the area values of opening elements, this does not mean the direct approach that uses semantic information in the model is wrong. The direct method is still a generic method to query an IFC building model when using BIMserver. It may not work in a few specific circumstances, such as the unusual storage of certain semantic information.

The validity of a computable rule written in the indirect approach is checked. The direct method retrieves the area value using the semantic information already stored in the model. The indirect method tried to find geometric parameters of opening elements, and obtained the area value through further calculations. The rule is imported into the query window in the same way as the rule is compiled in the direct approach. After running the check, the result is shown in Figure 6. The X dimensions, Y dimensions, and area values of all three opening elements in the rectangular shape are listed. These values match the area value in the origional building model.

```
Compilation successfull
Executing...

Total Opening Element in the model which are associated to slabs are 4
X dimension:6.0
Y dimension:4.75
Area calculated from geometry: 28.5
X dimension:25.0
Y dimension:15.0
Area calculated from geometry: 375.0
X dimension:6.0
Y dimension:4.75
Area calculated from geometry: 28.5

Execution complete
```

Figure 6. Checking Area Values of Opening Elements With Bimserver by Using Computable Rule Written in Direct Approach

CONCLUSION

A computable rule based on BIMserver is developed to query the area value of an IfcOpeningElement. As mentioned in last section, the opening element extrusion segments may have many profiles, and three kinds of profiles are defined in IFC 2×3. They are IfcRectangleProfileDef, IfcCircleProfileDef and IfcArbitraryClosed-ProfileDef. The IFC rectangle profile is the most common profile of the IfcOpeningElement. The rule developed is based on the IfcRectangleProfileDef. However, the other two profiles may also exist in building

models. For instance, Figure 7 demonstrates a paragraph of IFC code which defines an IfcOpeningElement with an arbitrary closed profile. The IfcArbitraryClosedProfileDef defines an arbitrary 2-D profile. From a list of points stored in IfcPolyLine, the outer boundary of this surface or solid can be constructed. It is relatively difficult to compute the area value of an opening element with an IfcArbitraryClosedProfileDef.

```
#2307=IFCOPENINGELEMENT('2xJZI91Df0WufvF4H8W09w',#42,$,$,'Opening',#2306,#2305,'160814');
  #42=IFCOWNERHISTORY(#41,#2,$,.NOCHANGE.,$,$,$,0);
  #2306=IFCLOCALPLACEMENT(#55,#131209);
  #2305=IFCPRODUCTDEFINITIONSHAPE($,$,(#2304));
    #2304=IFCSHAPEREPRESENTATION(#36,'Body','SweptSolid',(#2301));
      #36=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,1.E-009,#35,$);
      #2301=IFCEXTRUDEDAREASOLID(#2298,#2300,#9,1.);
        #2298=IFCARBITRARYCLOSEDPROFILEDEF(.AREA.,$,#2297);
          #2297=IFCPOLYLINE((#2290,#2291,#2292,#2293,#2294,#2295,#2296));
            #2290=IFCCARTESIANPOINT((2.36249093142856,39.0194276976316 2));
            #2291=IFCCARTESIANPOINT((2.36249093142856,27.01007190779952));
            #2292=IFCCARTESIANPOINT((5.695824264761892,27.01007190779952));
            #2293=IFCCARTESIANPOINT((5.695824264761892,35.09340524113289));
            #2294=IFCCARTESIANPOINT((13.96089350759504,35.09340524113289));
            #2295=IFCCARTESIANPOINT((13.96089350759504,39.01942769763162));
            #2296=IFCCARTESIANPOINT((2.36249093142856,39.01942769763162));
        #2300=IFCAXIS2PLACEMENT3D(#2299,#10,#6);
          #2299=IFCCARTESIANPOINT((14.22848067334061,38.84375000000005,1.));
          #10=IFCDIRECTION((0.,0.,-1.));
          #6=IFCDIRECTION((-1.,0.,0.));
        #9=IFCDIRECTION((0.,0.,1.));
```

Figure 7. Ifcopeningelement With an Ifcarbitraryclosedprofiledef

Besides, the computable rule compilers need to understand two programming languages -- EXPRESS and Java schema to effectively query building models. This cross disciplinary collaboration is often required to successfully complete such a project.

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BIM Server Requirements to Support the Energy Efficient Building Lifecycle

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ABSTRACT

Energy efficient building design, construction, and operations require the development and sharing of building information among different individuals, organizations, and computer applications. Building Information Modeling (BIM) servers are tools used to enable an effective exchange of data. This paper describes an investigation into the core BIM server requirements needed to effectively support information sharing related to energy efficient retrofit projects. The requirements have been developed through an analysis of existing functional capabilities combined with a case study analysis. The set of requirements identified includes fine-grained queries such as selective model queries, information queries (e.g. weather, building description), and operational information queries (by building parts, proximity, and context). A set of RESTful programming interfaces for building tools to access and exchange data, including security and data privacy issues, is being explored to provide a server-centric building information model exchange and interoperability to facilitate energy efficient retrofit.

INTRODUCTION

The topic of facilitating data exchange between different design and simulation tools in the Architecture, Engineering, and Construction industry (AEC industry) is gaining increasing interest. One notable fact is that AEC has its own tradition of ways to adopt the assistance from computer and information science in the whole building design life cycle (Watson, 2010). Instead of taking advantage of a server-centric solution, the workstation-based CAD approach, which dates back to 1980s, is still widely used by the AEC industry (Watson, 2010). In the current AEC work flows, the simulation processes are not fully integrated into the design and

modeling process (Hirsch et al., 2011). In most cases, engineers need to manually build models for simulation, which duplicates work that has already been performed. Approximately 80% of the effort needed to run a simulation is spent in building models (Bazjanac, 2001). With Building Information Modeling (BIM), attributes and data can be attached to a model, which potentially allows integrated analysis and simulation, especially for energy efficient retrofit projects (Beetz et al., 2010, Beetz et al., 2011). However, most of the analysis and simulation software have been developed by experts in different domains, and their formats are different in nature, which limits model reuse and data sharing among tools. To solve this problem, the requirements for the Building Information Modeling server are explored based on the existing open source platforms (e.g., BIMserver.org).

In this paper, "BIM Server" is a general concept that describes the server used for sharing building design data, and "BIMserver.org" refers to the specific platform implemented by bimserver.org. We investigate a set of core requirements for energy efficient building lifecycles and identify the gap between the current BIMserver.org implementation and the requirements. We give an outlook on the future work needed to fill in the gap. First, we introduce previous efforts on combining BIM with energy simulation tools leveraging the open source BIMserver.org. Then we present the details of generic requirements for building information exchanges in the Section "Requirements", and discuss the current status of BIMserver.org and future work in the Section "Discussion."

RELATED WORK

BIM based energy simulation. Currently BIM technologies have been widely adopted in the AEC industry for 3D-rendering, drawing extraction, estimation of cost, and clash detection (Eastman et al. 2008). Several previous efforts have tried to integrate building information models with energy simulation tools. McGraw-Hill (2009) surveyed that the lack of software interoperability and functionality is rated as one of the greatest obstacles to improving business value of BIM. Moon, et al. (2011) conducted case studies to evaluate the interoperability of a BIM based architecture model and performance simulation programs (e.g., EnergyPlus). In this paper, we identify a set of key requirements, among which some are new, that are needed for BIM-based energy efficient building lifecycle.

Previous work using BIMserver.org. The open source BIMserver.org (version 1.1 beta, 2012) enables users to host their own BIM server to centralize the information of any construction or other building related projects. Weiming et al. (2010) showed an agent-based, serviced-oriented approach to integrating data, information, and

knowledge captured and accumulated during the entire facility lifecycle with BIMserver.org. Recently, Singh et al. (2011) developed a theoretical framework of technical requirements for using BIMserver.org as a multi-disciplinary collaboration platform.

REQUIREMENTS

Internal data storage requirements. Internal data handling can be addressed using file-based and model-based approaches. These two approaches have different strengths and shortcomings. A file server's structure could be quite clear and simple, which is easy to implement. The underlying database could be a classical relational database. Adopting such a file server will not impact current energy-efficient retrofit workflows. The file server does not necessarily need a unified file format or a format translator. It stores files and facilitates the collaboration of sections of design and simulation teams that share the same file format. The basic unit of file server is a file, while sometimes users have to query data distributed in different files. For example, a simulation tool may need the height and width of all windows. However, a file server may not able to parse the information it stores semantically and cannot support such data export or other advanced functions such as model merging and partial model query (Beetz et al., 2010).

A model-driven server could compensate for the file server's drawbacks. A model-driven server doesn't save the files submitted by users into database directly. It parses the data in the file first and uses these data to construct its own pre-defined data structure and maintain a comprehensive model. The advantage of this method is that some advanced functionalities (e.g. clash detection, model merging) could be performed on the model easily (BIMserver 1.1 beta, 2012). Currently, BIMserver.org is a model-driven server which adopts Eclipse Model Framework (EMF, 2012) to represent the data model that is parsed from IFC files.

Web service interface. There are three kinds of popular web service interfaces: remote procedure call (RPC), service-oriented architecture (SOA), and representation state transfer (REST) interface (Fielding, 2000). RPC allows two distributed remote heterogeneous systems to call the functions or methods of each other. But their interaction and function calls deeply relate to the specific implementation of specific programming languages, which violates the principle of loose coupling in software engineering. SOA is widely adopted by many web service providers. Instead of relying on the specific implementation, SOA is driven by messages (events). The third option, the RESTful interface, is most suitable for BIM servers. The strength of the RESTful interface is its simplicity. In this

architecture, the representation of all resources would be abstracted as a Uniform Resource Identifier (URI). The resources here do not just refer to the files or other tangible objects; it also could be a composition of several files, a table, a query, a result set of queries, and any concepts. The web interface is essential to the usability of a server. As previously mentioned, simulations for different scenes and different purposes are highly domain-specific. Even equipped with a web-page or client-based query tool, the server cannot support all possible workflows and needs of specific data model composition, let alone the possible appearance of new simulation scenes and tools. The domain experts are the ones who know the specific data model request best in a simulation scenario. They can use the RESTful interface to manipulate the data model and build clients directly for one specific domain. A dedicated client could achieve partial model query from the model pool of the server for its own simulation. The easy-to-build clients based on a RESTful interface are loosely coupled with the server and make the methods of data selective model queries, information queries, and operational information queries flexible.

Automated query generation from model view definitions (MVD). IFC is an open source data format for facilitating information exchange in the whole building construction lifecycle which is widely used for BIM. Instead of using full IFC schema, an MVD would be defined for a subset of the IFC schema to satisfy one or several specific data exchange requirements. Whereas an MVD is independent of a particular IFC release, its realization is implementation dependent. It is critical to automate the data exchange process by generating queries from MVDs automatically. The automated generation of queries from MVDs will facilitate, simplify, and streamline information exchange between tools built around BIM servers, and enable flexible queries to BIM servers. This functionality will also enable a BIM server to selectively export relevant information for tools.

Query language. One of the limitations of the current BIMserver.org implementation is that users have to write a chunk of tedious Java code to perform sophisticated queries, which is not user friendly. The previous survey showed that the biggest obstacle for an effective use of BIMserver.org is client interface usability (Beetz et al., 2011). We recommend that the Java code should be hidden from the normal users. Figure 1 shows a code snippet from the BIMserver.org advanced query demo. Only the code in **bold** has to be specified by user. Other code requires extensive knowledge of the underlying programming language to construct and understand, and should be encapsulated by a higher-level declarative query language and made transparent to normal users.

```
@Override
public void query(IfcModelInterface model, PrintWriter out) {
```

```
    out.println("Running doors example");
    List<IfcBuildingStorey> stories = model.getAll(IfcBuildingStorey.class);
    Map<Double, IfcBuildingStorey> orderedStories =
        new TreeMap<Double, IfcBuildingStorey>();
    for (IfcBuildingStorey storey : stories) {
        orderedStories.put(storey.getElevation(), storey);
    }
    if (orderedStories.size() > 1) {
        IfcBuildingStorey firstFloor = stories.get(1);
        for (IfcRelContainedInSpatialStructure rel :
                firstFloor.getContainsElements()) {
            for (IfcProduct product : rel.getRelatedElements()) {
                if (product instanceof IfcDoor) {
                ifcDoor ifcDoor = (IfcDoor)product;
                        if (ifcDoor.getOverallHeight() > 2) {
                            out.println(ifcDoor.getName() + " "
                                + ifcDoor.getOverallHeight());
}}}}}}
```

Figure 1. Advanced query sample from BIMserver.org (version 1.1 beta, 2012)

A core requirement for the query language is to support partial model query. For example, user A wants window objects and their related geometric objects, while user B requires the same window objects and their penetration property. Although some general purpose query language is available already (e.g. SQL), it is difficult to achieve the partial model query of IFC data models directly (Adachi, 2003). An AEC industry domain-specific query language could be designed for such purpose. For the area that has special requirements on query and design, adopting a domain-specific language (DSL) has been proven as a viable solution. One such example is VHDL, a hardware description language (Camposano et al., 1991). To achieve an AEC domain specific query language, one could start from the query language that could execute partial queries on an IFC compliant data model. Dating back to 2003, PMQL is an effort that tried to achieve partial model query of IFC files (Adachi, 2003). GMSD goes one step further to support better "partial model query on specific model view," and less "request-response cycles" (Weise et al., 2003).

We believe a domain specific query language is needed and should have at least some of the following characteristics:

- Compatible with MVDs: Queries should be able to be (semi-)automatically composed based on the existing MVDs;
- Compatible with to the RESTful interface;
- Easy for normal users to construct queries;
- Hidden from the users behind GUI and support transaction queries with

ACID (atomicity, consistency, isolation, and durability) (Gray et al., 1993).
- Able to reuse routine queries.

DISCUSSION

Current BIMserver.org implementation. The open source implementation BIMserver.org is a promising platform that facilitates information exchange in building projects. It could be a valuable platform for the energy efficient retrofit project too. In the latest version of BIMserver.org, some requirements containing revision control, authority control, and clash detection have been implemented.

BIMserver.org 1.1 was released in November 2011. In this version, there are 9 new features, among which client library, new protocol buffer interface, and new plugins mechanism are most attractive and make the architecture of BIMserver.org more flexible (BIMserver 1.1 beta, 2011). Especially, the change in the plugin mechanism is critical. In version 1.0, the instances of plugins are created in the core part, intertwined with the BIMserver.org kernel logic. The new plugin infrastructure is implemented in the sub-project called "Plugin," one of the required projects on the build path of the BIMserver.org kernel. This brand new design allows the developers to add new functions to BIMserver.org easily and quickly.

Due to the complexity of constructing sophisticated queries as we mentioned in the section "Query language," BIMserver.org should encapsulate the routine Java code into some drop-down menu and/or check box based graphical user interface. Taking the query on doors as an example, shown in Figure 1, users need to check the object they want and the range of data and other criteria, like the "OverallHeight" should be more than 2 meters in the example. The back end could generate such code according to the user input automatically. Currently, using Java code is an implementation tradeoff. The ideal solution is to introduce a new query language that fully supports partial model query. Inspired by PMQL (Adachi, 2003) and GMSD (Weise et al., 2003), Beetz et al. (2011) plan to design such a new query language in their future work.

Integration of OpenStudio and BIMserver. OpenStudio is another integrated energy simulation and analysis platform created by the NREL (Guglielmetti et al., 2011). It can be used for managing models and data and facilitating analysis for tools such as EnergyPlus and Radiance. The range of tools that are supported by OpenStuido is not that wide currently, but it works quite well in some dedicated integrated simulation scenes like day lighting simulation. It is potentially useful to integrate OpenStudio and BIMserver. In such architecture, OpenStudio would focus on the parameter and analysis management, meanwhile, BIMserver could offer the

transactional query and data persistence service. To achieve this, a translation between the .osm data (OpenStudio file format) model and IFC data model might be needed to combine the formats supported by the two platforms respectively into one big data model set. Currently both OpenStudio and BIMserver have opened their programmable interfaces, which make the integration of the two platforms easier. We believe it is necessary to build links between the two platforms and make them interoperable.

SUMMARY

In this paper, we first investigated the key BIM server requirements for information exchange of energy efficient building retrofit projects, including automatic generation of queries from MVDs, the RESTful web interface, and domain specific query language. Such requirements would benefit partial model query and adoption of BIM server in energy efficient building lifecycle. The open source BIMserver.org implementation was used as the case study to discuss its current status and limitations. We then identified some future directions to fulfill these requirements based on the open source BIMserver.org.

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Automatically Updating Maintenance Information from A BIM Database

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ABSTRACT

With the development of building information modeling, knowledge sharing between facility management and design professionals has become possible. The use of building information modeling (BIM) technology in the design and construction phases of buildings is increasing. There is a need to expand the use of BIM beyond the two to three years design and construction phase into the facility management phase of buildings in order to facilitate tasks such as maintenance and to maximize its value to facility owners. However, the fact of current Architecture, Engineering, Construction and Operations (AECO) industry practice is that the facility management phase seldom uses the BIM models even when they are required by the owner in design and construction phase. This fact results in BIM models being wasted where they have the most value, in the facility management phase. This study is a part of the ongoing research of BIM-assisted Facility Management which is aimed to bridge the communication gap between design and facility management professionals. This paper focuses on automatic bidirectional communications between Computerized Maintenance Management Systems (CMMS) and BIM models on a database level.

INTRODUCTION

The AECO industry has shown a good deal of interest surrounding the use of BIM for facility management. The opportunities for leveraging BIM for facility operations are compelling, but the utilization of BIM in facility management is lagging behind the BIM implementation in design and construction phases. On one hand, designers and constructors seldom know what documents and other varieties of information are needed for the facility management phase. On the other hand, a limited degree of knowledge and experience gained in the operation and maintenance phase of these existing buildings is sent back to the design phase. This research is aimed at bridging the communication gap between design and facility management professionals on a facility database level. Since a Computerized Maintenance Management Systems (CMMS) is an important component of the operation and maintenance phase, it is imperative to obtain accurate information, e.g manufacturer information and equipment parameters, needed for the proper operation of CMMS

system. The ready availability of such data will reduce the maintenance period and minimize the down time of equipment. Through operations on the BIM database, data can be transferred bidirectionaly between BIM models and the CMMS system. A template that can transfer information bi-directionally between design and facility management software was developed.

LITERATURE REVIEW

Building Information Modeling (BIM) technology has undoubtedly changed the way the AEC industry executes design and construction, but will it also change the way facilities are operated and maintained (Autodesk 2008)? The AECO industry has expressed a good deal of interest in the use of BIM for facility management. The opportunities for leveraging BIM for facility operations are compelling, but the utilization of BIM in facility management is lagging behind the BIM implementation in design and construction phases(Akcamete et al. 2010).

Facility managers are the ones who responsible for the operations and maintenance of the designed and constructed buildings for years. However, there are many organizations and individual professionals involved in these fields. , The leadership of these organizations are beginning to communicate and collaborate, but, to date, have not served the facility and property managers well in the area of BIM (Cotts et al. 2010). On one hand, designers and constructors seldom know what documents and other varieties of information are needed for the facility management phase. On the other hand, a limited degree of experience in the use and operation knowledge of these existing buildings is sent back to design phase for consideration (Jensen 2008). The link between design and facility management is not sufficiently understood and usually avoided (Erdener 2003). Issues related to facility maintenance have been left out of the design decision-making process (Pati et al. 2010).

The operation phase constitutes approximately 60% of the total cost of a construction project. Main activities during operations are related to maintenance and repair (M&R). Reactive maintenance and repairs bring excessive expenses, but it must be remembered that most maintenance work is reactive (Akcamete et al. 2010, Mobley et al. 2008, Sullivan et al. 2010). It is not efficient because reactive maintenance cost three to four times more than the planned maintenance for the same repair (Mobley et al. 2008, Sullivan et al. 2010). So it is reasonable to support more planned maintenance work and not just reacting to failures. Sullivan, et al.(2010) recommended prioritizing the components in a facility, recording root causes of failures and analyzing equipment failure modes etc. in order to capture reliable information for reactive maintenance cost three to four times more than the planned maintenance planned maintenance. A reliable maintenance database holding historical information of maintenance and repair work is necessary for planned maintenance decisions. As significant unnecessary expenses occur in the current practice, there are ample opportunities for major savings in the operation phase; computerized supports are needed for the improvement of operation and maintenance activities (Akcamete et al. 2010).

In addition, the detailed design model is not useful for daily use by facility management. Since design software such as AutoCAD Revit, ArchiCAD etc. are for

use by design professionals, requiring facility management staff to use these software packages to query the information they need is both burdensome and inefficient. Only a portion of information from the BIM model is typically required for this purpose.

METHODOLOGY

As shown in Figure 1, the first step of this research is to identify the needs and possible solutions for the requirements of facility management. Existing FM software is examined and interviews have been done with several facility management staff. Although current facility management (FM) software may still have some problems such as not including enough information fields for maintenance work, it is not the focus of this paper. The information required by the FM software and other necessary information are added to the BIM model as parameters. Information needed for the software includes: Location ID, Building, Room Number, Floor, Description, Sq Feet, Requestor, and Phone. Description, requestor and phone should be inputted by the end user and is not related to the BIM models. So those three fields are not considered for parameters. Instead, the name of manufacture, the contact information of manufacture, the location of equipment, the equipment model number, and the warranty expiration date are added to the BIM model as shared parameters.

The BIM tool chosen here is Revit MEP as we focused our problem on MEP system maintenance. The functionality of Revit MEP is investigated to hold the shared parameter, which can be used for multiple projects and exported to external database and a Revit template is built using the parameters created for maintenance purpose. DBLink connections that can export Revit data to external database such as Access were also investigated. A case study of an educational facility is conducted to validate the proposed method for automatically updating information between BIM software and FM software.

CASE STUDY

A case study interview was conducted with the FM information system manager of large owner. The FM manager indicated that they were using an MS Excel file to collect information for equipment from contractors and designers and were using Automaid software to feed the data into their CMMS. The MS Excel format has been used for 14 years. From the CMMS perspective importing the data is already not a problem. This case study is focused on how to populate the MS Excel file from the BIM model automatically for importing into the CMMS software.

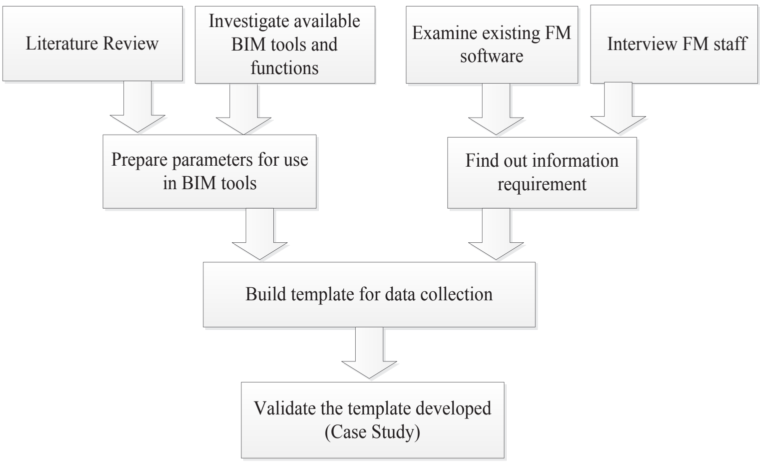

Figure 1. Process for database connection between BIM and FM

Once the required information and data fields have been determined after investigating the existing FM software and interviews with FM staff, the first step would be to prepare the template in Revit and a database export is used to add the required parameters to the Revit Model. Shared Parameters are used here because they can be shared by multiple projects and families, can be exported to ODBC and also appear in schedules. If project parameters are used, the parameter created can only be used for the current project but not shared by other projects. As parameters are set to be used for different projects, shared parameters are more appropriate.

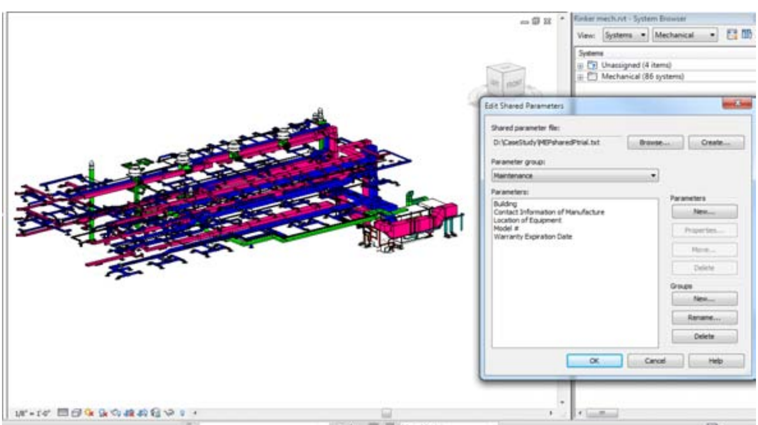

Figure 2. MEP Model and Shared Parameters Editing

Revit allows the user to build a schedule for single or multiple categories, based on the requirement of the end user, different schedule types can be chosen, a multiple category schedule is shown in Figure 3 by using the shared parameters set in Figure 2. Based on the import format that the FM software can accept, the template created in Revit MEP can be saved as an MS Excel file shown in Figure 4 or exported to ACCESS as a mdb file through DBLink as shown in Figures 5 and 6.

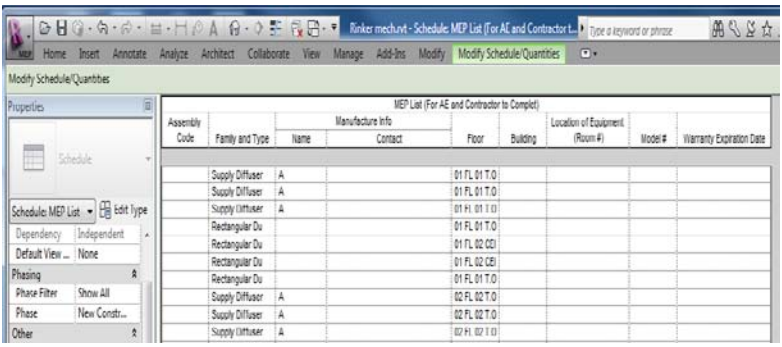

Figure 3. MEP List for Collecting Data in AEC Phase

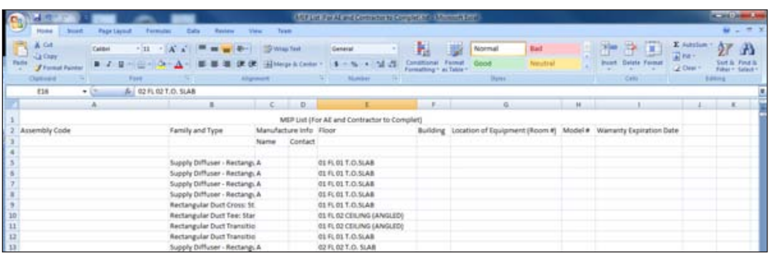

Figure 4. MEP List Export to Excel

Through DBLink, data behind the 3D visualization of the BIM Model can be calculated easily and as the mdb file can be imported back to the Revit model, any changes that happened in the ACCESS can be automatically have the corresponding change to the BIM model after import. In addition, the users can add new fields in the ACCESS database, and the new fields will be the shared parameters in the BIM model (WikiHelp 2012).

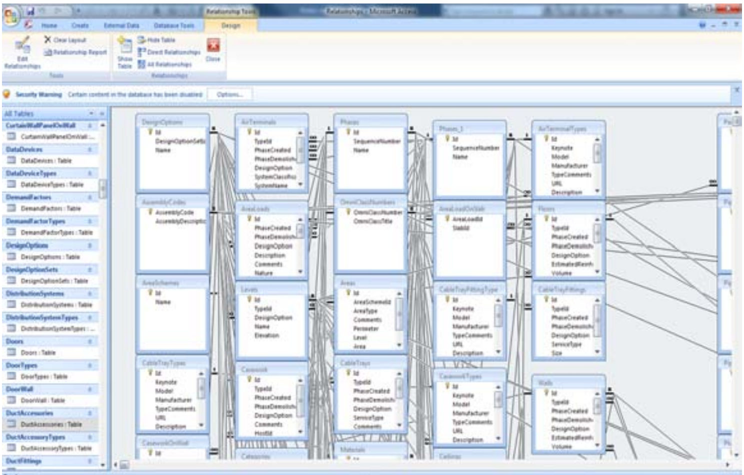

Figure 5. Relationships of Revit Classes

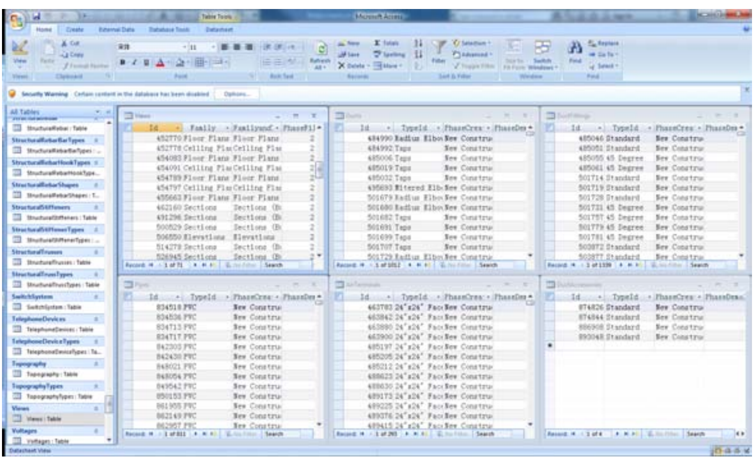

Figure 6. Tables in the Revit Database

Based on what information is needed for the FM software, as we need some more information that the existing FM software that is used by a university, some manipulation of the data field should be edited in the database before import into the FM software system.

CONCLUSIONS AND FUTURE RESEARCH

With the process proposed above, the template is built once in Revit and it can be used repetitively without rebuilding in the succeeding projects if the FM software does not require different data. When the designers and contractors input the required data during the modeling process, the template can be populated automatically and be ready to export.

With the development of building information modeling, knowledge sharing between the facility management and design professionals has become possible. The use of BIM technology in the design and construction phases of buildings is increasing. There is a need to expand the use of BIM beyond the two to three years design and construction phase into the facility management phase of buildings in order to facilitate tasks such as maintenance. The information of a building project that is created and collected in the design and construction phase is valuable for the facility management phase and can help to improve the effectiveness and efficiency of the FM group in operation and maintenance activities. However, the reality of current AECO industry practice is that the facility management phase seldom uses the BIM models even when they are required by the owner in design and construction phase. This fact results in that BIM models are wasted where they would have the most value, in the facility management phase. This paper is a part of the ongoing research of BIM-assisted Facility Management which is aimed to bridge the communication gap between design and facility management professionals. This study focuses on automatically bidirectionally communicating between CMMS and BIM models on a database level. The workflow and case study discussed in this study show that it is possible to automatically transfer information bidirectionally between BIM software and FM software. The storage of FM data in the BIM model can also compensate for the lack of information in current FM software such as cut sheets and 3D visualizations of the work order request, manufacturer contact information and equipment manuals are more easily located for the maintenance work. Future directions of this study may be conducted in querying the required information and fields from the FM software by using Add-Ins or any development by the FM software companies that can make the FM software more compatible with BIM software. As the BIM software package is for design purpose and tends to be expensive, it is not necessary for the FM staff to keep the software itself, if the FM software can contain the necessary information and views from the BIM that are required by the FM staff that would be sufficient for BIM-assisted Facility Management purposes.

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A Semiotic Analysis of Building Information Model Systems

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ABSTRACT

To further understanding about how to use building information systems to communicate, this paper uses computer semiotic theory to study how building information systems operate as carrier of meaning by introducing a semiotic framework for the analysis of building information systems. This framework consists of a basic sign typology and describes several mechanisms of how to compose basic signs to convey more complex meaning in three different semiotic domains: the use process domain, the system's content domain, and the system's user expression domain. The paper also provides a first illustrative application of the framework by analyzing the user interface of a construction process visualization tool. This initial analysis already shows that the semiotic framework can improve our understanding of how well meaning can be exchanged between the system and users.

INTRODUCTION

Semiotics is the study of signs and their use to convey social meaning (Andersen, 1997). Hence, systems that use models representing building information are at their core semiotic tools to support the communication of practitioners and the information exchange between computer applications. Semiotic theories therefore have the potential to help furthering understanding about how such building information systems achieve the communication of information. To leverage on this potential, this paper introduces an analytical framework to understand the use of signs in building information modeling applications that is based on the two strands of visual semiotics (Jewitt, 2001) and computer semiotics (Andersen 1997).

Next to the framework's theoretical introduction, the paper also illustratively shows that the analysis of building information model systems with the framework offers a number of benefits. For one, the framework helps system developers to better design building information model systems and to evaluate how readily possible users can understand and hence use the implemented

functionality. Additionally, the framework offers user of building information model systems and technology managers that wish to introduce such systems a helping hand with understanding possible courses of action while using the system. Finally, users and technology managers can gain a better understanding of how the systems can be used for decision making tasks.

The paper is structured as follows. It starts with an introduction of the semiotic framework. After this introduction the paper presents the application of the framework by analyzing the construction process visualization software Navisworks Timeliner. The paper closes with a short discussion of the analysis' results.

A SEMIOTIC FRAMEWORK TO DESCRIBE BUILDING INFORMATION MODEL SYSTEMS

The development of understandable building information systems is not an easy task because of their purpose to guide engineering decisions. To allow for ready understanding by users, systems need to reduce the complexity of the engineering decision making tasks. Additionally, users have to be able to relate to the options of the system according to the specific decision making situations they are facing. Computer semiotics is a powerful means to analyze how well a building information system can support a user's understanding in different situations. This is mainly because computer semiotic frameworks can describe the composition of the system as well as the context in which the system is used by the same set of concepts. In what follows I will introduce an initial analytical framework to describe building information systems in this way. The framework is mainly developed by drawing, but also extending Andersen (1997)'s seminal work in the area of computer semiotics.

Figure 1 illustrates the developed framework using UML notation. The framework consists of three main parts that each describes different semiotic functions. The first part is labeled as "process" and describes the composition of sign systems that describe the process of user interaction with the system. Process signs are abstract signs as they do not directly occur within the implemented computer system itself. They are rather used to describe the possible interaction processes of users with the system. From a process perspective every BIM system offers different use modes that allow users to complete several tasks. The completion of a task, in turn, requires users to conduct several actions. The second part of the framework, here labeled "content" describes the signs that allow users to initiate and follow these actions. This sign system represents the actual functionality of the system in its interaction with the user. Two different signs are used to interact with the user: handling signs and form signs. Handling signs represent the components of a graphical user interface that allow the user to control the system, such as buttons, menus, or action icons. The second type of signs are form signs. According to Andersen (1997) form signs can be assembled

to forms and represent the interaction from the computer to the user. For example, a 3D navigation window of a BIM application consisting of a number of (form) signs representing building components in a 3D illustration.

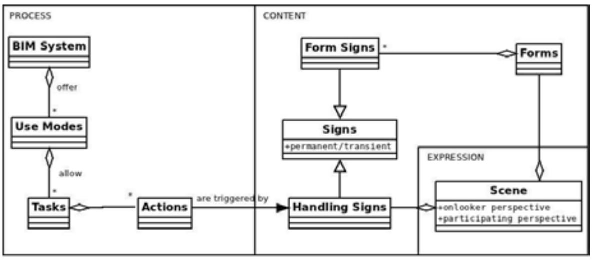


Figure 1. Semiotic framework to analyze and understand building information model systems.

It is important to realize that the concept of form in computer semiotics is, therefore, quite different than the form concept known in graphical user interface development that represents an assembly of fields allowing users to input data. Compilations of these two types of signs represent the content of the computer semiotic system. Signs can be either permanent or transient and are not only restricted to graphical information, but can also be, for example, conveyed through sound or heptic devices.

The final component of the framework is labeled “ expression”. The expression component is used to describe the final understanding that a certain scene generated by a computer has on the user. Computer systems compose scenes from the existing handling signs and the existing forms. This composition together is then interpreted by the user as a specific sign conveying a certain meaning. The meaning is composed of what Andersen (1997) calls an “onlooker perspective” - a perspective that is only passively viewed, and a “participating perspective” that allows users to directly interact with the system.

RESEARCH METHOD

To show the power of the presented analytical framework, I will illustratively analyze the user interface of a building information system to generate process simulations of construction operations - so called 4D models (Kamat et al., 2011). The practical use of such construction process visualizations has been described by, for example, Hartmann and Fischer (2007), Hartmann et al. (2008), or Mahalingam et al. (2010). As an example for a specific implementation of a system to generate and use construction process visualizations I analyzed the product Navisworks Timeliner from Autodesk.

At the outset the Navisworks Timeliner system can operate in two

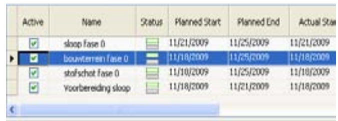
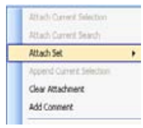
different modes. One mode allows for the creation of process visualizations by giving the user functionality to link 3D objects representing building components with planned construction activities. The other mode let's user control and view the construction process visualization itself. To guide the analysis of these two modes, I consulted a set of previously written guidelines that describe different tasks users can accomplish with the system in each of the two modes. From these guidelines, I then selected different tasks that deemed to be most importantly within the two different modes. After sketching the actions needed to complete these two tasks, I then analyzed the handling signs that make these actions possible and the form signs that visualize the intermediate and final outcomes of the task. Following the general differentiation between content and expression, at the end of the analysis, I then linked this content based description of the system to a description of the final expressions of the system to the user. The next section provides a detailed description of two exemplary tasks – one for each of the two above described modes.

MODE 1: GENERATING A 4D MODEL

Exemplary Task - Linking a set of 3D model objects with a schedule activity. According to the analyzed guidelines this tasks requires the existence of so called 'Selection Sets' - objects within Navisworks that represent a specific grouping of 3D building objects. Once such selection sets have been established (this is a different task I did not analyze in the limited scope of this paper), these selection set objects can be 'linked' with the objects representing project schedule activities, by using the computer mouse's right button while the mouse arrow is positioned over one of the rows within the schedule that represents the specific construction activity. After the right mouse button is clicked a so called context menu with textual symbols describing several possible actions appears on the screen. From the available strings within this menu, the user now can choose the 'Attach Selection Set' string. This again will open a new menu from which the user can select the final selection set.

Table 1 illustrates the outcomes of the semiotic analysis of this task with respect to the process and content domains. The table clearly shows the cascading character of handling and form signs in modern software applications. The resulting form sign of a completed action often is at the same time a handing sign that the user can use to initiate the next action. The left of Figure 4 illustrates the expression domain before and after the task. It is striking that there is almost no expressive feedback to the user after completing the task which easily might lead to wrongly established links.

Table 1. GUI Analysis with the semiotic framework: The task of linking a selection set of 3D objects with a schedule activity.

Action	Sign Type	Sign
"Right-Click" Activity	Handling	
	Form	
Select "Attach Selection Set"	Handling	
	Form	
Choose relevant selection set	Handling	
	Form	

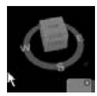
MODE 2: DYNAMICALLY REPRESENTING THE PROCESS VISUALIZATION

Exemplary Task - Dynamically analyzing a construction sequence animation. After a 4D model has been generated by linking 3D objects of building components with schedule activities, users can use the 4D system to animate the sequence. Users can control this animation by using a number of buttons. To start the animation, users have to activate the 'play' button. They can stop the animation at a specific temporal point of interest using a 'pause' button. Upon pressing any of the two buttons the buttons change its form. Again both buttons show a cascading behavior as they are instances of form signs and handling signs at the same time. Another action available to users during the animation is to navigate the displayed 3D model. This can be achieved by using a number of handling signs, to, for example, rotate or pan the view on the model. While navigating the model, a transient handling sign occurs in the middle of the view port to signify that a navigation action is in progress. The analysis of this task is in more detail illustrated in Table 2.

The right of Figure 4 illustrates the expression domain before and after this task. The expressive scene shows significant differences during and before

the task execution. For example, a system of form signs, such as text overlay and an update of the Gantt chart view to signify the construction activities at a certain temporary point in the animation.

Table 2. GUI Analysis with the semiotic framework: The task of dynamically analyzing a 4D model.

Action	Sign Type	Sign
Start Animation	Handling	
	Form	
Change View	Handling	
	Form	
Pause Animation	Handling	
	Form	

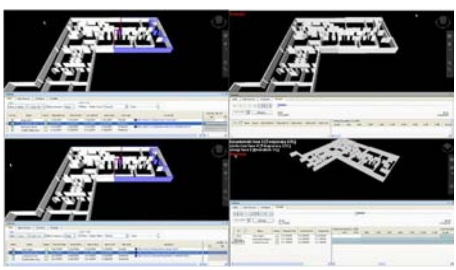


Figure 2: Overall semantic expressions of the system. The scenes presented to the user before (top) and after (bottom) the execution of task 1 (left) and task 2 (bottom).

DISCUSSION

Of course, the presented analysis is still very preliminary in nature and the scope of a conference paper does not allow for the more in depth description of modes and tasks of building information model systems. Therefore, this paper mainly focused on introducing the semiotic framework itself instead of on the illustrative application of the framework. Nevertheless, if nothing more, the above analysis already shows some applicability of the introduced framework to analyze and describe the functionality of this specific construction process visualization system. Similar descriptions of other tasks using the framework will potentially be

very helpful for system developers during the design of new system functionality, but also later on to document existing functionality.

The framework, in particular, is useful to understand problems potential users might have with using the system. In general, users can fail to understand computer systems for two semiotic reasons (Andersen, 1997):

1. The signs used by the computer system conforms to the principles of the, by the developers, intended semiotic system, but users fail to find a relation to what is to be signified by the implemented semiotic system.
2. The signs used in the computer system do not conform to the principles of the semiotic system as it is intended by the developers.

In the case, of the above analyzed construction process visualization system the first type of error can occur quite frequently in the onlooker perspective of the system while observing a 4D sequence. It might, for example, easily possible that a respective construction activity was linked to a wrong selection set. This would result in the wrong set of 3D objects being used to represent the ongoing construction activity. This example illustrates that the first type of understanding failure usually occurs due to inadequate interaction between the user and the system. These type of failures can be counteracted by providing clearer handling signs and, probably more importantly in this context, clearer form signs that show the immediate result of an action. For the above example, the objects within a specific selection set chosen by a user for a certain task could be highlighted in a transient manner after a completed linking task. This transient highlight would then provide an additional visual check for the user to confirm that the right link was established.

The other type of failure usually points to a problem with the implementation of the system itself. An example, for such a failure, can, for example, be found in older versions of Navisworks than the one I analyzed for this paper. In these previous versions, the representation of the schedule was implemented through a simple textual table listing activities and their start and end dates. This did not follow the general convention on construction projects to represent schedules using Gantt charts. This inconsistency with the general accepted principles of construction schedule sign systems sometimes hindered construction professionals to readily understand that construction process simulations actually represented previously established construction schedules.

CONCLUSION

If nothing more, this paper presents an initial framework to understand the semiotics of building information model systems. As discussed in the analysis section of this paper, such a framework can help system developers and researchers to better describe the features and possibilities of implemented systems to potential users. Further, it can help technology managers and users to

understand why the use of a system in a specific context failed. Finally, the framework can help developers and researchers to inform their development efforts of new systems by improving their understanding about how specific features of these systems can be potentially understood and, in turn, used.

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Comparison of BIM Cloud Computing Frameworks

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ABSTRACT

Cloud computing is a hot research topic and is quickly gaining recognition and application in combination with Building Information Modeling (BIM). However, since there is still lack of an authoritative definition of cloud computing, different parties in Architectural / Engineering / Construction (AEC) industry may have very different understanding on what is qualified as BIM cloud computing.

This paper proposes a system under which some of the currently available cloud computing frameworks are classified and the adoption of cloud computing in a specific context can be assessed, and reviews and compares several currently available BIM cloud computing frameworks under this system. The BIM cloud computing frameworks compared include dedicated cloud services for AEC industry such as Revit Server, Revit Cloud and STRATUS, and general purpose cloud services such as Advance2000 and Amazon. The proposed system can be used by IT implementers in the AEC industry when making decisions on adopting cloud computing for BIM applications.

INTRODUCTION

Cloud computing boasts faster application deployment and lower IT cost, which results in higher efficiency and increased agility for a business (Sun 2009). However, different opinions exist on what is qualified as cloud computing (Armbrust et al. 2009). The combination of cloud computing and BIM is quickly becoming a new buzz in the AEC industry, and hence the ambiguity on cloud computing is making its way in the AEC industry as well. An example is Autodesk Buzzsaw, a web-based project management application provided by Autodesk. As recent as in 2011, Autodesk advertised Buzzsaw as a Software as a Service (SaaS) product without any mention of clouds, but now it is advertised as part of Autodesk 360, the

integrated cloud service provided by Autodesk, although there are little if any fundamental changes to the software itself. A more thorough investigation on cloud computing in the context of the AEC industry is required in order to explain this transition.

The intent of this paper is not to redefine cloud computing with yet another definition. In this paper, first a general survey of the existing different opinions and consensus on cloud computing is presented followed by an analysis and classification of cloud computing applications and frameworks including both the general cloud service and the cloud services dedicated to the AEC industry. This may provide some insight to evaluate the organization and in choosing the appropriate cloud services when a construction organization is trying to move its business into the cloud.

DIFFERENT OPINIONS ON CLOUD COMPUTING

A general definition of cloud computing is remote control or software virtualization (Varkonyi 2011). Basically under this concept the application is installed and run on the server side, but controlled by the user on the remote client. What is being transmitted to and from the user is the user interface (UI) as well as the user's operations and commands. A specific terminal program may be needed, but sometimes the UI is completely contained in a Web browser. This concept has been introduced long ago and is applied by a lot of hacking applications. In the Window operating system, there is also a Remote Desktop Connection application under this definition. For definitions of cloud computing with something new, there are at least two representative yet widely different opinions on cloud computing, which could be roughly summarized as Software as a Service (SaaS) and Infrastructure as a Service (IaaS). SaaS refers to the applications delivered as services over the Internet. It is supported by the application vendors that directly deal with end users of their applications, such as Autodesk. As long as the application or services are delivered via the Internet instead of running on the local machine, it does not really matter how it is implemented on the backend. Some argue that the difference between this definition of cloud computing and the traditional applications are that the SaaS applications do not need local installation rather they are run in Web browsers. But then many current Internet applications like email and the World Wide Web fit perfectly within this definition. We argue that the essence of SaaS is really not how the application is delivered, but how the application is charged for, i.e. the business model. For traditional software applications, a user pays for each license or software seat installed, but in the SaaS model, you pay for the time that you are actually using the software, which is similar to the way one pays to play online video games.

The IaaS definition of cloud computing, also mentioned as computing as a utility or utility computing, focuses on how the system is implemented structurally in hardware and at the system software level. It envisions the ease of use of additional

computing resources just like using more electricity, where what you need to do is nothing more than plug in to your power supply (cloud provider). This concept is proposed by the big IT players such as Sun (Oracle) who deal with lower level IT infrastructures. To end users, the benefit is a much lower initial capital cost on new hardware and datacenter and the cost of personnel to operate the additional infrastructure when new applications needs to be deployed. The computing resources required can be purchased with much more flexibility. A computing-intensive task that requires one CPU to run for 1000 hours could be done in 1 hour utilizing 1000 CPUs, since the cost would be the same to the cloud user. So the user of the computing resources does not need to worry about purchasing the additional hardware only to be idled in the future if the task is a temporary one. It is analogous to leasing heavy construction equipment versus buying it.

CONSENSUS ON CLOUD COMPUTING

If a uniform definition of cloud computing is too difficult to come up with, at least there is consensus on some of the characteristics of cloud computing.

Virtualization. Virtualization of the hardware is what makes it possible to utilize the existing computing resources to their full potential, and is the technological foundation of cloud computing. A virtual machine is a software abstraction of hardware computing resources. It is the smallest container that could be deployed and managed as a complete computing system. Through the virtualization of the hardware resources, including storage, CPU and memory, several different virtual servers can be implemented in one physical machine that share the same hardware resources.

Virtualization enhances flexibility as the software can be deployed without being tied and restricted to a readily purchased specific physical server. With virtualization new applications can be deployed without interrupting existing applications; the whole existing computing environment, which may include several virtual machines, can be copied for testing or simply for backup, again without interrupting the work of existing servers.

Network delivery. Sun (2009) claims that "cloud computing is the next generation of network computing". All the definitions on cloud computing agree that cloud computing services should be delivered via a network instead of on a local machine. Network quality is also the main criteria to evaluate the cloud service quality. It is normally deemed that a cloud based application is acceptable only when the network latency is less than 50ms. The bandwidth of the network will reach 100-400 kbs accordingly (Pudney 2011).

One inevitable obstacle is the limited availability of network connections. One of the solutions is the expansion of network providers. The development of mobile networks is minimizing this issue in most urban and suburban areas. Another solution

relies on the software application. It is noted by Armbrust et al. (2009) that this issue has been researched on both the application and the protocol level. Successful applications include the IMAP email protocol and version-control systems like CVS.

On-demand computing resources. The computing resources here generally mean high speed CPUs and large memory and storage, but in the SaaS model it could also mean more seats or licenses of specific software applications when they are needed, although in reality this will depend on the kind of end user license model the software is adopting.

The simplest and first computing resource utilized in the cloud is storage. Even in the very early versions of Windows and Linux systems, one can mount a remote disk and use it just like a local disk. With Internet available, numerous online file storage services are provided by many different companies, including big players like Microsoft SkyDrive, Amazon Cloud Drive, Dropbox.com, and small ones like depositefiles.com or hotfile.com. Other critical computing resources like CPU and memory are being included in the cloud via virtualization. Through virtualization, the computing resources can be distributed to different users dynamically. On one hand, a single set of hardware can be shared by many different users concurrently; on the other hand, many CPUs can be clustered together so that the user can work as if on a single super CPU.

If a public cloud service provider has enough computing resources, it could deliver the resources in such a way that the user will get an illusion of infinite computing resources available when needed. For private clouds, instead of being infinite, the amount of total computing resources available will be restricted by the total computing resources the organization owns. But these limited computing resources can always be allocated among the users dynamically. For example, when the CPU is not being used by a designer developing a building information model, it can be automatically reallocated to be used by a rendering program.

Pay-by-use business model. To the end user of a cloud computing framework, the true benefit will not be achieved without the pay-by-use business model, under which the computing resources are flexibly billed and paid on a short-term per-use basis, only for the amount of actual computing resource consumption by the end user, like CPU hours used or disk space used. This model is also known as pay-as-you-go or usage based pricing (Armbrust et al. 2009).

When planning a datacenter, it is designed to handle the peak workload, which exceeds the average work load by a factor of 2 to 10, which means most of the time only 5% to 20% of the computing resources are actually being used (Armbrust et al. 2009). This is a huge waste of the computing resources and money. Combining the infinite computing resources with the pay-by-use business model, companies could eliminate the upfront cost of IT infrastructure planning and maintenance. The cloud

user does not need to rigorously predict and commit to a certain amount of computing resources from the provider. They could start small, yet get the computing resources when they are needed. If they realized the additional computing resources are not necessary anymore, they can always release them without obligation. Thus the risk of IT over-provisioning or under-provisioning due to a too optimistic or a too pessimistic prediction is eliminated. This model also gives the user the opportunity to trade money for time savings. A task that requires 1000 CPU hours can be finished in approximately one hour with 1000 CPUs rented from the cloud provider.

COMPARISON OF BIM CLOUD FRAMEWORKS

Cloud frameworks are classified according to their abstraction (virtualization) level, based on the classification criteria proposed by Armbrust et al. (2009), but with extensions specific to the AEC industry. Generally, the deeper the abstraction level, the more virtualized computing resources will be available to the user to manipulate; and the more advanced IT skills and personnel are required.

Within software application. On this level some parts or functions of the application is integrated with backend cloud computing resources. Two parts that are mostly moved to cloud is storage and computing intensive functions. As discussed above, storage (including backend backup and synchronization among multiple copies of the file) is one of the first computing resources being moved into cloud. Revit Server is one of such cloud functions implemented in Autodesk Revit.

It is expected that software applications are moving the computing intensive functions into the cloud where parallelism can be exploited to utilize hundreds of CPUs to finish a task in a short time. Photo rendering based on the building information model is a good example that especially suits this application. Autodesk Revit already has a cloud rendering add-in that can upload the project information into the cloud and return the finished rendering picture when it is ready.

These kinds of cloud applications are transparent to the user, meaning that the user does not need to be aware of the fact that cloud computing is being used instead of local computing resources. Therefore, decision of whether to use the cloud or the local version of an application will not affect the workflow, but the cloud version will generally bring additional benefits like collaboration with partners or less time spent on rendering.

Within domain/vendor platform. Those cloud solutions are not limited to a particular application, but they also clearly stipulate their intended domain of use, sometimes only within a range of limited products from the same vendor. Some basic IT skills including programming in a certain language and basic system configuration knowledge are required. The API usually enforces a specific application structure and standard for the user to choose from. On the other hand, the vendor usually will

provide detailed tech support on the products, and will take care of the interoperability issues between the products within the platform. It would be relatively easy for a general IT department of a small or medium construction company to start such a cloud with the help from the provider.

The Autodesk 360 cloud solution is a typical domain/vendor software platform cloud computing model that does not need hardware level reconfiguration of the current IT infrastructure of the organization. Autodesk currently has several products being advertised as part of its cloud computing infrastructure, while Autodesk 360 is the collection of those cloud-based tools, with Autodesk Vault data management software as a primary product. The main focus of Autodesk 360 is data management, which is basically adding the file storage cloud functions discussed above with a nicer interface integrated in current applications such as Revit and Navisworks. The collaboration with external partners in a single project is provided by Autodesk Buzzsaw.

Another trend on this level is mobile interactive applications. They are identified as a kind of application especially suitable for cloud computing because they require high availability and may not have the computing power to run the application locally. Via Autodesk Cloud a model can be shown in a browser without any software installed on the computer, and it is expected to be widely used on smart phones and tablet computers on the construction jobsite.

High-level general purpose cloud frameworks. High-level general purpose cloud frameworks are based on computer industry standard and facilitate interoperability between different platforms. The basic model is to keep the program and data running in the cloud, while only transferring a GUI to the user. This kind of cloud framework does not limit the applications that could run on the platform, so they support general purpose computing instead of a certain category of applications.

On this level the system generally will take care of routine data management automatically, like system backup, failure recovery and data replication. It is relatively easy to get started compared to the low-level cloud frameworks, but advanced IT skills are still required to manipulate the programmatic API and to get the system running smoothly. Performance should be adequate to run general office applications, but may not be adequate for real time communication of intense computing applications. Examples of the cloud applications on this level include J2EE and Microsoft Azure.

STRUTUS is an example of cloud services on this level and is built by Stephenson & Turner, New Zealand (Pudney 2011). A broker server is in charge of assigning connections to the server farms. Computing resources on the servers are virtualized as a pool that is scalable simply by adding new hardware. The desktops that used to run Revit locally become a thin-client interface between the user and the cloud servers in this configuration, greatly reducing the cost of investing in new

laptop/desktop computers.

Low-level system software and hardware virtual machine. At this level the IT infrastructure within the company may need an overhaul to accommodate the requirement of cloud computing. Examples of cloud services on this level include Amazon Elastic Compute Cloud (EC2) and VMware systems. Technically it would be appropriate to subdivide this level into two sublevels: a level on system software (VMware) and a level on hardware virtual machine (EC2). But since this detailed division is not very useful in the AEC industry context, they will be discussed together.

The users on this level can use the powerful application programming interface (API) provided by the service provider that can control almost the entire virtual machine, from the kernel operating system to the application software, but significant IT skill is needed to manipulate the API and to configure the virtual machines. Data safety and redundancy management are also usually left to the user, since those functions are very difficult to implement automatically at this level.

These requirements of advanced IT skills may not be within the reach of most construction companies, but they will have the alternative of using a consulting company to manage the IT resources. This is also an outstanding opportunity for small and medium construction companies to rent high-end virtual datacenter capabilities at only a fraction of the cost of actually building and operating one from scratch.

STRUTUS mentioned above is a typical private cloud developed, used and maintained by a single organization. Advance2000 is a public cloud service provided by IT vendors to the general public (France 2010). Instead of focusing on the remote access capability emphasized by STRUTUS, Advance2000 system focuses on the complete utilization of the currently existing workstation/server computing resources of an organization. Almost all the business logic can operate in the cloud. With abundant network bandwidth support, a company could deploy a remote office very quickly with almost no IT infrastructure change.

CONCLUSIONS

Cloud computing is built on existing well-established approaches and technologies. However, by inventing a new way on how to develop, deploy, maintain and pay for the applications and infrastructures, cloud computing is defining a new computing environment. Under this model computing resources, including both software and hardware, can be rented like utilities without purchasing or signing long-term contract commitments with an IT service provider. As a result the cost and risk of actually owning the IT infrastructure is shifted from the computing resource consumer to the cloud computing provider. Cloud computing is seen as having the

potential of transforming the IT infrastructure of the AEC industry.

Different parties in the AEC industry have their own specific computing requirements regarding cloud computing. Based on the framework proposed in this paper, the first consideration should be how cloud computing is supported on the software or platform level by the currently used software application vendors. If the software used happens to have cloud support, it would be a great starting point to use the cloud with minimal cost. If those options are not available, the company should consider using general purpose or system level cloud computing frameworks. However, those frameworks generally require a high level of IT skills and a much higher initial investment. The benefit could also be difficult to trace since try trial and errors approaches are not avoidable in during the initial deployment.

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Post-disaster Robotic Building Assessment:
Automated 3D Crack Detection from Image-based Reconstructions

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ABSTRACT

Natural disasters can compromise the structural integrity of buildings. Three dimensional post-disaster building models, created using image-based 3D reconstruction techniques, would help early responders assess the extent of the damage. Image-based 3D reconstructions are advantageous as they only require a camera and tens of pictures to create a 3D mesh model. Under some circumstances responders can collect these images; however, if a building is suspected to have sustained significant damage, it may be neither safe nor straightforward to examine its structural integrity. Therefore, an approach is needed which allows responders to remain away from compromised buildings while gathering images for a 3D model. We propose the use of a small ground robot to take pictures of building elements remotely. Once the images are collected, an element model is created using a pipeline of Structure from Motion, dense reconstruction, and surface modeling. This model is compared to a pre-existing CAD model or examined to assess the likelihood of any structural damage. We also demonstrate a new automatic 3D crack-detection algorithm to assist examiners in identifying structural defects. Our preliminary results show that this process can successfully identify numerous cracks in the 3D reconstruction of a sample concrete column. The perceived benefits of the proposed method in a post-disaster situation are also discussed in detail.

INTRODUCTION

Natural and man-made disasters are becoming an increasing concern as the population of urban areas continues to grow. In dense urban environments these disasters can cause extensive structural damage to a large number of homes, offices, and public buildings. Human lives are at great risk in the initial disaster; nonetheless, search and rescue efforts afterwards (and later, damage assessment and reoccupation) can still be perilous due to uncertain knowledge of buildings' stability. If the information required to assess stability could be gathered and processed remotely,

early responders and engineers could more effectively respond, perform detailed assessments, and better plan for rescue and recovery in the affected areas. Here photography represents one quick and effective method of collecting data about a building's condition. Pictures collected in the proper fashion can be used to create a 3D model of a damaged structure. It may be safe for people to walk around and take these images from the exterior of buildings; however, examining interior supporting elements such as columns and beams would require entering into a compromised building and potentially put a responder's life at risk.

To address these challenges, this paper presents a new automated post-disaster building assessment that could be carried out by a small mobile robot. In the proposed method, the operator would remain safely outside the building structure while the robot, equipped with a digital camera and wireless controls, enters the building to gather the images needed to reconstruct a 3D model. Once a 3D point cloud model is reconstructed, the outcome will be assessed using a new algorithm to identify and color-code locations for cracks. The resulting models enable the geometrical characteristics of the cracks to be quickly and easily measured and ultimately lead to an accurate assessment of all building elements.

In the following, first prior research on automated crack detection and image-based 3D modeling approaches is overviewed. Next, a motivating scenario and the process for 3D reconstruction and crack detection are described in detail. Finally, the validation case study and the discussion of the potential benefits and limitations are addressed.

RESEARCH BACKGROUND

Automated crack detection. There are a variety of different crack detection techniques that exist for various materials. Some of the previous research benefits from application of a laser scanner. Despite the benefits, a laser scanner is an expensive, heavy device which can significantly increase the payload on a robot. In addition it requires significant power for operation and may require several markers for registration of the scanned point cloud. Because of these limitations, their application may not be very attractive.

On the other hand, in the past few years several research groups have proposed the use of image-based approaches for crack detection. Examples of these efforts include 2D crack detection for asphalt roads (Koch and Brilakis 2011, Saar and Talvik 2010), or building surfaces (Zhang et al. 2011, Zhu et al. 2011). Despite their benefits, these approaches do not provide 3D depth information and as a result do not enable measurement of severity of these cracks.

Automated image-based 3D reconstruction. In recent years, several research groups have proposed techniques that can automatically generate 3D point cloud models from a collection of digital images (Golparvar-Fard et al. 2012; Furukawa et al. 2010, Snavely et al. 2006) . Popular techniques such as Structure-from-Motion (SfM) rely on identifying "feature points" that are common among the images and projecting them into three dimensional space. SfM output can also be paired with dense reconstruction methods, which results in more dense 3D point clouds than just the feature points alone. The model produced by a dense

reconstruction can also be post-processed to create a continuous surface model (mesh) of an object. The mesh elements can then be examined to determine a variety of useful information for assessing the geometric properties of the original object.

MOTIVATING SCENARIO

After a tremor in an earthquake-prone region of the U.S. rescue crews are dispatched to search for survivors. Once they complete their initial searches in the hours following the quake, surveying and recovery efforts begin, and engineers and building inspectors start to examine the integrity of potentially damaged structures. A building which shows some visible cracking and loose debris on the exterior is declared unsafe to enter for a full assessment. Inspection teams equipped with a small ground robot (with a high resolution camera) arrive on the scene and set up at a safe distance from the damaged structure. They remotely navigate the robot into the building and locate a vital structural support (e.g., a concrete column on the first floor of an office building). Once the entire column is visible to the robot's camera an autonomous algorithm drives it around the target, collecting a series of 40-50 images as it goes. These images are transmitted back to the base station where a powerful computer begins to construct a detailed 3D model. The robot is then driven to the next structural element, and the process is repeated.

Once the images have been collected and 3D models generated, they are analyzed with a crack detection algorithm such as the one presented herein. The inspectors then examine the color-coded models, assessing the extent of the damage, and determine if the building is safe for reoccupation or a more detailed human investigation.

This robot-assisted process could also help complete the "Rapid Building and Site Condition Assessment" form provided by the National Center for Preservation Technology and Training (NCPTT, form also used by the Federal Emergency Management Agency) (Streigel et al. 2011). The form lists a variety of basic information regarding the inspection date and time, type of structure, amount of damage, etc. For instance, in the "Evaluation" section, the robot-based reconstruction would be ideal for identifying and quantifying a "Collapsed or off foundation", "Leaning, other structural damage", and "Foundation damage", to name a few areas of use. It could also easily deliver a detailed structural evaluation if it were recommended in the "Further Actions" subsection, and provide an estimate of the overall building damage. This NCPTT form is referenced here simply to illustrate how robotic assessment could be integrated into existing emergency procedures.

PROCESS PIPELINE AND DETECTION METHOD

The 3D mesh model used by the crack detection algorithm (CDA) is generated using a semi-automated pipeline (all steps except trimming are automated). Figure 1 illustrates the image-based 3D reconstruction pipeline used in this work.

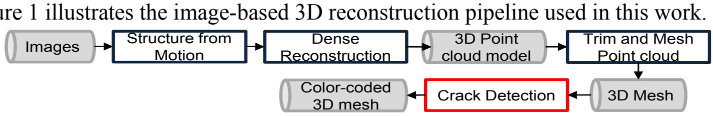

Figure 1. Pipeline Used to Process Images

First, a series of approximately 50 images is collected from locations equally spaced around the target object to reconstruct. These images are fed into a structure-from-motion algorithm (Snavely et al. 2006), which was modified to use SIFTGPU algorithm (Wu 2007) for rapid feature point detection. The outputs go into a Clustering Multi-View Stereo algorithm (Snavely et al. 2010) to generate a dense 3D point cloud model. Next, the point cloud is trimmed and using the Poisson surface reconstruction approach (Kazhdan et al. 2006), a colored mesh model is created.

Once the colored 3D mesh model is created, it is rotated so that the object's sides are aligned with the XYZ axes, and the Y direction is along the long axis of the object. At this point the main new work presented in this paper (represented in Figure 1 by the box labeled "Crack Detection") begins.

The new crack detection algorithm (CDA) is derived from a very basic principle: if an element of a building (e.g., a column) is undamaged, its surface normals should be perpendicular to the element's axial direction. An undamaged element can have any consistent cross-section (even circular) and this principal will still hold true. Inversely, if an element is damaged, then some of its surface normals should not be perpendicular to the element's axial direction.

These criteria provide the basis for creating the CDA. The Poisson mesh creates hundreds of thousands of individual triangular mesh elements, and the building element's axial direction is aligned with the Y-axis. By examining the surface normal for every mesh element, its orientation relative to the axial direction can be computed. If the normal is within a threshold angle of perpendicular the element is considered undamaged (not cracked), but if it is far from perpendicular the element is considered to be damaged (cracked) and marked as such. Functionally, what this will do is identify all Poisson mesh elements whose surface normals point more up or down than directly outward from the building element. A diagram of the normals comparison is shown in Figure 2.

In the figure the angle β represents the difference between the axial direction and the normal of a given surface mesh element. Taking the absolute value of $90-\beta$ creates a tolerance for slight deviation either up or down from perfectly perpendicular. If $|90-\beta|$ is greater than a threshold angle (e.g., 15°) then the element does not align well with the rest of the column and is considered part of a crack. The pseudo code for the algorithm is presented in Table 1.

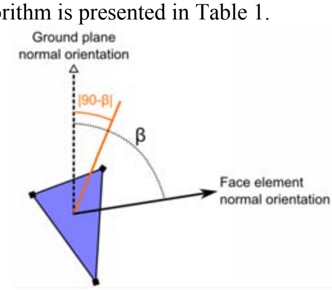

Figure 2. The Normals Angle Comparison Criteria for Crack Detection. The Building Element's Axial Direction is Along Ground Plane Normal.

Color-coding enables rapid crack identification when the output model is viewed. In the proposed method, red tinting is used to indicate detected cracks whereas green tinting is used to indicate uncracked areas. In practice this clearly demarcates the cracked regions, as can be seen in the figures in the results section.

Table 1. The pseudo code of the proposed algorithm

```
Load all mesh face elements (3, 3D points per element)
Examine a face element
Compute its surface normal (from 2 vectors connecting the 3 points)
Compare its normal to the ground plane/axial direction (angle β)
If |90-β| > threshold (e.g. 15°)
        Mark as cracked (tint red)
Else
        Mark as uncracked (tint green)
End If
Move to next face element
Save all tinted elements
```

Another type of detection that is used but was not listed in the pseudocode is a determination of surface completeness. When a Poisson mesh model is created, all of its points are by default set to pure white. A simple closest point heuristic is used to transfer the colors from the dense point cloud to the mesh model. The same algorithm is also used to calculate surface completeness. Any mesh vertices remaining pure white (RGB 255,255,255) after the texture-mapping do not have a corresponding point in the original point cloud. They are artifacts of the Poisson reconstruction. Therefore, the area associated with face elements containing these points can be computed and marked as "incomplete". Comparing this value to the total area provides a percentage of surface completeness. This is an important parameter to report, since if the physical surface is not completely reconstructed, some cracks or structural defects existing in reality may not be automatically detected and identified from the incomplete model.

EXPERIMENTAL SETUP

A full-scale experimental setup was created in order to assess the real-world performance of the crack detection algorithm. The target object to reconstruct was a 140(h)×53(w)×23(d) *cm* section of concrete cracked during a load test. It contained two major cracks on the "front" side, with the upper, larger one having a height of approx. 10*cm* and a depth of 5-6*cm*, and the lower, smaller one having dimensions of approx. 3*cm*(h)× < 2*cm*(d). There were several smaller cracks appearing on the column as well (see Figure 4 in the Results section).

This concrete column was placed in the center of a flat, clear area and photographed using a point-and-shoot digital camera attached to a small mobile ground robot built by Virginia Tech's Unmanned Systems Laboratory (Figure 3).

From previous testing it was determined that 48 images should be sufficient to produce a detailed reconstruction. Therefore, these images were collected by positioning the robot at 30*cm* intervals along a circle with a radius of 2.4*m* around the column (this distance was chosen since it allowed the entire column to be visible in every camera frame).

Once all 48 of the 7 megapixel images were collected (which took about 5 minutes) they were transferred to a six core, 3 GHz computer for processing. They were run through the image-based 3D reconstruction pipeline described above, and after one hour of computational time, a dense reconstruction of the column and surrounding area was created (current implementation performs all reconstruction steps sequentially and as a result has a high computational cost). This point cloud was trimmed to contain only the column and meshed. Afterwards, it was rotated and scaled prior to running the crack detection algorithm implemented in Matlab.

Figure 3. Small ground robot platform and camera used to acquire images. The robot is approx. 45 x 40 cm, and the camera was mounted 45 cm above ground.

EXPERIMENTAL RESULTS

The point cloud model of the column captured a full 360 degrees and contained some 309,000 colored 3D points. The generated Poisson mesh from the dense reconstruction contained 228,000 vertices and 455,000 faces (solver divide = 12, octree depth = 12). Using the completeness criterion discussed above the meshed model was determined to be 100% complete. A sample image of the column and its various models are shown in Figure 4.

Figure 4. From Left to Right, the Concrete Column Used as a Test Element, the Point Cloud Model, and the Poisson Mesh Model.

Following the creation of the 3D mesh model the crack detection algorithm was run to test its performance. The CDA successfully identified a wide range of cracks visible on the column, including both the 10*cm* and 3*cm* high ones previously mentioned. It was also able to pick up several other smaller cracks and surface defects in the concrete, including a crater-shaped depression appearing on the back of the column (not visible in the images shown here). However, cracks which were perfectly vertical or too small to be reconstructed in 3D (less than 0.5*cm* height)

could not be automatically identified. Finding perfectly vertical cracks is not possible using the current version of the algorithm, since it only examines normals for deviation from perpendicular, regardless of the direction they point in that plane.

Figure 5 presents the color-coded model after analysis with the CDA. Notice that the cracked regions (areas whose mesh element faces are not perpendicular to the column's axis) are clearly identified with a reddish hue. The figure also demonstrates the effect of changing the threshold angle for detection. In the upper left corner, the more conservative angle criterion of 20° is used, which allows for greater deviation before an element is flagged as part of a crack. The larger image uses the standard angle criterion of 15°, and the lower left corner uses 10°. The 10° threshold, as expected, finds the largest number of cracks. In these experiments, the range of angles chosen represents the region in which cracks were successfully identified without returning too many false positives.

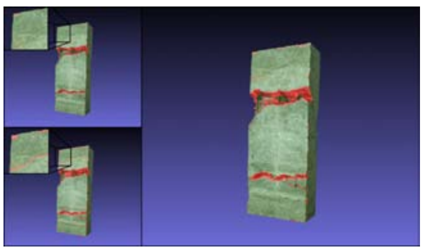

Figure 5. Colored Mesh Model after Running Crack Detection Algorithm. The Threshold Angle is Varied Between 20° (Upper) to 15° (Right) to 10° (Lower).

Model scaling based upon knowledge of the first two camera positions (approx. 30*cm* apart) also worked well. Using only those two points in the reconstruction, the model was automatically scaled to 97% of its true dimensions, and from the model the estimated cracked area was 1322cm^2. Additionally, the crack detection algorithm was able to locate and mark some cracks which were difficult to identify in the original images (see Figure 6).

CONCLUSIONS

This work successfully demonstrated a new automated 3D method for identification of cracks in building elements. Cracks of heights 10*cm* and 3*cm* were found and color-coded on a 3D model of a 140*cm* tall concrete column, and some were able to be identified in 3D that were very difficult to see in 2D images. Cracks smaller than 0.5*cm* could not be detected because they were not reconstructed in 3D.

Figure 6. An Illustration of One of the Benefits of the Algorithm – A Crack That is Difficult to Locate in A 2D Image is Found and Clearly Identified in 3D.

It is perceived that this algorithm and the robot-based image collection presented herein would be ideal for use in post-disaster scenarios. First responders and engineers could remain out of unstable structures and still gather the information they need to perform a detailed damage assessment. Furthermore, while the crack detection algorithm was applied to image-based 3D reconstructions, since it operates from a meshed model, the source of that model is not significant. Laser scanners or other advanced mapping methods could easily be used to collect the data as well.

FUTURE WORK

Several potential improvements are apparent when comparing the motivating scenario with the experimental setup. First, a wider variety of building elements should be reconstructed and examined (e.g. different sizes of columns, concrete walls). Fully autonomous image taking and processing are also under development and would be the next logical step towards simplifying the process. It would also be ideal for the robot to automatically map a series of columns, not just a single column (though this might just consist of repeating the single column process). Use of other robotic platforms, such as quadrotor aerial robots which could fly and avoid ground-based obstacles, would also assist in image collection. Structural analysis could also be automatically conducted to assess the impact of the cracks. Combining all proposed improvements would create a fully autonomous process for building structural analysis and help speed disaster recovery efforts.

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Evaluating Physiological Load of Workers with Wearable Sensors

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ABSTRACT

The U.S. construction industry suffers from high rates of fatalities, injuries and illnesses. Non-fatal injuries and illnesses also lead to low construction productivity. Among various types of hazards construction workers are exposed to, excessive physiological loads have generated unnoticed but profound negative impacts on construction productivity and safety. This research aims at automatically detecting the physiological load of construction workers by using wearable sensors. The research utilized off-the-shelf bio-sensors that collect heart rate and energy expenditure in real time. Biomedical measurements were carried out during masonry wall construction. The collected data were analyzed statistically and compared with the subjective feedback from test participants. The authors introduced an index to quantify the level of physiological load for construction workers. The ultimate goal is to develop a prevention system that reduces fatalities and injuries, and increases construction productivity on construction sites by automatically monitoring workers' physiological conditions in real time.

INTRODUCTION

The construction industry employs almost 7% of the total U.S. labor workforce (BLS, 2009). Preliminary numbers from 2009 indicate that construction related accidents accounted for 816 deaths; a number that constitutes 19% of the total work related deaths across all industries (BLS, 2010). In 2009, the incident rate for non-fatal occupational injuries and illnesses involving days away from work per 10,000 full-time workers was 382.1 in the construction industry, compared to an average of 117.2 among all industries (BLS, 2009).

Moreover, construction productivity in the U.S. remains a critical issue. The construction industry is a major contributor to the U.S. economy. According to the U.S. Bureau of Economic Analysis - USBEA (2011a), 3.4% of the U.S. gross domestic product (GDP) is generated by the construction industry. The contribution of the construction industry to the national GDP increased from $384 billion in 1998 to $501 billion in 2010. A study by the National Institute of Standards and Technology (NIST) and the Construction Industry Institute (CII), using an index based on total installed cost per field work hour, suggested a general decline of

project-level construction productivity from 2000 to 2007 (Kang, et al., 2009). Industry-level construction productivity estimates by several scholars also tend to show a general pattern of productivity decline (Dale W. Jorgenson et al., 2005; Dyer & Goodrum, 2009).

Although low construction safety and productivity are two different issues, they are both influenced strongly by the physical condition of construction workers. A better understanding of physical capacity and the limitations of construction workers may enhance worker productivity and reduce the potential for injuries (Oglesby et al., 1989).

Due to the labor-intensive nature of construction industry, construction workers frequently suffer from high physiological demands. Multiple construction trades including bricklayers, scaffolders, carpenters, plumbers and painters suffer from excessive exposure to physiological load (Hartmann & Fleischer, 2005). Powell & Copping (2010) found that workers in the construction industry suffer significant detriments to their performance under fatigue conditions induced by inadequate sleep. By examining the physiological workload of construction laborers, Abdelhamid & Everett (2002a) concluded that most of the workers were working at fatiguing levels. Many construction activities are involved with repetitive tasks such as bending rebar, lifting and handling heavy construction materials. The recovery time for repetitive tasks can be longer than three times the load time due to the fatigued state of workers (Hartmann & Fleischer, 2005). Moreover, many workers in the construction industry are not aware of their physical state under high physiological workloads or the corresponding consequences.

The proposed study used wearable nonintrusive sensors to monitor the physiological workload of construction workers in real-time. Test participants constructed masonry walls after observing the actual activities on construction sites and learning from experienced bricklayers. The rest of the paper is organized as follows: the next section presents the research background and motivation; followed by the description of research methodology and test setup; the last section analyzes the test results and concludes the paper.

BACKGROUND AND MOTIVATION

Excessive physiological workload in construction workers results in decreased productivity, lack of motivation, inattentiveness, poor judgment, low work quality, accidents and injuries (Brouha, 1967). Frederick Taylor observed that the output of strong men who carried cast-iron pig increased from 12.5 long ton per day to 47 long ton per day when they worked 42% of the time and rested the remaining 58% of time (Taylor, 2005). Rohmert's law shows that the maximum length of time that a person can exert a muscle decreases exponentially with the maximum force (Kerkhoven, 1961). Workers performing tasks involved with heavy energy demands tend to be more productive in the morning than in the afternoon (Oglesby et al., 1989).

Construction health and safety is also threatened by frequent exposure to high physiological loads including overexertion and repetitive tasks. In 2009, 13.76% of the nonfatal injuries were caused by overexertion with a large portion involving lifting. Repetitive motion accounts for 2.53% of the total non-fatal injuries and illnesses in the construction industry (BLS, 2010).

Apart from low productivity, physiological loads exposed to construction workers lead to poor construction health and safety. Although it is widely recognized that fatigue induced by heavy physiological workload commonly exists among construction workers (Abdelhamid & Everett, 2002a), only a few studies have been conducted to measure fatigue on construction site due to lack of efficient or comprehensive methods. Fatigue is well researched in the manufacturing, aviation and transportation industries and is reported to be the cause of several most visible incidents in the world including the grounding of the Exxon Valdez, the Three Mile Island and Chernobyl nuclear accidents, and the BHP Texas oil refinery disaster (Gomez, 2007; National Transportation Safety Board, 1999). The critical role of fatigue in other industries can be applied to the construction industry because of the common elements shared among these industries such as repetitive work tasks, operation of heavy equipment, work shifts and complicated work processes (Powell & Copping, 2010). For example, vehicle and mobile heavy equipment, which are commonly used in transportation and aerospace industry led to 469 deaths (37.7%) out of a total of 1,243 construction deaths (CPWR, 2007).

Three basic methods have been deployed to measure the physiological demand. The first method, introduced by Frederick Taylor, is to observe the work performed by individuals under a given ratio of work and rest time (Taylor, 2005). The second method is to measure heart rate during and after the given task is performed (Abdelhamid & Everett, 2002b). The third method is to measure the energy expenditure indirectly from oxygen intake (Oglesby et al., 1989). In the construction industry, these three measuring methods are usually time-consuming and carried out manually after construction completion. Therefore, the results tend to be error-prone since they cannot reflect the actual physiological conditions onsite.

With the development of modern bio-sensing technology, some advances have been achieved in measuring the physiological load of construction workers. There are a few studies available to evaluate the physiological loads of construction workers. Abdelhamid and Everett evaluated the physiological demands during construction work from two aspects, the heart rate and oxygen uptake (Abdelhamid & Everett, 2002b). The KB1-C system deployed by Abdelhamid and Everett to measure the oxygen intake required test participants to wear thick masks and carry boxes on their back while performing construction activities. This measurement was intrusive and interfered with the regular performance of construction workers. Faber et al. measured the physiological loads on construction workers to investigate the effects of 12h work-shifts and extended workweeks (Faber et al., 2010; Turpin-Legendre & Meyer, 2003). The measurement was carried out before and after the 12h work-shift which could not reflect the actual conditions during construction work. Turpin-Legendre and Meyer measured the physiological workload of construction workers under different personal protective equipment (PPE). However, the metabolic rates of construction workers were subjectively observed and recorded, and these measurements tended to be error-prone (Faber et al., 2010; Turpin-Legendre & Meyer, 2003). Gatti et al. compared the effectiveness and accuracy of different physiological status monitors (PSMs) during the tests such as weight lifting, moving arms, and running on treadmill (Gatti et al., 2011). Considering the dynamic nature of

construction work and harsh environments onsite, further tests are needed to validate the results.

METHODOLOGY

Two types of wearable bio-sensors were utilized to monitor the physiological load during the test. One was a heart rate monitor which measured the heart rate of the test participants with a chest strap. The heart rate sensor comprises of three parts, a chest strap which measures the heart rate and sends out signal; a wrist watch which communicates wirelessly with the chest strap and stores the data; the heart rate data are uploaded to a local PC. Another sensor measured energy expenditure and was tied to the arms of the test participants. Raw data were uploaded to an online computing center, which provided feedback, including energy expenditure. Both sensors were off-the-shelf products and no calibration was performed prior to testing.

Test participants were asked to provide verbal expressions on their subjective feelings about the physiological load and fatigue condition. Afterwards, paper-based surveys were conducted with participants to collect ratings of perceived exertion (RPE) based on Borg's CR-10 scale (Borg & Ottoson, 1986). This instrument is a 10-point category scale to identify the exertion of participation after physical work. The higher the RPE, the more exertion perceived by the test participant.

Four indexes, including average heart rate, average energy expenditure, peak heart rate and peak energy expenditure are calculated from the output of the utilized wearable sensors. Different levels of physiological loads can be specified by the ranges of these indexes, which are specified in Table 1.

Considering the variance in the physiological load classifications due to different indexes, the authors introduced an innovative index to compare the overall level of physiological load. A rank from 1 to 5 is assigned to light work, moderate work, heavy work, very heavy work and extremely heavy work. Then, the ranks specified by different indexes are integrated together to represent the overall level of physiological load. The equation can be expressed as Eq 1,

$$\beta_j = \frac{\sum_{i=1}^{4} R_{ij}}{4}$$

β_j is the overall level of physiological load for test participant j. R_{ij} is the ranking of physiological load of index i for test participant j. The higher β_j, the higher level of the overall physiological load.

Lastly, these results are correlated to the interview and RPE of the test participants to evaluate the effectiveness of these proposed wearable sensors in evaluating the physiological loads on construction sites.

Test description. A test was designed to monitor the physical conditions of test participants while they were performing bricklaying tasks. The authors chose the masonry activities to test mainly because bricklayers suffer from frequent overexertion related injuries, which lead to time away from work. In 2005, the rate of back injuries and illnesses was 75.4 per 10,000 workers in the masonry trade, which was the highest of all trades in the construction industry (CPWR, 2007).

Table 1. Index Range to Evaluate Physical Load

Index	Range	Work Load	Literature
Average Heart rate (bpm)	Up to 90 90-110 110-130 130-150 Over 150	Light work Moderate work Heavy work Very heavy work Extremely heavy work	(Astrand & Rodahl, 1986) (Brouha, 1967)
Average Energy expenditure (cal/min)	Up to 2.5 2.5-5.0 5.0-7.5 7.5-10.0 Over 10.0	Light work Moderate work Heavy work Very heavy work Extremely heavy work	Adapted from (Astrand & Rodahl, 1986) based on 5 kcal per liter of oxygen (Wilmore et al., 2008)
Peak Heart Rate (bpm)	75-100 100-125 125-150 150-175 Over 175	Light work Moderate work Heavy work Very heavy work Extremely heavy work	(Abdelhamid & Everett, 2002b)
Peak Energy Expenditure (cal/min)	2.5-5.0 5.0-7.5 7.5-10.0 10.0-12.5 Over 12.5	Light work Moderate work Heavy work Very heavy work Extremely heavy work	(Wilmore et al., 2008)

The bricklaying test was conducted in the civil engineering lab at the University of Southern California. Standard concrete masonry blocks were selected to construct a piece of wall which was 2.4 m by 2.6 m. There were 6 blocks in one course of the wall and 13 courses in total. Each block was 0.2 m in width, 0.4 m in length, 0.2 m in height, and weighed approximately 7.5 kg.

Bricklayers often need to repetitively lift, maneuver and handle heavy construction materials such as concrete masonry units (Hess et al., 2010). When constructing the wall above head level, the test participants stood on an electronic lifting platform, which simulated the role of scaffolds on construction sites. In order to stimulate real conditions on construction sites, test participants went on a field trip to observe and learn how bricklayers actually work at a masonry construction site in Los Angeles. Project managers were present to guide the test participants and provided instructions and experience. Test participant information is listed in Table 2 in detail.

Test results. The heart rate and energy expenditure statistics of the test participants are presented in Table 3. The average energy expenditure of the test participants ranged from 2.6 kcal/min to 3.5 kcal/min, which agreed with the energy expenditure range, 2.5 kcal/min to 4 kcal/min, for bricklaying task specified by Oglesby et al. (Oglesby et al., 1989). Participant 2 had the highest average heart rate which was 32.3% higher than participant 1 whose average heart rate was the lowest. The average energy expenditure of participant 2 was also the highest, which was 34.62% higher than the lowest average energy expenditure. A significant increase is observed both in

Table 2. Test Participant Information

	Test Participant 1	Test Participant 2	Test Participant 3
Age (years)	22	24	21
Height (cm)	176	174	185
Weight (kg)	70	60	75
Gender	Male	Male	Male
Race	Asian	Asian	Asian
Smoker	No	No	No
Health problems	None	None	None
Test duration (min)	60	54	48

Table 3. Heart Rate and Energy Expenditure of Test Participants

	Test Participant 1	Test Participant 2	Test Participant 3
Resting energy expenditure (kcal/min)	0.8	0.9	0.9
Average working energy expenditure (kcal/min)	2.6	3.5	3.1
Peak energy expenditure (kcal/min)	3.7	4.1	5.6
Resting heart rate (bpm)	84	91	76
Average working heart rate (bpm)	102	135	103
Peak heart rate (bpm)	118	176	132

energy expenditure and heart rate between resting and working conditions. The average working energy expenditure increased by at least 225% when test participants started to work, while the average heart rate increased by less than 48%.

According to the index classification of workload, the interpretation of energy expenditure and heart rate to different levels of workload are specified in Table 4. These four indexes together show that the workload for test participant 1 was

Table 4. Classification of Workload Based on Heart Rate and Test Participants

	Test Participant 1	Test Participant 2	Test Participant 3
Classification of work based on average energy expenditure	Moderate work	Moderate work	Moderate work
Classification of work based on peak energy expenditure	Light work	Light work	Moderate work
Classification of work based on average heart rate	Moderate work	Heavy work	Moderate work
Classification of work based on peak heart rate	Moderate work	Extremely heavy work	Heavy work
Overall level of workload	1.75	2.75	2.25
Borg CR10 scale	6	8	7

between light to moderate; for participant 2 it was between light to extremely heavy; for participant 3 it was from moderate to heavy. Different classifications of the physiological load level among test participants are understandable considering individual differences in physical and health conditions.

Three test participants described their feelings after the bricklaying tasks. The highest overall level of workload for a test participant was 2.75. His heart rate was significantly higher than the other two. Test participant 2 perceived the highest exertion as 8 which identified the workload as between very strong to extremely strong. Test participant 2 also claimed to take the longest time to recover, “nearly two days to recover from the fatigue”.

The authors kept record of the heart rate and energy expenditure of different test participants throughout the test. Figure 1 is one example demonstrating the changes of heart rate and energy expenditure throughout the test. The graphs show a significant increase in heart rate and energy expenditure when participant 1 started to work. There are more peaks and troughs in the heart rate graph, which shows that heart rate is more sensitive to breaks during masonry construction.

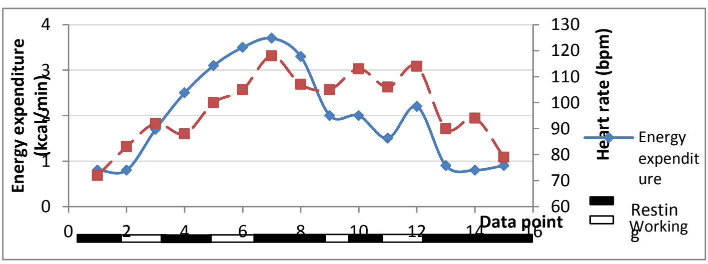

Figure 1. Heart Rate and Energy Expenditure of Participant 1 during the Test

CONCLUSION

The authors conducted research aimed at evaluating the physiological load of construction workers with wearable sensors in a non-intrusive way. Two types of sensors were deployed to monitor the physical condition of test participants, while they were performing the bricklaying task. The output from these two sensors was statistically analyzed to classify the physiological load level of the task. An index was developed to evaluate the overall physiological load. The results showed that the proposed wearable sensors were effective in evaluating the physiological load in a nonintrusive way. Heart rate was proved to be more sensitive to the break during the construction test. However, the change of magnitude in energy expenditure is much greater than heart rate under physiological load. The agreement between the level of overall workload and the RPE of test participants shows that the proposed index can efficiently evaluate the physiological load for different individuals. However, it must be noted that the test participants were not real construction workers. It is expected that the same activity would have a lesser impact in terms of fatigue on real construction workers. The reliability of the statistical results is also limited with the small number of test participants. Future test should cover more test participants in order to further validate the statistical conclusions. The authors plan to conduct the

test on a real construction site for detecting physiological load on construction workers in a non-intrusive way after the proof of concept validation.

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Development of Virtual Laser Target Board to Tunnel Boring Machine Guidance Control

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ABSTRACT

This research aims to develop a virtual laser target board methodology for tunnel boring machine (TBM) guidance control during tunneling operations. Current practice for TBM guidance using physical laser targets is evaluated. Coupled with a fully automated TBM tracking system resulted from in-house research, the virtual laser target board program is proposed to provide an effective aid for TBM operators and field managers in making critical decisions for tunnel alignment control. Comprehensive data processing procedures are carried out to determine: (1) TBM's position in the underground space, including any registered points on the TBM, e.g. center of TBM's cutter head; (2) tunneling progress; (3) line and grade deviations of the tunnel alignment; and (4) TBM's three-axis body rotations. Field experiments on a 2.4 m diameter TBM were conducted to collect registration data for on-line processing by the virtual laser target board program.

INTRODUCTION

It is crucial to precisely position tunnel boring machine (TBM) in the underground space, so as to guide it to advance along the as-designed alignment in tunnel construction (Thomson 1993). The current practice for TBM guidance largely relies on the traditional laser guidance system to project a laser point on a physical target board fixed on the TBM. The limitations of this practice, however, partially contribute to the high risks associated with tunneling projects, such as out-of-tolerance alignment deviations, project delay and budget overrun. Actually, tunneling productivity would be severely degraded due to excessive time and efforts in laser system setup and frequent calibration. Besides, the manual method for tunneling operations data collection undermines both efficiency and effectiveness in project management and control. For instance, the tunnel alignment deviations and tunneling progress (referred to as "Chainage" in tunneling terms) are manually recorded by TBM operators and specialist surveyors on a daily basis. The resulting data are often kept as separate paper-based records, which need days or even weeks to be compiled, post processed and analyzed. The analysis results often come back too late to be

helpful. Consequently, project managers have yet to be able to detect any out-of-tolerance alignment errors in real time, while the TBM operator largely counts on the laser beam as a rough guidance aid and draws on personal experience to exert steering control on the TBM (Shen et al. 2012).

As the result of recent research, we have developed a fully automated TBM tracking solution to replace traditional laser targeting systems (Shen et al. 2011a; Shen et al. 2011b). A robotic total station is employed to automate the continuous processes of TBM tracking and spatial data collection inside the tunnel. The precise positions of the TBM in the underground space, as well as any line and grade deviations from the as-designed tunnel alignment are computed in real time.

As a continuous effort, this research aims to develop a virtual laser target board methodology to be coupled with the automated TBM tracking system. It provides an effective aid for TBM operators and field managers in making critical decisions on a near real-time basis. Comprehensive data processing procedures are carried out to determine: (1) TBM's position in the underground space, including any registered points on the TBM, e.g. center of TBM's cutter head, which is invisible in the field; (2) tunnel chainage; (3) line and grade deviations of the tunnel alignment; and (4) TBM's three-axis body rotations. The computational solution is promising to lend substantial decision support for not only tracking the construction progress but also visualizing tunnel alignment deviations on the fly.

The remainder of this paper is organized as follows: first, pros and cons of existing physical laser targets are evaluated. Next, the overall design of the virtual laser target board program is described, followed by illumination of key data processing procedures. The last section reports the field experiments on a 2.4 m diameter TBM in preparation of the registration data for the virtual laser target board. The main findings and implementation plan of the research are discussed in conclusions.

EVALUATION OF EXISTING LASER TARGETS

Laser has been extensively employed as a primary aid for directional control in tunnel construction (Maidl et al. 1996). Typically, a laser station is firmly fixed in the tunnel, which projects a laser beam along the desired tunnel alignment on a laser target mounted on the TBM. Existing laser targets can be classified into passive and active ones by their underlying technologies.

Passive Laser Target Board

The passive laser target board has been widely used in the majority of tunneling projects. As shown in Figure 1, the passive laser target board is commonly made of an aluminum or polyethylene plate. The position of the target board, in terms of the horizontal offset and vertical elevation of the board center in relation to TBM's central axis, is precisely surveyed. Location of the laser station as well as the laser beam's orientation are then accurately set up and calibrated by specialist surveyors. When the laser beam hits the target board, the TBM operators can infer the current line and grade deviations of tunnel alignment by examining the offsets of the laser

spot on the board. Besides, the TBM's three-axis orientations are measured by use of two accessary devices: the advancing direction of the TBM (yawing in the horizontal plane) is determined through incorporating a transparent front target (see Figure 2a), while pitching and rolling in the vertical planes are gauged using a two-axis bubble leveler installed on the TBM (see Figure 2b).

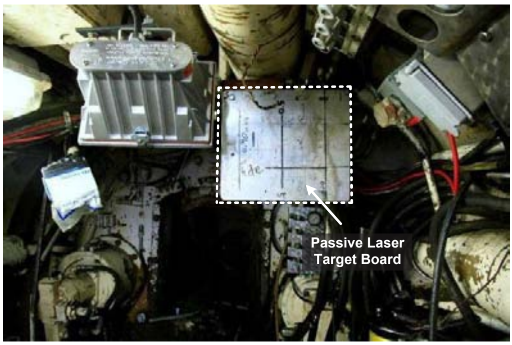

Figure 1. Passive laser target board mounted on TBM.

(a) (b)

Figure 2. Accessory devices for passive laser target: (a) transparent front laser target; and (b) two-axis bubble leveler.

Active Laser Target Unit

The active laser target unit makes enhancements to the passive system by integrating sophisticated mechanical, optical and electromagnetic subsystems. Typically, the

active laser target unit combines two laser target boards (transparent front board and rear board) and an electronic two-axis leveler into a single body. Note the positions of the laser spot registered on the two target boards are digitized using two digital cameras in the video laser target unit (see Figure 3a), or through laser-sensitive photocells on the target boards of the electronic laser target (see Figure 3b). Similar to the passive laser target board system, the yawing angle is determined through examining the laser spot's positions on the two targets, while the pitching and rolling angles are obtained from the electronic leveler embedded in the active target units. On the down side, the high complexity in system design may compromise system reliability while considerably increasing the system's price and consumption cost, including system maintenance and technical service (Shen et al. 2011b).

(a)

(b)

Figure 3. Active laser target units: (a) video laser target; and (b) electronic laser target (Tacs GmbH 2012; VMT GmbH 2012).

Limitations of Physical Laser Targets

One of the major limitations associated with the physical laser targets lies in relatively low reliability and accuracy. This is mainly caused by: (1) potential human errors in initializing or calibrating the laser beam's orientation, (2) the dispersion and refraction of the laser beam over a long distance, and (3) the difficulty to receive the laser's projection over a long distance due to restricted screen size of target boards, potentially leading to excessive out-of-tolerance deviations (Thomson 1993). Typically, the maximum application distance for the laser guidance system is around 200 m. In addition, the laser beam's orientation is commonly required to be calibrated by specialist surveyors once every other day.

Besides, the tunneling productivity is considerably undermined by the routine maintenance of the laser station, such as mobilization, initialization and calibration. The survey task for maintaining the laser station inside the congested tunnel is challenging, tedious and time consuming, requiring a crew of specialist surveyors around five hours to set up a new laser station. Meanwhile, all of the tunneling operations have to be halted during this work process. The problem is even worsened when encountering tunnel sections of curved alignment, where the laser station has to be relocated and calibrated every day. The construction cost is therefore increased significantly due to low tunneling productivity and extremely heavy tunnel survey workload.

VIRTUAL LASER TARGET BOARD DESIGN

In this research, we propose a virtual laser target board design to be coupled with the fully automated TBM tracking system. As shown in Figure 4, the virtual laser target board program integrates five basic functions, namely: (1) automated control of the robotic total station, (2) wireless data communication, (3) on-line data processing, (4) data visualization that mimics a passive laser target board, and (5) data recording. Comprehensive data processing procedures are thus carried out to determine: (1) the coordinates of a limited quantity of tracking points fixed on the TBM, which are automatically surveyed by the robotic total station; (2) the coordinates of any registered points on the TBM through computation, like the center of TBM's cutter head, (3) the tunnel chainage, (4) the line and grade deviations of the tunnel alignment, and (5) the TBM's orientations, including the three body rotation angles of yawing, pitching and rolling, as shown in Figure 4.

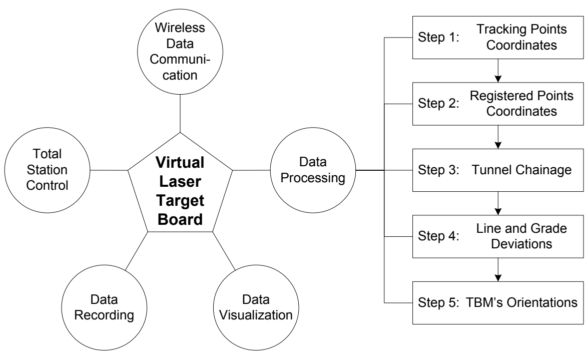

Figure 4. Schematic design of virtual laser target board's functionalities and data processing procedures.

This research focuses on how to calculate the coordinates of any registered points on the TBM (Step 2 in Figure 4), as other related computing methods are systematically addressed in Shen et al. (2011a), Shen et al. (2011b) and Shen et al. (2012). As shown in Figure 5, the three tracking points C1-C3 are mounted on the rear end of the TBM. Points A (the center of TBM's rear end) and B (the center of TBM's cutter head) represent TBM's central axis. Since the as-designed tunnel alignment is related to TBM's central axis, points A and B's coordinates are therefore crucial to determine the TBM's position and orientations, together with the tunnel chainage and alignment deviations. The two points, however, are invisible in the field and hence cannot be readily surveyed.

A computational approach is developed to determine the coordinates of the two registered points A and B. Two Cartesian coordinate systems are utilized in facilitating the calculation, including the local geodetic frame (*l*-frame, referred to as North-East-Up frame in Figure 5), and the TBM's body frame (*b*-frame, referred to as X-Y-Z frame in Figure 5). The method of frame transformation is then applied to convert the point coordinates from the body frame to the local geodetic frame (Rogers 2007; Shen et al. 2011a).

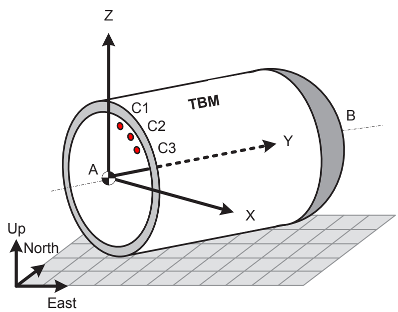

Figure 5. Point coordinates transformation in two coordinate systems.

Given the coordinates of the three tracking points C1-C3 surveyed in both the local geodetic frame (*l*-frame) and the TBM's body frame (*b*-frame), a frame transformation matrix *T* is defined as:

$$\begin{pmatrix} C1 \\ C2 \\ C3 \end{pmatrix}_l = T \begin{pmatrix} C1 \\ C2 \\ C3 \end{pmatrix}_b$$

The transformation matrix *T* can be solved using the optimal Quaternion algorithm (Wahba 1965; Shen et al. 2011a). Suppose the coordinates of the points A and B are registered in the body frame by traditional surveying, the corresponding coordinates in the local geodetic frame are then determined by:

$$\begin{pmatrix} A \\ B \end{pmatrix}_l = T \begin{pmatrix} A \\ B \end{pmatrix}_b$$

TBM SURVEYING AND DATA PREPARATION

Site surveying of a 2.4 m diameter TBM was carried out on December 12, 2011 at the mechanical shop of the City of Edmonton, as shown in Figure 6. The three tracking points (model: CTS Leica Compatible Mini Prism 65-1500M) are mounted at the rear end of the TBM using a tailor-made prism bracket (see Figure 7). Their visibilities have been confirmed by experienced site engineers and surveyors. The point coordinates of the TBM's rear center (Point A in Figure 7) and the cutter head center (Point B in Figure 6) as well as the three tracking points were surveyed precisely. The coordinates in the body frame are then calculated, as given in Table 1.

Table 1. Point Coordinates in TBM's Body Frame.

Point	Coordinates		
	X (mm)	Y (mm)	Z (mm)
A	0	0	0
B	0	4,580	0
C1	408	0	814
C2	695	0	751
C3	797	0	476

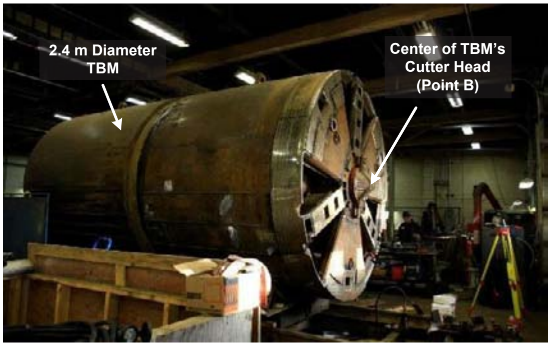

Figure 6. Site surveying of 2.4 m diameter TBM.

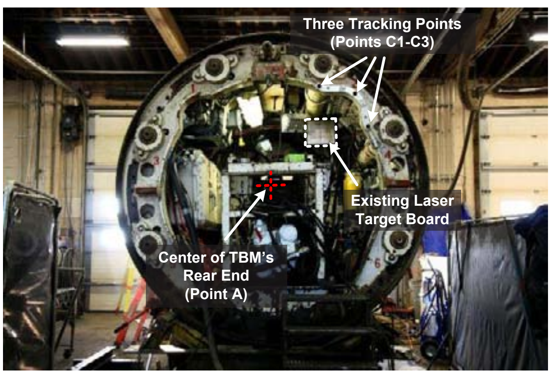

Figure 7. Three tracking points mounted at TBM's rear end.

CONCLUSIONS

The TBM tunneling method has been extensively applied for tunnel construction. The lack of effective TBM guidance solutions, however, partially contributes to the high risks on tunneling projects, including out-of-tolerance alignment deviations, project delay, quality defect, budget overrun, or even failure of the whole project.

In this research, we have proposed the virtual laser target board methodology in order to address the limitations identified in the conventional physical laser targets. Coupled with the automated TBM tracking system resulted from in-house research, the virtual laser target board program will integrate five functions, including (1) automated total station control, (2) wireless data communication, (3) real-time data processing, (4) analytical result visualization, and (5) data recording. A computing solution is developed to determine the coordinates of any registered points on the TBM that cannot be surveyed in a straightforward way during the course of TBM operations. This further facilitates the calculation of TBM's position and orientations,

as well as tunnel chainage and line and grade deviations of tunnel alignment. Field experiments on a 2.4 m diameter TBM were conducted in preparation of the TBM registration data in order to realize the virtual laser target board development. In close collaboration with the Design and Construction Section of the City of Edmonton, the research is scheduling to be implemented in a 2.4 m diameter and 1,040 m long drainage tunnel project in Edmonton, Canada for field evaluation from April 2012.

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Enhancement of Construction Equipment Detection in Video Frames by Combining with Tracking

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ABSTRACT

Vision-based object detection has been introduced in construction for recognizing and locating construction entities in on-site camera views. It can provide spatial locations of a large number of entities, which is beneficial in large-scale, congested construction sites. However, even a few false detections prevent its practical applications. In resolving this issue, this paper presents a novel hybrid method for locating construction equipment that fuses the function of detection and tracking algorithms. This method detects construction equipment in the video view by taking advantage of entities' motion, shape, and color distribution. Background subtraction, Haar-like features, and eigen-images are used for motion, shape, and color information, respectively. A tracking algorithm steps in the process to make up for the false detections. False detections are identified by catching drastic changes in object size and appearance. The identified false detections are replaced with tracking results. Preliminary experiments show that the combination with tracking has the potential to enhance the detection performance.

INTRODUCTION

On-site tracking provides useful data for site monitoring such as productivity measurement, activity sequence analysis, and safety management. Tracking technologies, such as Global Positioning Systems (GPS) and Radio Frequency Identification (RFID) have been used to generate real-time information on the position of construction entities across time. The tests and applications of these technologies showed their outstanding performance and suitability to construction sites. However, it is necessary to install tags or sensors on entities when using these technologies. This requirement obstructs their application in large-scale, congested construction sites where numerous entities need to be tagged.

As an alternative to these technologies, vision-based methods have been investigated. Positioning of objects in a camera view is attainable through object detection or object tracking. Object detection recognizes an object category (e.g. face

and vehicle). For example, an algorithm of face detection intends to recognize all faces in images. However, it does not provide the identification of each single face. In other words, it cannot distinguish a face from another. Also, the detection algorithms may fail to detect a positive object due to limitations on the training of all different views. On the contrary, object tracking finds a position of a unique object regardless of its object category, based on its previous location and appearance in video frames. Therefore, in order to initiate the tracking process, a prior position of an object has to be manually determined.

It is not feasible to achieve effective monitoring of construction sites by using either object detection or tracking because of their weaknesses such as false detections and manual initialization. However, their weaknesses can be overcome through each other. From this perspective of view, we present a novel hybrid method for locating construction equipment, that combines the function of detection and tracking algorithms. The method detects construction equipment in the video by taking advantage of entities' motion, shape, and color features. The three types of features are handled through background subtraction, Haar-cascade, and eigen-images, respectively. Detection of construction equipment automatically initiates the tracking process. Tracking results step in the process to make up for the false detections. Also, object tracking provides identity of each object through the matching between consecutive frames. Preliminary experiments show the significant enhancement of the detection by the combination with tracking.

BACKGROUND

In recent years, automated monitoring of construction resources has been achieved by state-of-the-art technologies such as RFID and GPS. Numerous GPS systems have been developed for monitoring construction equipment. Each GPS sensor mounted on equipment captures the location via satellites, and transmits the data to a central module mobile network. It enables visualizing the location of all equipment on a single map (Henderson, 2008). RFID-based systems are broadly used in construction projects as well. Skanska employed an RFID system to track pre-cast concrete elements from casting to assembly in a football stadium construction project (Sawyer, 2008a). RFID systems have been used for monitoring workers and equipment as well (Sawyer, 2008b). For example, RFID tags attached on tower cranes are used for preventing collisions among the cranes (Gomez, 2007).

The monitoring systems based on GPS and RFID technologies require installing tags on entities to track. The need for tags limits their use for tracking in large-scale, congested sites. For this reason, vision technologies have drawn growing interest in construction. Vision-based object detection recognizes an object category by image features which all objects of the category have in common. Image features can be categorized into three types – shape, color, and motion. Haar-like features (Viola and Jones, 2001) and HOG (Dalal and Triggs, 2005) are well-known shape features. Both exploit image gradients which are differences of intensities between adjacent regions. The Haar-like feature is a vector of image gradients, while the HOG feature is a collection of local histograms of gradient directions. In order to detect various appearances of an object category, the features are trained through machine

learning. For example, Viola and Jones (2001) trained Haar-like features with an Adaptive Boosting algorithm (Freund and Schapire, 1997) for face detection. Dalal and Triggs (2005) applied HOG features trained with SVM (Support Vector Machine) (Joachims, 1999) to human detection.

Color is a simple and intuitive feature to recognize an object. It is effective for detecting unique-colored objects. A color histogram (Swain and Ballard, 1991) is one of the simplest color features. It is easy to calculate and invariant to rotation and translation. However, it is sensitive to illumination conditions, and lack of spatial information. The color histogram has been widely used for image segmentation and content-based image retrieval in which spatial information is not critical (Huang et al., 2004; Zhang et al., 2009). Eigen-images contain both color and shape information. Eigen-images are also known as eigen-faces since they have been mostly used for face recognition (Turk and Pentland, 1991). Eigen-images are eigenvectors of a pixel covariance matrix which is calculated with a large number of training images. Only a certain number of principal eigenvectors that corresponds to high eigenvalues are remained and used to reduce processing time and memory space.

Background subtraction (Mcfarlane and Schofield, 1995; Stauffer and Grimson, 2000) detects moving objects. When a camera view is fixed, it estimates a background model by obtaining dominant pixel values across frames. Moving objects are detected by finding foreground blobs where the difference of pixel values between the current frame and the background model exceeds a threshold. Background subtraction detects all objects in motion regardless of their appearances. It is computationally efficient. However, it cannot identify object categories. Also, it is hard to differentiate one object to another when they partially overlap each other.

Recently, several approaches have been made for detecting construction entities. Park et al. (2011b) presented a method for detecting wheel loaders. They applied the Semantic Texton Forests approach (Shotton et al., 2008), which detects objects through segmentation and classification. Chi and Caldas (2011) proposed a real-time detection method that classifies construction entities including construction equipment and workers. Their method uses background subtraction and exploits characteristics of foreground blobs for classification.

Vision-based tracking methods are introduced to construction, aiming at minimum cost and human interaction. They are capable of tracking a large number of entities without any sensors on the entities. Park et al. (2011a) performed a comparative study on 2D vision trackers to find appropriate methods for construction entities. Yang et al. (2010) presented a vision tracking method for tracking multiple construction workers. Gong and Caldas (2010) applied vision tracking to facilitate productivity analysis. While the tracking data in these works was limited to 2D pixel coordinates, Brilakis et al. (2011) has recently proposed a framework of 3D vision tracking. It provides 3D coordinates using multiple onsite cameras.

METHODOLOGY

This paper presents a hybrid method that combines object detection and tracking for localizing construction equipment. In the method, detection and tracking algorithms work in a complementary way, providing location data across frames.

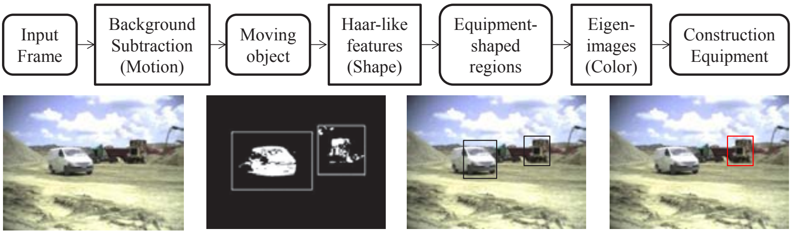

Figure 1. The framework of equipment detection

Detection results have priority over tracking, and tracking makes up for false detections. In addition to location, equipment type and each entity's identity are determined by detection and tracking, respectively.

The detection of construction equipment is comprised of three steps. The three steps exploit motion, shape, and color features, respectively (Fig. 1). The first step uses background subtraction to extract regions of moving objects. Cameras are fixed on construction sites so that they have static background scenes. The objects in motion (foreground blobs) are detected by comparing the current frame with the background scene. This step narrows candidate regions down to moving object regions. It significantly reduces the overall processing time by limiting the region of interest in the next step. It also prevents false positive detections of the next step that could occur in the static background region.

The second step is to find the shape of construction equipment out of the candidate regions. Haar-cascade features (Haar-like feature trained with Adaptive Boosting) are employed for this purpose. For training, a large number of positive and negative images are used. Furthermore, it requires several independent trainings for distinct views. For example, rear and side views of a wheel loader (Fig. 2) should be trained independently because of the great difference in their appearances. In this paper, four views (front, rear, left, and right) are trained independently, which results in four separate models. All four models are jointly used for searching every piece of construction equipment.

Potential chances of false detections are still remained in the motion- and shape-based detection. For example, a moving object that exhibits a similar shape of construction equipment can be detected through the first and second steps. The third step filters out these false detections based on eigen-images which contain color information. When exploiting color features, it is important to select color components that can best characterize colors of construction equipment. Even though construction equipment is generally yellow, there are other colors of equipment such as red and green. Also, RGB (red, green, and blue) values and gray-scale intensity vary depending on illumination conditions. Therefore, instead of RGB or gray-scale intensity, the proposed method employs the HSV (hue, saturation, and value) color space. Among the three components, it uses saturation which measures the purity of the color since most equipment has relatively pure colors. Similar to the second step, eigen-images are trained separately for each view of equipment. Training is achieved through SVM. Fig. 2 illustrates eigen-images for rear and left views of wheel loader. Fig. 2 also shows the images reconstructed with 30 principal components of eigen-

(a) (b)

Figure 2. (a) Rear (b) and left views of a wheel loader: 4 principal components of eigen-images (right upper), and the reconstructed image (right lower)

images. It should be noted that only lower half part (red) is used for side views because backgrounds (yellow) accounts for a substantial portion of the upper half (Fig. 2).

According to Park et al.'s comparative study (2011), a kernel-based method (Ross et al., 2008) is used for tracking. The method tracks objects by making inferences about their current locations based on previous appearances and locations (or motions). It utilizes eigen-images and the particle filter to model the objects' appearances and the motions, respectively. Different from the eigen-images used in detection, those in tracking are constructed with the whole area regardless of the view since the background is also useful information for the inference.

As described earlier, the detection method requires separate trainings of different views. Higher detection rate (recall) is achievable by increasing the number of views. However, it will demand considerably increased computational efforts. Even when taking a large number of views into account, it is hard to eradicate possibility of false detections due to illumination changes or signal noises. To resolve these problems, detection results are combined with tracking results. It allows higher detection rate with a small number of training views. Gaps between the trained views are filled with tracking results. Also, tracking delivers identity of each object which is valuable when tracking multiple objects of the same type. The first detection of an object initiates tracking. Afterwards, detection and tracking are executed simultaneously. The proposed method basically relies on detection results for location. For each frame, the location results of tracking and detection are matched based on the distance between them. The tracking result is used only when there is no detection result matching with it. When detection results of consecutive frames show drastic changes in the object size or appearance, they are regarded as false positives and replaced with the corresponding tracking result. In addition, if detection results are missing for a certain length of time, the method regards an object disappeared (e.g. total occlusion or leaving the view) and stops processing.

IMPLEMENTATION, EXPERIMENTS & RESULTS

The proposed method is implemented using Microsoft Visual C# in .NET Framework 4.0 environment. As a preliminary experiment, the implemented method is tested on two videos recorded with a wheel loader which is executing the loading/unloading process. They contain 959 (Video 1) and 773 (Video 2) frames,

Table 1. The number of training images, and template sizes used for detection

Views	Haar-cascade			Eigen-images		
	# of training images		Template size	# of training images		Template size
	Positive	Negative		Positive	Negative	
Left & right	603	3000	35×21	603	4000	30×15*
Front & rear	412	3000	24×28	412	4000	20×20

*The template is constructed for lower half of the view

and they are resized to 800×600. The second video starts with a wheel loader's entering the view and includes two occlusion cases. The number of training images and template sizes involved in the second and third steps of the detection is presented in Table 1. 30 principal eigen-images are used for each view. The detection algorithm is designed to maximize precision rather than recall, since low recall can be compensated by tracking results while low precision can cause tracking of false positive objects.

The experiment compares three methods: 1) detection-only, 2) tracking-only with manual initialization, and 3) detection combined with tracking (proposed method). Method 1 detected the wheel loader from 468 and 187 frames in Video 1 and 2, respectively. These values were significantly increased to 955 and 697 by using the proposed method, which result in 99.6% and 90.1% recall. Above all, no false positive was made on both test videos, which leads to 100% precision. The 76 (=773-697) frames of Video 2, in which the method fails to extract locations, are associated with total occlusions or the wheel loader's entering the view. Fig. 3 shows examples of results which compare Method 2 and 3 (the propose method). The 1st row of Fig. 3 illustrates an occlusion case. The proposed method identified the disappearance of the wheel loader based on continuous absence of detection results, and the process stopped (no result in 3rd image). The process resumed when it appeared again (4th image). When the wheel loader made a turn, the proposed method appropriately switched over to the rear view, while Method 2 tended to keep its rectangle region (the 2nd row of Fig. 3).

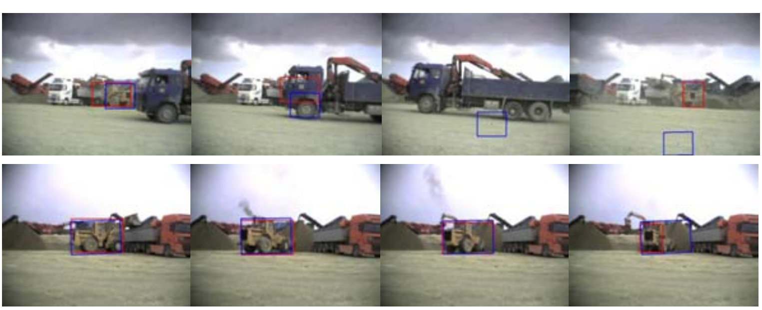

Figure 3. Results of the proposed method (red) and a tracking method (blue) under total occlusion (1st row) and viewpoint change (2nd row)

CONCLUSION

Trajectories of construction entities are useful for efficient monitoring of construction sites. GPS and RFID technologies have been applied for localizing entities, and their outstanding performances have been reported. However, the tagging requirement limits their application in large-scale, congested sites. Vision-based approaches are introduced as an alternative to GPS and RFID. Both detection and tracking methods can be used for locating construction entities in a camera view. A detection method locate all objects of a specific category in an image while a tracking method locate a unique object based on its location in previous frames. False detections and manual initialization hinders the separate use of detection and tracking algorithms for construction site monitoring. In this paper, a novel method for localizing construction equipment in the video frames is presented. The method fuses detection and tracking algorithms to compensate their shortcomings and acquire both category and identity information. The detection algorithm employed in this method exploits background subtraction, Haar-cascade, and eigen-image for motion, shape, and color features, respectively. A kernel-based tracker initiated by the detection algorithm makes up for false detections. The proposed method was tested for localizing a wheel loader. Significant improvement of detection rates was observed through the integration of detection and tracking. As a future work, extended experiments on other types of equipment will be performed to fully validate the performance of the method.

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Real-time and Automated Recognition and 2D Tracking of Construction Workers and Equipment from Site Video Streams

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ABSTRACT

This paper presents an automated and real-time algorithm for recognition and 2D tracking of construction workers and equipment from site video streams. In recent years, several research studies have proposed semi-automated vision-based methods for tracking of construction workers and equipment. Nonetheless, there is still a need for automated initial recognition and real-time tracking of these resources in video streams. To address these limitations, a new algorithm based on histograms of Oriented Gradients (HOG) is proposed. The method uses HOG features with a new multiple binary Support Vector Machine (SVM) classifier to automatically recognize and differentiate workers and equipment. These resources are tracked in real-time using a new GPU-based implementation of the detector and classifier. Experimental results are presented on a comprehensive set of video streams on excavators, trucks, and workers collected from different projects. Our preliminary results indicate the applicability of the proposed approach for automated recognition and real-time 2D tracking of workers and equipment from a single video camera. Unlike other methods, our algorithm can enable automated and real-time construction performance assessment (including detection of idle resources) and does not need manual or semi-automated initialization of the resources in 2D video frames. The preliminary experimental results and perceived benefits of the proposed method are discussed in detail.

INTRODUCTION

Real-time and automated recognition and tracking of construction workers and equipment is one of the most challenging topics in automation of vision-based construction performance monitoring. It is the key capability for the assessment of construction productivity, safety, and occupational health. In recent years, several researchers have proposed different methods for tracking construction entities (e.g.,

workers, equipment, and materials). Nonetheless, these methods in the case of workers and equipment mainly require manual or semi-automated initialization of the resource in 2D video frames, and do not achieve real-time performance. Another major challenge due to the nature of the task is the variations in visual appearance owing to different clothing of the workers, articulation, cluttered backgrounds, and illumination conditions which are typical in dynamic construction scenes. To address these limitations, this paper presents a new approach for automated and real-time recognition and tracking of dynamic construction entities in video streams. The proposed method uses the Histogram of Oriented Gradients (HOG) to automatically recognize and differentiate between workers and equipment with a multiple binary support vector machine (SVM) classifier. These resources are tracked in real-time from the site video streams using a GPU implementation of the detector and classifier. The final outcome of the proposed method recognizes these entities in every frame of the video and can track them in real-time.

In the following sections, first the state-of-the-art techniques in worker and equipment recognition and tracking are reviewed. Next, the new method developed for automated detection and real-time 2D tracking of dynamic resources is outlined. The experimental results are presented, the perceived benefits and the limitations of the proposed method are discussed in detail.

BACKGROUND AND RELATED WORK

Current Practice of Performance Assessment. A large number of construction companies are still using traditional data collection methods for performance analysis including direct manual observations, methods adopted from stop motion analysis in industrial engineering (Oglesby et al. 1989), and survey based methods. Although these methods provide beneficial solutions in terms of improving performance, yet they are labor-intensive (Gong and Caldas 2011, Su and Liu 2007) and can be subjective. The significant amount of information which needs to be collected may also adversely affect the quality of the analysis (Golparvar-Fard et al. 2009, Gong and Caldas 2009). Such limitations minimize the opportunities for continuous benchmarking and monitoring which is a key element in performance improvement. Hence, many critical decisions may be made based on incomplete or inaccurate information, ultimately leading to project delays and cost overruns. In recent years, several researchers have focused on developing techniques that can automate performance monitoring. These techniques mainly focus on tracking of construction workers and equipment as a critical step towards automation of performance assessment. In the following, several recent sensor-based and vision-based efforts are reviewed and limitations are discussed.

Current Research in Tracking Construction Resources Using Sensors. Over the past few years, several researchers have focused on tracking the construction entities using Radio Frequency Identification (RFID) (Ergen et al. 2007, Navon and Sacks 2006) and Ultra Wideband (UWB) technologies (Cheng et al. 2011, Teizer et al. 2007). In other cases (Grau et al. 2009, Song et al. 2006) joint application of RFID and GPS is proposed. Despite the potential, RFID tags and UWB technologies require

a comprehensive infrastructure to be installed on the jobsite, and in the case of GPS, the line of sight in many locations may adversely impact their benefits. These techniques achieve high precision in tracking, yet do not provide information about the nature of the operation or actions that the workers or equipment are involved in.

Current Research in Vision based Tracking of Construction Resources. Although recent studies in the Architecture/Engineering/Construction (AEC) community have emphasized on the need for cost effective and automated monitoring techniques and particularly camera-based approaches, to-date none of the existing methods could automatically recognize workers and equipment and track them in real-time. Current methods for recognition and tracking of workers and equipment (e.g., Yang et al. 2011, Brilakis et al. 2011) have several assumptions on their assessments (e.g., expected known locations for tracking tower crane, or application of Scale Invariant Feature Transforms (SIFT) for initial recognition) which can limit their applications in uncontrolled settings. In a more recent work, Park et al. (2011) proposed a method for 3D tracking the construction resources by using a stereo camera and SIFT and SURF (Speeded Up Robust Features) detectors. This work mainly focuses on the 3D tracking assuming a correct recognition of resources in 2D and does not propose a particular approach for learning and recognition of the resources. The method is also validated with small dataset of a steel plate, a van and a single worker. Rezazadeh and McCabe (2011) also evaluated combinations of several existing object recognition and background subtraction algorithms to recognize onsite dump trucks in video streams. Another recent work in worker and equipment tracking is (Chi and Caldas 2011). These works benefit from a background subtraction algorithm to differentiate between the moving object and the stationary background. Despite the good performance, background subtraction does not allow idle resources to be detected which can limit its application for performance assessment purposes.

In the computer vision community, there is a large number of emerging works in the area of person recognition and pose estimation (Yang and Ramanan 2011, Felzenszwalb et al. 2010, Dalal and Triggs 2005). The results of these algorithms seem to be both effective and accurate and in case of Felzenszwalb et al. (2010) can also track deformable configurations which can be effective for action recognition purposes. Although, these methods could help develop automated algorithms for recognition and tracking of resources, yet in most cases they are only applied to controlled settings. Nevertheless, certain elements of these works can be effectively used to create new techniques for worker and equipment recognition and tracking. In this study, we build upon the work of Dalal and Triggs (2005) and propose a novel vision-based approach for integrated action and location monitoring.

PROPOSED METHODOLOGY

Our proposed method for recognition of workers and equipment involves application of a *sliding* detector window. The basic idea is that the detector window scans across a 2D video frame at all positions and scales. During this process, the detector window is tiled with a grid of overlapping blocks in which the features will be extracted. This strategy provides two key benefits: 1) detection of workers and

equipment while idle; and 2) detection of workers and equipment in close proximity of each other which is a key issue for safety assessment purposes. In the following the process of detecting workers and equipment within each detector window is described.

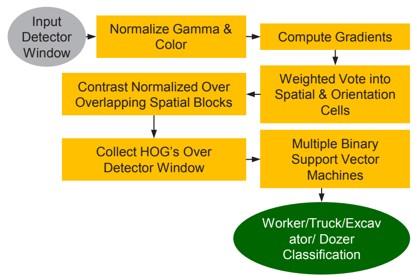

Figure 1: Resource Localization in 2D

Recognition and Classification. An overview of our method for detection of workers and equipment is presented in Figure 1. The main idea is that the local shape and appearance of workers and equipment in the detection window can be characterized by the distribution of local intensity gradients. In Dalal and Triggs (2005), this is implemented by dividing the detector window into small spatial regions "cells", for each cell accumulating a local 1-dimensional histogram of gradient directions over the pixels of the cell. For invariance to varying illumination, we also contrast-normalize the local responses before using them. This is done by accumulating a measure of local histogram over larger spatial regions "blocks" and using the results to normalize all of the cells in the block. The resulting normalized descriptor blocks are called the HOG descriptors. Tiling the detector window with a dense grid of HOG descriptors with/without overlapping windows results in resource feature vectors which are then placed into the binary SVM classifier.

Real-time Tracking of the Localized Resources. Despite the great potential of the HOG descriptors, they suffer from one major problem: high computation time. Similar to many sliding window algorithms, HOG detector is relatively slow and hence unattractive for real-time applications. To address this limitation, we build upon the work of Prisacariu and Reid (2009) which details an implementation of the HOG based sliding detector window algorithm using the NVIDIA CUDA parallel computing framework. This method achieves a real-time performance of the standard sequential implementation of Dalal and Triggs (2005). In our work, we train our dataset using the algorithm presented in the previous step. For testing, we use the parallel computing platform to achieve real-time performance. In the following we first present the structure of our testing and training datasets, plus our validation metric. Next, the experimental results are presented in detail.

EXPERIMENTAL SETUP

Creating a Comprehensive Testing/Training Database. Due to the lack of databases for benchmarking visual recognition and tracking of construction workers and equipment, it was necessary to create a comprehensive database for both training and testing purposes so that it can be released to the community for further development of new algorithms. For this purpose, we collected 300 hours of video

streams that were recorded from five different building and infrastructure projects. From these videos, a total of 2380, 967, and 18969 frames were structured for recognition of excavators, trucks, and workers respectively. Our excavator and truck datasets include 4 and 2 different model and types of equipment per category. In the case of workers, the dataset was mainly collected from concrete placement and steel erection crews. In order to create a comprehensive dataset with varying degrees of viewpoint, scale, and illumination, the videos were collected over the span of six months and for each video recording session, the camera was placed at two different distances and at 3~4 different locations along a semi-circle around the construction resources under study.

To prove the concept, from the collected video streams, a total of 2316, 721, and 631 frames were used for initial experiments on excavators, trucks, and workers, respectively. These frames were divided into two groups of training and testing by a ratio of 2/1. The classifiers were trained for the training dataset and their performances were evaluated using the testing dataset.

Metric for Performance Evaluation. To validate the performance of our algorithm, we choose the same metrics of Dalal and Triggs (2005) and plot the Detection Error Tradeoff (DET) curves on a log-log scale featuring miss rate versus FPPW (False Positive Per Window). These curves present the same information as precision-recall graphs, yet allow small probabilities to be detected more easily. These terms are defined as follows:

$$miss\ rate = 1 - recall\ rate = \frac{\sum FN}{\sum(TP + FN)} \quad (1)$$

$$FPPW = \frac{\sum FP}{\sum(TN + FP)} \quad (2)$$

wherein $\sum FN$ is the number of false negatives, $\sum(TP + FN)$ the number of detected positives and false negatives, and finally $\sum FP$, and $\sum(TN + FP)$ are the number of false alarms and total number of true negatives and false alarm instances in our testing results. Based on these DET curves, the better performance of detector should achieve minimum miss rate and FPPW. Similarly in this work, we will use miss rate at the 10^{-4} FPPW as a reference point in the DET curve.

EXPERIMENTAL RESULTS

Figure 2 shows the results of our overall recognition. As observed our truck detector show better performance compared to the excavator and worker datasets. This is mainly attributed to the fact that our truck dataset had a more limited variety in pose and camera viewpoint. In order to study the impact of the window size, the number of cells and their size, the percentage of detector window overlap, and the number of bins and orientation in the accuracy of

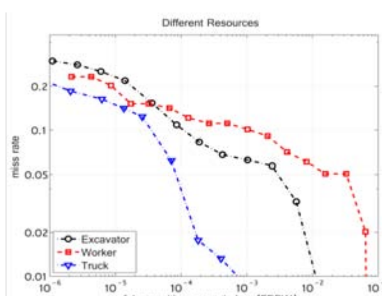

Figure 2: Resource Recognition

detection, we performed exhaustive set of experiments as follows:

Impact of Detector Windows Size and Overlap- In our experiments we tested two different sizes of detecting window (in the form of number of pixels) and also the percentage of overlap between windows for detection in cases of close proximity of workers and equipment. Figure 3a shows the results of these experiments for detection of excavators. As observed in the case of 120×120 pixels detector windows, a reasonable high performance is achieved. Given the assumption that our video frames are high definition (1920×1080 pixels), this shows the robustness of our approach to different scales and camera distances. Figure 3b shows performance results in three different degrees of sliding window overlap. As seen, overlaps of up to ¾ in the case of excavators (which are occlusions in real-world) will not have any impact on the accuracy of our detection.

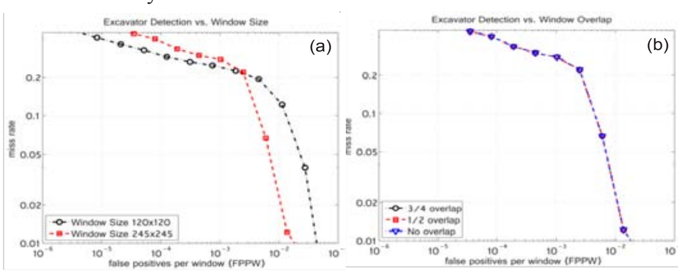

Figure 3: Detection Error Trade-off Curves for Detector Window Size

Impact of Different Bins/Orientations for HOG Descriptors- In our experiments we tested a total of four different numbers of bins and two orientations (180˚ degrees assuming symmetrical directions for gradients) for both worker and excavator categories. Figure 4 shows the results of these experiments. As observed, 18bin histograms with orientation of 360˚ degrees, and 9bin histograms with orientation of 180˚ degrees show better performance for worker and excavator classes respectively.

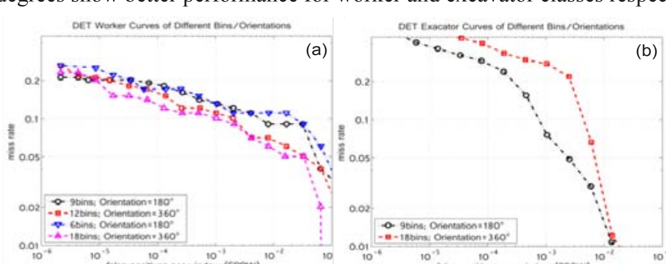

Figure 4: Detection Error Trade-off Curves for Different

Impact of Cell Size and Number of Cells per Block of Detector Window- Figure 5 show the impact of various cell size and number of cells per block on the accuracy of the detector window. As observed, a combination of 16×16 pixels per cell, 4×4 cells per block with ¾ of overlap show the best performance.

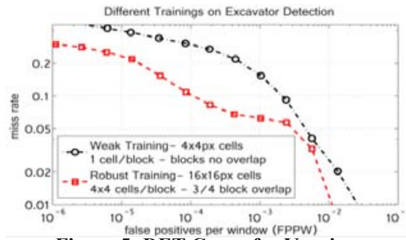

Figure 5: DET Curve for Varying

Testing with New Video Streams. In addition to testing the developed algorithm with the testing dataset, we also tested our developed algorithm using new video streams that were not included in the testing or training datasets (i.e., from different project sites (see Figure 6)). In most cases, reasonable performance on recognition of all categories was observed. In several cases, a number of false alarms (FP) and False Negatives (expected to be detected but the detector did not find it - FN) were observed. Figure 6 shows two examples were in Figure 6a shows the excavator that is detected. In this video, at far end left, a half occluded excavator is observed in a small 2D area which is not detected by our algorithm. Figure 6b shows an example on worker detection that three workers are accurately detected. One worker who is bending is not detected (FN). This is related to the lack of instances of workers with non-standing body postures. Also there is a false alarm where in the leg of the worker is detected as the worker. More results can be found at

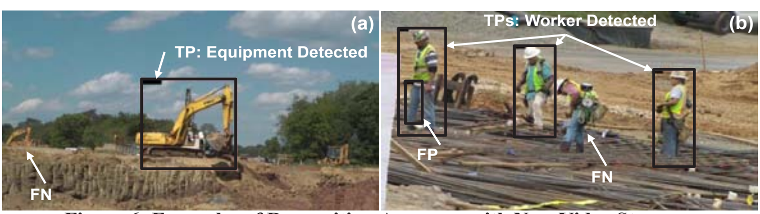

Figure 6: Examples of Recognition Accuracy with New Video Streams

http:///www.raamac.cee.vt.edu/realtimetracking

CONCLUSIONS

In this paper, we presented a new method for automated and real-time recognition and 2D tracking of construction workers and equipment using site video streams. Our results hold the promise of applicability of the proposed method for automated productivity, safety, and occupational health assessments. Future work includes more exhaustive training/testing, in addition to studying the impact of various parameters on recognition accuracy. We also need to develop a new algorithm to benefit from recognition across multiple frames and perform detection for cases where the dynamic resource has left the camera field of view, or is fully occluded. A part-based detection algorithm for enhancing recognition of resources in sever occlusions and high percentage of overlapping is under development.

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Component Level Cyber-Physical Systems Integration: A Light Fixtures Example

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ABSTRACT

Digitally addressable lighting systems offer tremendous opportunities for performance monitoring and control of individual light fixtures. However, the locations of individual light fixtures within a building are not easily differentiable; as such, facility managers cannot easily distinguish and control each fixture. Virtual models contain semantic representation of objects which enable users to visually identify, distinguish and interactively monitor and control building components. To monitor and control light fixtures from these models, each physical fixture needs to be tightly integrated with its virtual representation such as to enable bi-directional coordination. Bi-directional coordination between virtual models and physical light fixtures offers tremendous opportunities for enhancing progress monitoring during construction, and performance monitoring and control during the operations and maintenance phase. Thus, this paper presents an approach to component-level cyber-physical systems integration using light fixtures as an example. A system architecture describing the enabling technologies and their roles is presented and a practical implementation is also presented to demonstrate the functionality and utility of the proposed approach.

INTRODUCTION

A significant proportion of electrical consumption in commercial buildings can be traceable to inadequate monitoring and control of lighting systems (Newsham et al., 2004). Yuan and Wobschall (2007) identified that enhanced monitoring and control of light fixtures is possible using digitally addressable lighting systems. Digitally addressable lighting systems consist of a network of controllers and lighting devices, having digitally addressable lighting interfaces (DALI). DALI systems are presently used in a number of construction projects and have been found useful for spaces with multiple uses and areas where lighting levels and configurations are likely to change over time (e.g. classrooms and conference rooms). Existing DALI control systems consist of a graphical user-interface for monitoring and controlling light fixtures. With this graphical interface, it is difficult to identify and distinguish each fixture for the purpose of controlling the fixtures. Also, locations of individual light fixtures within a building are not easily differentiable; as such, facility managers cannot control each item. Virtual models contain semantic representation of objects

which enable users to visually identify, distinguish, interactively track and monitor the status of building components during construction (Chin et al., 2008). These virtual models are mainly used in the preconstruction and construction phases with few application in the operations and maintenance phases of buildings. However, much more benefit can be derived from these models by extending their use to the construction, operation and maintenance phases of a facility's lifecycle. Specifically, the virtual lighting models can be used for tracking and monitoring the status of light fixtures during construction and for performance monitoring and control during the facility management phase. This will enable users to visually identify each light fixture, and its location within a room or space, for enhanced control.

Anumba et al (2010) identified that integrating virtual models and the physical construction can improve the information and knowledge handling from design to construction and maintenance phases, hence enhancing control of the construction process. Thus, integrating virtual models and the physical light fixture components can enable installation status tracking, performance monitoring and control of light fixtures throughout a building lifecycle. An effective integration will enable bi-directional coordination between virtual models and the physical light fixtures. This approach is termed a cyber physical systems approach. In the context of this research, a cyber-physical systems approach is taken to mean a tight integration and coordination between virtual models and the physical construction.

This paper focuses on describing a cyber-physical systems approach to integrating virtual models and the physical light fixtures for the purpose of identifying and tracking the installed locations of light fixtures during for construction for the purpose of improving energy management in buildings. This paper presents the key enabling technologies required for a cyber-physical systems approach to integrating virtual models and physical light fixtures. A cyber-physical system architecture which brings together the key enabling technologies and their roles, is also presented. An implementation of the proposed approach with Triadonic lighting system is described.

ENABLING TECHNOLOGIES FOR BIDIRECTIONAL COORDINATION BETWEEN VIRTUAL MODELS AND THE PHYSICAL CONSTRUCTION

The key enabling technologies for enhancing bi-directional coordination between virtual models and the physical construction are discussed below:

Digitally Addressable lighting Systems. The DALI is an electrical interface and bus protocol mainly used for the control of lighting systems (Rubinstein, 2003). DALI is an international standard that enables the exchangeability of dimmable ballasts from various manufacturers. Figure 1 shows a DALI-bus segment that has bus-master controller installed. A bus-master can control up to 64 individually addressable ballasts. This means ballasts on the same circuit can be controlled independently. The DALI network allows the bus-master to communicate with all of the ballasts at once, groups of ballasts or individual ballasts. The communication functions include on/off, dimming level, fixture type and fading time. Another feature of DALI is the ability to diagnose problems, such as lamp brightness, lamp failure and lamp type. With DALI, individual addresses can be assigned to light fixtures. These individual addresses will

enable system developers to link the physical light fixtures to the corresponding virtual light fixtures for control.

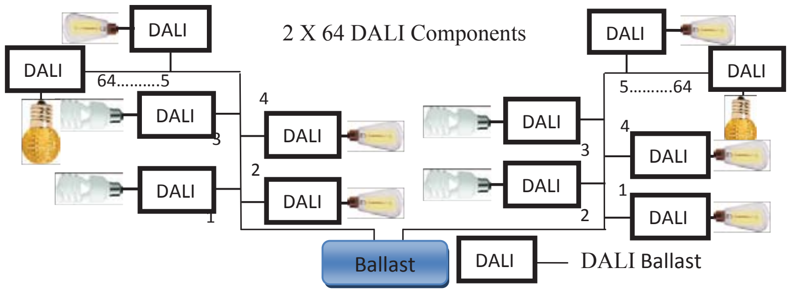

Figure 1. Layout of a DALI network

RFID and Wireless Sensors. Passive RFID tags and other environmental monitoring tags are proposed for this application. Passive RFID tags can be easily attached to each light fixture and scanned for their ID using a RFID reader. The scanned ID can then be used to bind the physical tags with their virtual representation in the model. Binding RFID tagged fixture components with their virtual representation in the model will enable the status (installation) of the light fixture to be tracked in the office. Also, this serves as a means of identifying and distinguishing each tagged fixture and their location in the model, thereby, enabling facility managers to control the fixture components in the constructed facility.

OVERVIEW OF CYBER-PHYSICAL SYSTEMS APPROACH TO MONITORING AND CONTROLLING LIGHT FIXTURES

The cyber-physical systems approach consist of two key features (as shown in figure 2), namely the physical to cyber and the cyber to physical bridge. The physical to cyber-bridge is the sensing process, which involves using passive RFID tags to identify, distinguish and bind the physical light fixtures to the virtual fixtures during construction. This bridge also involves capturing and monitoring the status during construction and post construction phases (such as light on and off, power failure and lamp failure) of the lighting systems from the model. The cyber to physical-bridge represents the actuation which shows how the sensed information affects the system. In this context, actuation is taken to mean making control decisions from the sensed information (from the physical to cyber-bridge) and/or using the sensed information to physically control light fixtures. Thus, the process of binding the physical light fixtures with their virtual representation and using the virtual model to monitor and control the light fixtures illustrates the bi-directional coordination between virtual models and the physical fixture components shown in Figure 2.

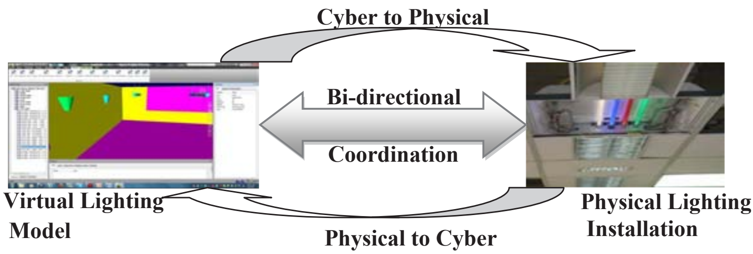

Figure 2. Features of Cyber-Physical Systems for Monitoring and Control of Light Fixtures

The Cyber-Physical System Architecture. The cyber-physical systems architecture in Figure 3 brings together the key enabling technologies as a framework for bi-directional coordination between virtual models and the physical light fixtures. The architecture is based on multiple layers, which are explained as follows:

Sensing and Device Layer. The sensing and device layer consists of wireless sensors (such as RFID system and occupancy sensors) and client devices. The RFID system consists of passive tags and readers for identifying and storing status information about light fixtures. The wireless sensors sense the environment and capture data such as daylight and presence. The client devices such as the tablet PCs provide access to the sensed data from the sensing layer and enables entry of information through the user interface.

Actuation Layer. This layer consists of the virtual lighting model which is accessed through the user interface. The model serves two purposes: it enables the electrical contractor bind each virtual light fixture with their corresponding physical representation in the model. The model also enables the facility manager/owner to visualize and monitor the sensed information from the contents and storage layer. They can also control each physical light fixture through the user-interface. By controlling each fixture through the user-interface, control messages are sent to the contents and application layer.

Communication Layer. This layer contains the Internet and wireless communication networks: local area networks (which use Wi-Fi to enable access to the internet). These communication networks connect mobile devices to the office to allow for collaboration and information sharing. The communication networks also allow the control messages from the office PC or facility manager's office to be transferred through the internet to the DALI layer.

Contents and Application Layer. The contents and application layer contains the database server and the control application. This layer stores, analyses and is constantly updated with information collected from both the communication and actuation layers.

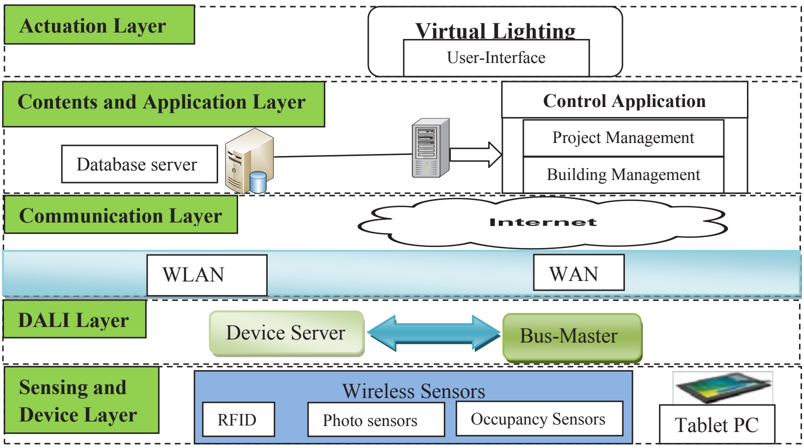

Figure 3. The Light Fixtures Cyber-Physical Systems Architecture

The stored information includes fixture type, location, status, model update information and component lifecycle data. The control applications use the sensed data from the database to make control decisions which can be visualized using the virtual prototype interface in the actuation layer.

DALI Layer. The DALI layer serves as the main interface to the light fixtures. It consists of the device server and bus-master. The device server collects and transmits control messages from the communication layer and fixture ballasts respectively. The control messages transferred through the communication layer is used to control the ballasts using the bus-master. The bus-master also captures fixture or ballast condition messages and sends it to the contents and applications layer through the communication layer.

Two aspects of the approach

There are two aspects to the proposed approach namely, tracking and monitoring light fixtures during construction and performance monitoring and control during the post-construction phase.

Tracking and Monitoring of light fixtures during construction. This involves tracking the status of light fixtures from arrival on the job site to installation. On arrival at the site, the light fixtures are tagged with passive RFID tags (if the light fixtures are not already tagged from the manufacturer's yard). As each tagged fixture is installed, the electrical contractor scans the fixture tag using a tablet PC with an integrated RFID scanner. The tablet PC has a virtual model of the facility. On scanning the tag on the fixture, the electrical contractor binds the tagged fixture with the corresponding virtual fixture in the model and changes the status to 'installed' in the model. Binding the physically tagged fixture with the virtual fixture (in the model), creates opportunities for the electrical contractor to create individual controls

for the fixtures. This virtual model can be shared by the model coordinator, who monitors the progress of work in the site office and can identify which components have been installed and uninstalled.

Performance monitoring and control of light fixtures. During the building lifecycle, the facility managers and owners can remotely use the virtual model to identify and distinguish the locations of each fixture within a physical space for the purpose of enhancing access to individual lighting units and controlling the energy performance of buildings. When the light fixtures are controlled remotely, control messages are sent over the Internet using the TCP/IP protocol to a device server. The device server sends the control messages in the form of an IP address to the bus-master. This bus-master filters and sends the control messages to the appropriate light fixture, as each fixture has a unique address from 1-64 or 0-63. Facility managers can also remotely observe and query the status (ballast failure, lamp failure, power failure, device type) of each or group of fixtures remotely through the model. For example, the status and specification of defective fixtures can be communicated to the facility managers (in real-time) through the model so that they can replace them. This is particularly important as problems can be identified and diagnosed early, thus, reducing the need for routine maintenance checks and enabling the owner/facility manager control over the facility.

IMPLEMENTATION OF ACTIVE MONITORING AND CONTROL SYSTEM FOR LIGHT FIXTURES

This implementation is a proof of concept consisting of two phases (discussed in detail below). For demonstration purposes, only the 'Performance Monitoring and Control' system was implemented.

Tracking and Binding the Physical light fixtures with the virtual representation. The interface shown in Figure 5 was created for capturing the ID of the tagged fixture and tracking their status. Clicking on the 'Track and Bind' button, the application prompts the user to scan a tagged fixture. On scanning a tagged fixture, the tag ID number is captured in the TagID textbox (Figure 4) and the user selects the virtual fixture from the selection tree. The captured ID number appears in the property tab of the selected fixture in Navisworks (Figure 4). Clicking on the 'Install' or 'Uninstall' button, changes the 'Status' property in the model.

Performance Monitoring and Control. This was implemented using the Triadonic DALI system installed in the DALI laboratory in the Department of Architectural Engineering at the Pennsylvania State University. The DALI laboratory is a 1,200 sq. ft. facility housed in the Engineering Unit on campus, and contains over 70 examples of state-of-the-art light fixtures, including color changing fixtures, TV lights, spotlights, and typical commercial lighting. On accessing the performance monitoring and control system the interface in Figure 5, is initiated. Each button on the interface represents commands for controlling the light fixtures. The user selects a fixture from Navisworks selection tree and clicks on any of the command buttons on the interface.

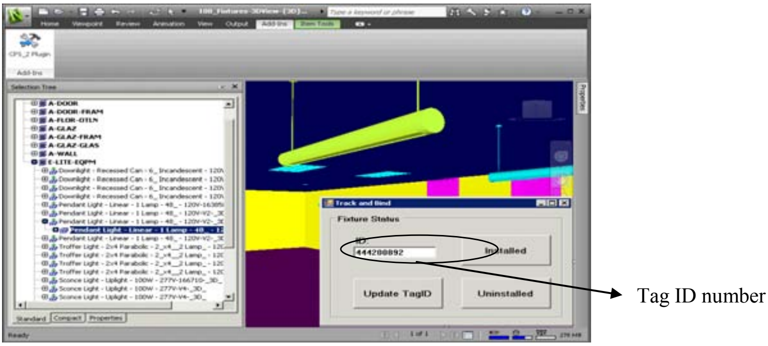

Figure 4. Track and Bind Interface with selected fixture and TagID

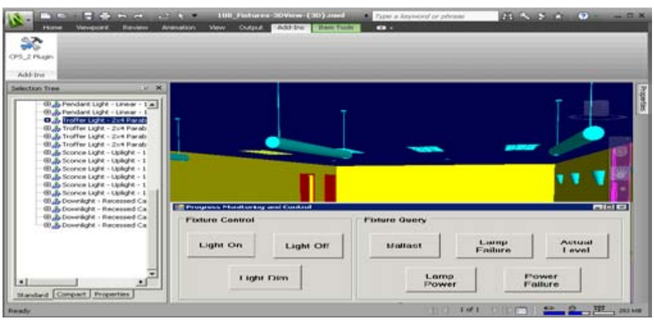

Figure 5. Initiated interface for progress monitoring and control

The clicked command button sends control messages in the form of IP addresses wirelessly through the device server to the bus-master. The wireless technology was used to synchronize the control messages between the tablet PC and the DALI system (Figure 6). The bus-master interprets this command and sends it to the appropriate fixture.

Figure 6. Triadonic DALI system

The bus-master also monitors the light fixtures for messages or responses on the status of the fixtures. For example, when a lamp is turned on in the lab, the

corresponding virtual fixture is turned on in the model and the status property updates to illustrate this change.

SUMMARY AND CONCLUSIONS

Cyber-physical systems approach offers potential opportunities for enhancing bi-directional coordination between virtual models and the physical components. The cyber-physical system approach described in this paper involves the use of passive RFID tags to identify, distinguish and locate tagged components, from the design model. The sensed information from the tags is used to make control decisions and to physically control the construction process/constructed facility. This approach has been demonstrated through the development of a system for tracking, monitoring and controlling light fixtures throughout a facility lifecycle. A system architecture is presented which describes the key enabling technologies including, DALI system, RFID and wireless sensors, mobile devices, communication network and virtual prototyping technology. The key conclusions that can be drawn from this work are:

- RFID tags can identify and distinguish components; this makes the technology suitable for tracking and monitoring the installation of light fixtures during construction;
- Bi-directional coordination between virtual models and the physical construction has potential opportunities for improving progress monitoring and lifecycle performance monitoring and control of light fixtures, thus improving energy management;
- The proposed approach indicates that cyber-physical systems approach plays an important role in enhancing bi-directional coordination between virtual models and the physical construction;
- There is considerable potential/opportunity for the application of cyber-physical systems to other aspects of the construction project delivery process, facility management, and other operations.

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3D-Modeling For Crane Selection And Logistic For Modular Construction On-Site Assembly

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ABSTRACT

Adequate crane position on construction site required large amount of site data to be collected, prior to any lift operation. Existed permanent/ non-permanent obstructions as well as objects being placed on their final position, must be considered for each lift. This paper presents a methodology for crane selection and on-site utilization evolutionary algorithm for multi-lifts for modular construction. The proposed methodology accounts for cranes capacity limitation as well as evaluates the crane carrier/body position and orientation. State-of-the-art methodology incorporate evolutionary algorithm that reacts to dynamic changing site conditions.

This paper introduces a case study where the objectives were to simplify and optimize the field assembly operation for 5- three-storey dormitory buildings including bridges and large roofs in McGregor Village for Muhlenberg College in Allentown, Pennsylvania, USA. Each dormitory contains three types of modules and a total of 18 separate modular units. Fully habitable elements were delivered securely on flatbed trailers to the site in advance. An all-terrain mobile hydraulic crane placed in the center of construction site lift each module and placed like a puzzle floor by floor for each building at predefined position. All 100 lifts were conducted in only 10 working days.

INTRODUCTION

Construction industry recognizes modular – or manufacturing housing as a one of any construction method. Its primary advantages are quality workmanship and on-site completion time. When off-site completed products are transported to the construction site, then crane lifted in the final spot in a matter of days. Research in modular construction is extensive and some authors refer it to the low-rise multi-family housing development [Murdock]. Use of robotics method to automate the

model development process and reduce on-site labor has been presented in [Nasereddin], [Bock], and [Editorial Leonard]. Also, the challenge related to a crane selection at construction site is addressed [Al-Hussein 2001, and Al-Hussein 2005]. Most effective way of utilizing modular off-site construction can be recognized in the construction of school/ dormitories, campuses buildings or affordable housing [Cardenas, and Atkinson]. Other examples successful modular construction implementations are health care units, from single check-up rooms to operating theaters or pharmacy centers [Editorial Health, Editorial Hospital, Editorial Operating, and Editorial Pharmacy]. When complicated mechanical components or multi-dimension construction site movement are involved, transforming the intellectual ideas into drawings is not a complicated task. The paper sketches are the first media to receive human brain idea output. Often, these "data" are the only evidence of new development and they are not recorded any other way. Capturing a knowledge of bright and successful ideas may be challenging if is not digitally recorded in the form of CAD solid modeling, mathematical algorithms and then presented virtually as animation or simulations. Analyzing and testing cranes in 3D has a proven record of success in assisting the construction industry or analysis assembly and complicated movement using tilt-up panel construction method [Al-Hussein 2005, Manrique]. Closing the gap between simulation and visualization and address visualization of the design constraints are the other examples of computer technology assistance [Olearczyk 2009, Olearczyk 2010]. Communication as an important way of exchange information and solve the problem is a key factor not only on construction site. To better understand concept of design, schedule and allocation resources over construction time virtual reality (VR) tool plays significant role. This dynamic graphical depiction is able to shows the proposed design just as the final product would appear in the real world.

METHODOLOGY

The proposed methodology is based on four modules, as illustrated on Figure 1. Input section contains all available lifted object parameters and available crane/rigging configuration arrangement.

Main process includes crane load and capacity check, crane location assessment, crane boom clearance arrangement and lifted object trajectory evaluation, which will be in detail elaborated. The main process is subject to criteria restrictions including lifted object size, crane renting cost, and specific ground preparation for crane placement, schedule or weather conditions. As an output user may extract information flowing between the main segment modules or analyze final results, such as object path, obstruction conflicts or lifted object sequence priority suggestions.

Crane load capacity check. Total lifting weight may not exceed current crane configuration lifting capacity with added industry standard safety factor. When controlled equation is not satisfied, crane capacity is lower than total weight, and the analyzed crane configuration is rejected. Rejection does not terminate operation but activates the re-define operation. Thus operation modifies input parameters within own criteria and introduces again for load capacity check. At the same time operator is notified that lift capacity reach its 85% instead of 80%. Final limit (corporation

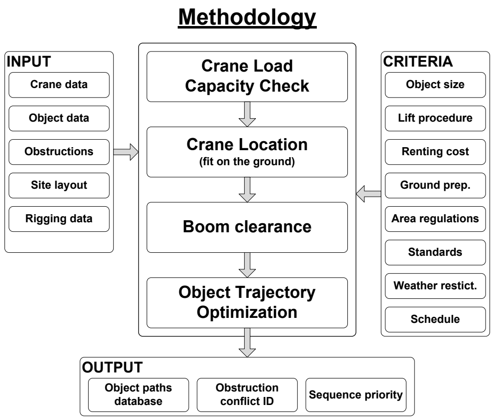

Figure 1. Methodology flow chart

standard) may be introduced and if algorithm reach that value configuration is rejected. This option allows algorithm "exploring" possible solutions making module as a semi-intelligent.

Crane placement location;

Crane placement location is far more complex operation that simple load capacity checks. Many scholars presented their views and points. Extensive work has been done on single crane lift analysis [Al-Hussein 2005, and Manrique] and multi-lift crane position placement. Crane location input includes three data segments related to site, crane, and lifting object parameters. Site data provides information about available layout areas, surveying and ground density, and obstruction under and above ground level. Crane related data includes outriggers, configuration, counterweight, and superlift space requirements, as well as spreader bar availability or boom attachment additions. Object data includes weight, geometric center (GC), lifting lugs dimensions, and additional supports for temporary storage. This process starts with calculating the geometric center of all objects. The crane center of rotation point was placed in the calculated geometric center point. Circles representing crane radiuses were attached to each object set-point (GC) and maximum values were assisted in crane selection process.

Boom Clearance Evaluation;

The next step in the methodology main process objective is analysis of the remaining crane configuration for its boom clearance to obstructions. It is defined by the maximum crane boom reach radius dimension and accordingly modified if obstruction is on its way. To satisfy objective requirements a table of predefined hydraulic crane configuration were establish. Table 1 shows crane boom configurations.

Table 1. Crane boom configurations

Scenario	Equipment	Given	Calculate
1	Main boom	Boom length, lift radius	Boom angle, tip height
2	Main boom, extension	Boom + extension length, lift radius	Boom angle, tip height
3	Main boom, extension	Boom + extension length, boom and extension angle	Lift radius, tip height

Table shows three different scenarios and two boom configurations. It also describes input parameters for each configuration and expected output. In each scenario adequate equations were developed and solved, graphical representations were introduced for visual clarification.

As an extended part of boom clearance evaluation *Boom clearance to slope surface* analysis was developed. A further expansion algorithm goes beyond an analysis of the boom position in the normal plane (flat roof shape) in relation to the building, and in keeping with the analysis outlined by Shapiro. Figure 2 shows a layout of the critical crane boom position and the referenced parameters.

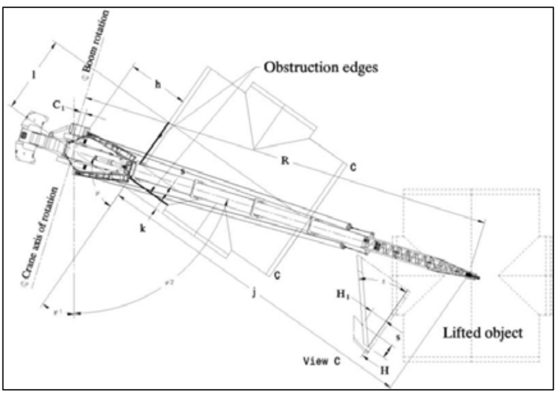

Figure 2. Plan view of the crane boom obstruction

Critical dimensions include boom obstruction calculations such as boom center line to obstruction edge angle (f), boom radius (*R*), and boom rotation center to obstruction edges distances, horizontal (*h*) or vertical (*k*). Figure 3 shows actual site picture for boom clearance. However, while such analyses calculate the required clearances of the erected crane boom to potential obstructions, they fail to address a situation where the roof has an inclined configuration.

The present study involves that particular configuration with the intent to develop a solution that addresses the situation where the crane boom position is not in the normal plane but in the inclined roof shape to the building structure. Figure 4 shows graphical interpretation of Shapiro A boom to flat roof analysis and proposed B boom to slope roof solution.

Figure 3. Picture of the crane boom clearance

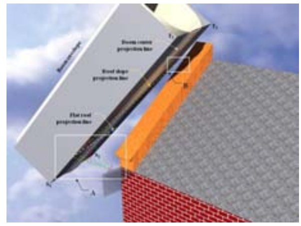

Figure 4. Boom obstruction clearance analysis

This complex geometrical configuration is supported by 2D drawings and 3D isometric layouts where the calculated minimum clearance, between the crane boom and the inclined roof, defines the exact position of the lifted object. Such a lift configuration, where the obstruction is between the lifted object and the crane boom envelope, is common on construction sites. Engineers would like to schedule a maximum number of lifts without relocating the crane. In some situations reconfiguring the crane for one or two lifts can be more cost-effective.

Object trajectory optimization. The proposed algorithm layout is based on extensive research on a few heavy crane lift operation projects. The algorithm will be explained step-by-step with respect to crane-object-obstruction relation movement at specific crane configuration and lifted object parameters. Figure 5 shows an expanded trajectory algorithm flowchart.

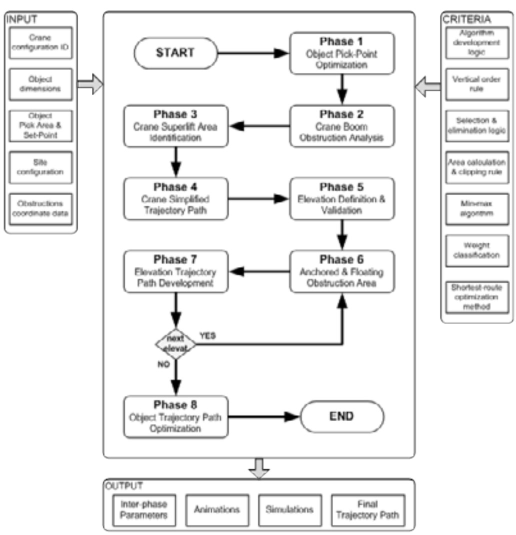

Figure 5, Algorithm micro-level flowchart

It consists of eight phases with clearly defined objectives and output identification direction. Phases 6 and 7 are placed in a short loop to evaluate each elevation separately and store full or partial solutions. Phase 8 analyzes developed paths to find the optimal solution and create the final trajectory path definition. Only certain data is engaged in the process of mathematical calculations, which directly create evaluated output. Also, due to the limited information that is required for evaluation at this stage, only part of the criteria participates in filtering the desired data. The described process analyzes single iteration with the given crane position, object pick areas, and object set point location. The entire methodology concept is presented in the form of tasks and decisions blocks. The input parameters include essential information for the modeling process, including the object's data that contains dimensions and weight parameters, and the crane's data that includes specifications such as dimensions, radiuses, and lifting capacities. Also, the input box stores information about construction site configuration and potential coordinate values of obstructions. Each specific parameter in the input box refers to a set of data required in order to run the algorithm operations. As an example Phase 3 objective is to develop a restricted crane superlift area(s) for a crane with a wheeled superlift attachment. Figure 6 shows final output of Phase 3 crane superlift area identification

Another important section is Phase 5 with objective to validate vertical order (VO) elevation creation for crane set-point, object pick-point and set-point, as well as develop obstruction elevation analysis planes. Figure 7 shows final task of the phase with full elevations development.

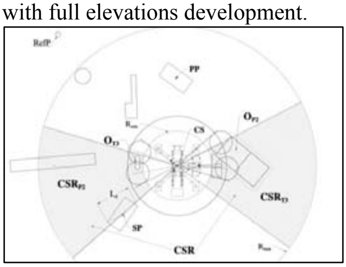

Figure 6. Superlift restriction area

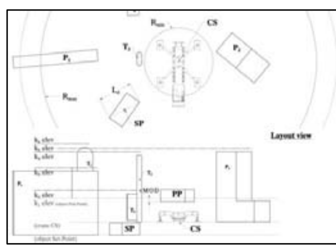

Figure 7. Trajectory elevation

Final Phase 8 objectives are to develop connection elevation lines, including object pick-point or/and set-point connection, assign weight values connections, and develop a routine to optimize trajectory path. Figure 8 shows trajectory paths web CAD model.

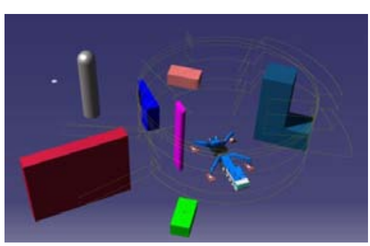

Figure 8. Trajectory paths web - isometric view

This state-of-the-art methodology approach recognizes, analyzes, and optimizes the crane lifted object spatial trajectory. It is divided into concise phases, which act as independent problem solving methods, but are connected into a smooth flowing process. Each phase structure starts from objective description then shows and discusses proposed phase flowcharts. This technique creates a feeling of full descent into the problem and clearly explains the solution in the form of graphical pictures, which are supported by mathematical equations.

CASE STUDY

The proposed methodology is best described through a case study, which involves construction of five three-story dormitory buildings for Muhlenberg College in Allentown, Pennsylvania. Construction replaces old outdated (1981) and inadequate single level dormitory space units, which accommodated only 56 students. Each of the building had six apartments, most with one double bedroom and three singles. These solid-looking attractive buildings were manufactured in Lebanon, N.J. by Kullman Building Corporation. Each building consists of 18 modules, which must meets specific rules related to size and weight. Figure 9 shows a CAD model of one new dormitory exploded view and Figure 10 occupied dormitory at the beginning of the school year.

Figure 9. Dorm CAD model exploded view

Figure 10. Occupied dorms

CONCLUSION

The entire logical concept is based on solid groundwork and expert knowledge that involves professionals from several different academic fields, such as construction and mechanical engineering faculty, mathematics faculty, and computer science and engineering management department scientists. But the most critical field expert knowledge, which must be recognized, came from individuals who on a daily basis are involved in the real situation and must deal with and solve critical and complicated crane-object-obstruction relations. The methodology was tested in a number of challenging case studies, one of which is mentioned in this paper.

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Extraction of Construction Regulatory Requirements from Textual Documents Using Natural Language Processing Techniques

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ABSTRACT

Automated regulatory compliance checking requires automated information extraction (IE) from regulatory textual documents (e.g. building codes). Automated IE is a challenging task that requires complex processing of text. Natural Language Processing (NLP) aims at enabling computers to process natural language text in a human-like manner using a variety of text processing techniques, such as phrase-structure parsing, dependency parsing, etc. This paper proposes a hybrid syntactic (syntax/grammar-related) and semantic (meaning/context-related) NLP approach for automated IE from construction regulatory documents, and explores the use of two techniques (phrase-structure grammar and dependency grammar) for extracting information from complex sentences. IE rules were developed based on Chapter 12 of the 2006 International Building Code; and the approach was tested on Chapter 12 of the 2009 International Fire Code. Initial experimental results are presented, empirically evaluated in terms of precision and recall, and discussed.

INTRODUCTION

Construction projects are regulated by various rules and regulations from all levels of authorities, such as the International Building Code (ICC 2006). Manual compliance checking of construction projects to the various rules and regulations is costly, time-consuming, and error-prone. Many efforts have been made towards automated compliance checking (ACC), such as checking building envelope performance (Tan *et al*. 2010), building design (Eastman *et al.* 2009), accessibility (Lau and Law 2004), and structural safety (Garrett and Fenves 1987), etc. However, none of them achieved full automation; the extraction of regulatory requirements from regulatory text and its representation in a computer-processable format is still conducted manually or semi-automatically. To address this research gap, the authors are proposing an approach for automatically extracting regulatory information from regulatory text (e.g. building codes) to support automated regulatory compliance checking. Our approach utilizes various Natural Language Processing (NLP) techniques. This paper presents our automated information extraction (IE) approach –

including how to extract information from complex sentences – and discusses initial experimental results.

NATURAL LANGUAGE PROCESSING

Natural language processing (NLP) aims at enabling computers to understand and process natural language text and speech in a human-like manner. Examples of NLP tasks include part-of-speech (POS) tagging (i.e. tagging each word with its part of speech, such as noun, verb, etc), named entity recognition, co-reference resolution, and machine translation, etc. (Marquez 2000). Information extraction (IE) is a subfield of NLP that aims at extracting targeted information from text sources to fill in pre-defined information templates. Few research efforts have utilized NLP techniques in the construction domain for a variety of applications, such as concept and relation extraction from construction contracts (Al Qady and Kandil 2010), construction document classification (Caldas and Soibelman 2003), and request for information (RFI) meta-model building (Zhu *et al.* 2007), etc. In comparison to previous efforts, this research: 1) deals with a different application (automated compliance checking), 2) addresses a different level of NLP/IE (processing text to automatically extract regulatory requirements and represent them in a semantic format), and 3) takes a deeper semantic approach for NLP (utilizing a domain ontology for identifying semantic text features) (Zhang and El-Gohary 2012).

HANDLING SENTENCE COMPLEXITY

Languages are complex. In English, one meaning can be expressed in multiple ways, with varying terms and grammars. Also, one sentence can be significantly long, with continuously added phrases and clauses. These two phenomena lead to the difficulty of IE tasks, because the burden of pattern matching (a core technique in IE that utilizes sequential combination of text features to recognize target information) increases nonlinearly with the complexity of a sentence. In this paper, the authors address this problem by aiming at reducing the number of matching patterns using two techniques: phrase-structure grammar and dependency grammar.

Phrase-structure grammar (PSG). A PSG is a set of phrase structure relations (PSRs). A PSR is defined by a generative rule (a rule that predicts which combinations of tokens will form a grammatical sentence) of the form: L → R, where L and R are lists of tokens and the PSR defines the mapping from L to R (Levine and Meurers 2006). Context free grammar (CFG) is a special type of PSG. In CFG, L is a single nonterminal (a symbol that could be further broken down) and R is a sequence of terminals (literal symbols that cannot be further broken down) and nonterminals. In this paper, we use CFG for feature generation (for the remainder of the paper we use CFG and PSG interchangeably). Figure 1 shows the constituent tree of the sentence "The minimum net glazed area shall not be less than 8 percent of the floor area of the room served" produced by parsing with PSG. For example, applying the first CFG rule: 'Sentence' →NP VP, we could derive the nonterminals 'noun phrase' (NP) and 'verb phrase' (VP) from the root node (the nonterminal 'Sentence').

Dependency grammar (DG). The basic construct for DG is the pairwise relation between two words. In each relation, one of the words is called "head" and the other is called "dependent". Parsing with DG is more straightforward than with PSG, because it only needs to connect existing nodes (i.e. the words in a sentence), while in PSG more intermediate-level nodes need to be created. Thus, parsing with DG is simpler, but less expressive (Covington 2001). Figure 2 shows the dependency tree of the same sentence (that was used in Figure 1) produced by parsing with DG. Each arrow points from a head to the corresponding dependent, with the dependency relation labeled on top.

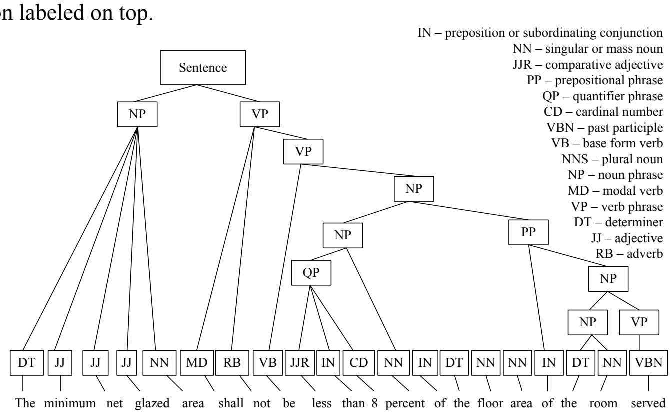

Figure 1. A Sample Constituent Tree Produced by Parsing with PSG.

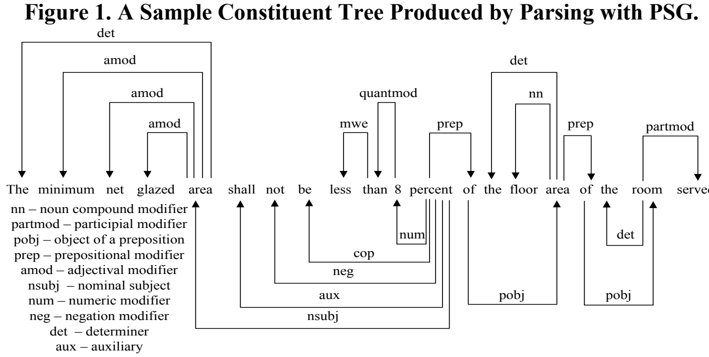

Figure 2. A Sample Dependency Tree Produced by Parsing with DG.

PROPOSED AUTOMATED INFORMATION EXTRACTION APPROACH

Summary of the proposed approach for automated IE. To address the research gap of automated regulatory IE for ACC in construction, the authors had proposed an approach utilizing syntactic (i.e. syntax/grammar-related) and semantic (i.e. meaning/context-related) information, whose potential effectiveness has been preliminarily tested and verified (Zhang and El-Gohary 2012). In order to compare

PSG and DG in terms of their ability to handle sentence complexity, two modified versions of the previously proposed approach are used. Both versions are composed of six phases: 1) Preprocessing: aims at preparing the text for feature generation. It includes tokenization (i.e. recognizing each word, punctuation, and symbol as a token), sentence splitting (i.e. recognizing sentence boundaries), and morphological analysis (i.e. mapping each word to its root form); 2) Feature Generation: aims at generating a variety of syntactic and semantic features to be used as building elements of matching patterns for IE. It includes POS tagging, sentence complexity handling, gazetteer compiling (i.e. producing lists of words or phrases belonging to specific categories such as list of cities. The information that a word or phrase belongs to a certain list in the gazetteer could be used as a feature for IE), and ontology development (i.e. developing an ontology to model domain knowledge in the form of a hierarchical structure of concepts, relations, and axioms. The concepts and relations modeled in the ontology could be utilized as features for IE); 3) Target Information Analysis: aims at selecting the information elements (concepts and relations) to be extracted based on the type of requirement to be checked, and arranging the extraction sequence. For example, 'subject', 'compliance checking attribute', 'comparative relation', and 'quantity' are information elements for quantitative requirements, and the extraction sequence is arranged as 'quantity' >'subject' >'compliance checking attribute' > 'comparative relation'. This phase includes target information identification, and extraction sequence resolution; 4) Development of Extraction Rules: aims at constructing the extraction rules based on the features generated in Phase 2. The left-hand side of the rule defines the pattern to be matched, and the right-hand side defines which part of the matched pattern is to be extracted. This phase includes matching pattern construction (i.e. compiling the matching patterns for each target information element), feature selection (i.e. selecting the features to be used in matching patterns), and development of rules for resolving conflicts in extraction (i.e. developing rules for handling conflicts such as the existence of multiple instances for one information element, or no existence of instances for an information element). The matching patterns take the format of a sequential combination of features. For example, the pattern " 'building element' 'MD' 'comparative relation' 'CD' 'unit' 'IN' 'quantitative compliance checking attribute' " matches a quantitative requirement, where 'building element' and 'quantitative compliance checking attribute' are concepts in the ontology; 'MD','CD', and 'IN' are POS tags for modal verb, cardinal number, and preposition conjunction, respectively; and 'comparative relation' and 'unit' are gazetteer features; 5) Extraction Execution: aims at extracting all targeted information using the extraction rules; and 6) Evaluation: aims at evaluating the performance of IE in terms of precision and recall, by comparing IE results with a gold standard. Phase 2 to Phase 6 can be iterated until a satisfactory performance is achieved. For further elaboration on each phase, the reader is referred to Zhang and El-Gohary 2012.

Variation with phrase-structure grammar. In addition to the features of string terms, POS tags, gazetteer lists, and ontology-based semantic information; phrase tags are used as features to build matching patterns for IE. PSG is used to generate phrase tags. Based on the rules of PSG, phrase tags are assigned when a certain

combination of POS tags and/or phrase tags are encountered. For example, the rule "QP → JJR IN CD" states that the phrase tag "QP" (quantifier phrase) should be assigned when the sequence of POS tags "JJR IN CD" is encountered, as in the phrase "less (JJR) than (IN) 0.07 (CD)".

Variation with dependency grammar. In addition to the features of string terms, POS tags, gazetteer lists, and ontology-based semantic information; dependency relations are used as features to build matching patterns for IE. Because one dependency relation only takes two words, and the two words are usually not adjacent in a sentence, it is difficult to use dependency relations directly in matching patterns. Therefore, in this paper, the authors utilize the spans of dependency relations as features in matching patterns. For example, the dependency relation "det" (determiner) connects the words "the" and "area" in the phrase "the minimum net glazed area". So, we assign the feature "det" to the span of this dependency relation (i.e. the phrase).

COMPARATIVE EXPERIMENTAL RESULTS AND ANALYSIS

To evaluate and compare the performance of PSG and DG in handling sentence complexity in the context of automated regulatory IE, we tested our approach on extracting quantitative requirements from Chapter 12 of the 2009 International Fire Code, with IE rules developed based on Chapter 12 of the 2006 International Building Code. A quantitative requirement is a rule defining the relationship between a quantitative attribute of a subject and a specific quantity. We extract four information elements for each requirement, which are 'subject' (a 'thing' that is subject to a particular regulation, such as a building element), 'compliance checking attribute', 'comparative relation', and 'quantity'. For example, in the sentence "Yards shall not be less than 3 feet in width"; 'yard', 'width', 'greater than or equal', and '3 feet', are 'subject', 'compliance checking attribute', 'comparative relation', and 'quantity', respectively. We used GATE (General Architecture for Text Engineering) tools (Univ. of Sheffield 2011) for conducting syntactic analysis (tokenization, sentence splitting, gazetteer compiling, POS tagging, morphological analysis) and semantic analysis (ontology-based meaning analysis) of the text, as well as for constructing matching pattern rules and executing IE. We used the following features for constructing matching patterns: string terms, POS tags, gazetteer lists, ontology-based semantic information, and features for handling sentence complexity as described below.

For the experiment with PSG, a set of PSG rules were derived from a portion of the regulatory document, based on the POS tags and the phrase tags (Santorini 1990; Bies *et al.* 1995). Examples of the derived PSG rules are "NP → NP PP; NP → DT JJ NNS; PP → IN NP", which state that the phrase tag "NP" should be assigned when the combination of the phrase tags "NP PP" or the combination of the POS tags "DT JJ NNS" are encountered, and the phrase tag "PP" should be assigned when the combination of the POS tag "IN" and the phrase tag "NP" is encountered. All phrase tags that appeared on the left hand sides of PSG rules are candidate features to construct IE matching patterns.

For the experiment with DG, we used the Stanford parser to generate Stanford typed dependencies (Marneffe and Manning 2008). All Stanford typed dependency relations are candidate features to construct IE matching patterns. Each dependency relation represents the span of text covered between the two words in that relation. For example, a “det” relation exists between “the” and “area” in the phrase “the net free ventilating area”; thus the feature “det” will cover the whole phrase of “the net free ventilating area”.

Experimental results. For evaluation, a gold standard was manually constructed. It has 21 ‘subject’ instances, 17 ‘compliance checking attribute’ instances, 21 ‘comparative relation’ instances, and 21 ‘quantity’ instances. Precision, recall, and F-measure were used to evaluate the IE performance of both versions of our proposed approach. The number of matching patterns and the amount of running time were used for comparing the manual effort and computing efficiency of both approaches, respectively. The experimental results are summarized in Table 1. Three points are observed: 1) Both PSG and DG managed to handle sentence complexity (overall F-measure is higher than 0.94 in both cases), with the performance of DG being slightly better than PSG; 2) Using DG, less manual effort is needed to construct IE matching patterns; 3) Considering the task of generating Stanford typed dependency as part of preprocessing, the IE running time using DG is much less than that using PSG. Table 2 shows an example of correctly-extracted information from the following sentence: “The maximum quantity of Type I solvents permitted at any work station shall be 1 gallon”.

Analysis of results. Both versions of the proposed approach achieved high IE performance, and the F-measure with DG is about 0.026 higher than that with PSG. Analyzing the results, we found that: 1) Because DG-based parsing is more direct; DG is less susceptible to parsing errors. This is the main reason why the approach with DG has a slightly better extraction performance than that with PSG. For example, the DG version successfully recognized “Type I solvents” as one subject instance, while the PSG version failed. Because “I” was incorrectly parsed as a PRP (unknown, but probably possessive pronoun), the matching pattern “NNP NNP NNS” in PSG failed to match. The “det” feature in DG, on the other hand, was not influenced by that parsing error, and “The maximum quantity of Type I solvents” was successfully recognized as a noun phrase; 2) Because DG-based parsing is simpler; DG requires less matching patterns in comparison to PSG. For example, the feature “det” in DG saves a lot of enumerations of matching patterns for the subject noun phrase. Because any adjective, adverb, participle, or any combination of them modifying the head of a noun phrase always appear after the article and before the head of the noun phrase, they are automatically covered in the span of the dependency relation “det”; 3) DG requires less time in executing IE because the complexity of sentence is tackled in the preprocessing phase when dependency relations are generated. This could be an advantage of DG, because preprocessing is usually separated from the main IE process; and 4) since the availability of dependency relations in DG is limited by the dependency parser used, while grammar rules in PSG can be formulated more freely; PSG is more flexible than DG in the type of target information it can extract.

Table 1. Comparative Experimental Results.

Number of Instances	Subject	Compliance Checking Attribute	Comparative Relation	Quantity	Total
in gold standard	21	17	21	21	80
extracted with PSG	21	16	21	21	79
extracted with DG	21	16	21	21	79
correctly extracted with PSG	20	16	21	18	75
correctly extracted with DG	21	16	21	19	77
Precision with PSG	0.952	1.0	1.0	0.857	0.950
Precision with DG	1.0	1.0	1.0	0.905	0.975
Recall with PSG	0.952	0.941	1.0	0.857	0.938
Recall with DG	1.0	0.941	1.0	0.905	0.963
F-Measure with PSG	0.952	0.970	1.0	0.857	0.943
F-Measure with DG	1.0	0.970	1.0	0.905	0.969
Matching Patterns with PSG	32	1	2	15	50
Matching Patterns with DG	5	1	2	6	14
Running Time with PSG (sec.)	1.611	1.171	0.431	0.7	3.913
Running Time with DG (sec.)	0.325	1.171	0.431	0.271	2.198

Note: the running time for generating Stanford typed dependencies is 16.478 seconds (not included in the running time with DG).

Table 2. Example of Information Extraction Result.

Subject	Compliance Checking Attribute	Comparative Relation	Quantity
type I solvent	quantity	less than or equal	1 gallon

CONCLUSIONS AND FUTURE WORK

In this paper, the authors presented a hybrid syntactic and semantic approach for automated information extraction (IE) from construction regulatory documents for supporting automated compliance checking (ACC) in construction. The paper explored the use of two techniques (Phrase-Structure Grammar (PSG) and Dependency Grammar (DG)) for extracting information from complex sentences. Comparative experiments were conducted using GATE tools (Univ. of Sheffield 2011). The experiments focused on extracting quantitative requirements from Chapter 12 of the 2009 International Fire Code (ICC 2009). The results show that: 1) The F-measures for IE using both techniques are more than 0.94. As such, we may conclude that both techniques managed to handle sentence complexity; 2) In comparison to PSG; DG performs better in extracting information from complex sentence structures, because DG-based parsing is simpler. DG is more ‘immune’ to parsing errors, requires less matching patterns for IE, and needs less running time (excluding preprocessing time); and 3) PSG is more flexible than DG in the type of target information it can extract. These results are preliminary in nature. Further experimentation is needed on different types of requirements, other regulatory documents, and on larger samples of text. In future work, the authors will explore the ways to optimize the proposed IE approach through combining PSG and DG. Our future work on ACC will also explore automated IE from other types of construction

documents (e.g. contract specifications) and will also cover checking of designs and construction operational plans (e.g. construction environmental plans) for compliance to extracted regulatory and contractual requirements.

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The 3-D Global Spatial Data Model (GSDM) Supports Modern Civil Engineering Practice and Education

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ABSTRACT

This paper discusses concepts and procedures that civil engineers use to handle both generic 3-D spatial data and geospatial data referenced to the Earth. A consequence of the digital revolution is that spatial data are now characterized as digital and 3-D. The principles used by Gerard Mercator (1512-1594) in conformal mapping and René Descartes (1596-1650) in solid geometry are brought forward in the context of information management as envisioned in the 1955 Grinter Report and more recently realized in geographic information systems (GISs) and 3-D applications such as GPS, laser scanning, and LIDAR. The 3-D global spatial data model (GSDM) provides a computational environment that preserves 3-D geometrical integrity, is standard world-wide, supports existing "flat-Earth" applications, and serves as a foundation for the global spatial data infrastructure (GSDI). While spatial data computations are standard in civil engineering practice, the concepts related to geospatial data should also be included in civil engineering practice, education, and curriculum design.

INTRODUCTION

Generic spatial data are described by rules of solid geometry. Spatial data referenced to the Earth are called geospatial data. The terms "spatial" and "geospatial" are often used interchangeably and many rely on context to discriminate between the two. While the rules of solid geometry are applicable to both categories, this paper describes using the global spatial data model (GSDM) as a way to handle 3-D digital geospatial data in addition to spatial data. A paper on geometry and spatial data relationships may fail to gain traction because the rules of solid geometry are well-proven and have remained unchanged for generations. Engineers learn coordinate geometry (COGO) computations, use COGO in many applications, and many take COGO for granted. But, there is more. This paper updates spatial data concepts as related to the use of 3-D digital geospatial data in civil engineering applications. In years past, a civil engineering educational program typically contained 3 or 4 surveying courses with focus on various concepts ranging from simple flat-Earth computations based on plane Euclidian geometry to higher level surveying courses on route surveying, control surveying, municipal surveying, photogrammetry, and maybe even geodetic surveying. Cross disciplinary courses such as cartography, map projections, and/or geography were typically included as

electives or found only in a graduate program. Courses devoted to land (boundary) surveying were either missing or offered only as an elective. It has been felt by many that land surveying concepts and practice could be learned on the job as an apprentice. Although eloquently argued otherwise over the years, even today, a college degree is not required to be eligible for licensure as a surveyor in 39 states (Thompson 2011).

With publication of the Grinter Report (ASEE, 1955), the focus for many civil engineering programs began to shift to a greater emphasis on engineering sciences including mechanics of solids, fluid mechanics, thermodynamics, transfer and rate mechanisms, electrical theory, and nature and properties of materials. Surveying came to be viewed as a "hands-on" topic and, over the past 50 years, has been dropped from many civil engineering programs. To pick up the slack, leaders in the surveying profession (Gibson 2009) pushed for establishment of separate surveying programs to serve the broad spectrum of surveying activities and practice. There have been many successes over the years and there are currently more than 25 reputable ABET accredited surveying programs in the U.S.A. (Burkholder, 2011). To its credit, the surveying profession has grown to embrace much more than just land surveying and the term Geomatics is being used to represent a broader discipline. But, with regard to surveying engineering, two unfortunate trends have also occurred; 1) surveying has ceased to be part of many civil engineering programs and 2) the engineering component of most surveying engineering programs has taken a back seat to other topics. Very few EAC accredited surveying engineering programs prepare graduates to take and pass the NCEES Fundamentals of Engineering exam.

A single surveying (Geomatics) course can be a valuable component of a CE program if it reinforces engineering concepts such as measurements, coordinate systems, spatial data models, error analysis, and non-trivial computations. But, it is difficult to cover all of those topics adequately in one course. Two conflicting views are that a single Geomatics course should be included early in the CE curriculum to help the student gain a broader perspective of fundamental engineering concepts. An alternate view is that a single Geomatics course should come much later in a baccalaureate CE program and, building on student maturity in engineering sciences, include higher-level computational concepts such as spatial data modeling, coordinate systems, network adjustment, error propagation, and functional analysis. The ideal scenario would be to include at least two separate Geomatics courses in all CE programs. But, recognizing the pressure to reduce total credit hours for a BS degree, if offering two or more courses is not a possibility, the first choice should be to offer at least one higher-level Geomatics course in each CE undergraduate program.

With regard to the use of geospatial data, the impact of the analog/digital transition described herein needs to be incorporated in both civil engineering practice and in civil engineering education. Specific recommendations are: 1) ASCE should become pro-active by including modern spatial data concepts in continuing education efforts. 2) ASCE should promote inclusion of high-level spatial data concepts in all civil engineering programs, and 3) ASCE should lobby for enhanced EAC surveying engineering criteria in the ABET accreditation process. Consideration, adoption, and use of the GSDM can enhance the success of all three recommendations.

BACKGROUND

Surveying has been around ever since ancient Egyptian "rope stretchers" re-established boundaries following annual floods of the Nile River. Others describe development of surveying as beginning with Euclidian geometry or activities of the Roman Empire engineers. This discussion begins with the works of Gerard Mercator (1512-1594) because Mercator developed what is now known as a conformal map projection. In addition to being able to represent the curved Earth on a flat map, the unique feature of a conformal map is that angles on the spherical Earth are projected without distortion onto a flat map. The beneficial consequence in Mercator's day was that navigators could plot a course on a Mercator map from one port to another as a straight line and sail a constant bearing to travel port to port (Crane, 2002). Note – even though a straight line on the map was not the shortest possible route, the Mercator map greatly simplified navigation. Mercator projections are still used extensively in the Universal Transverse Mercator (UTM) projections and for numerous state plane coordinate zones in the United States. Mercator projections are also used by various GPS vendors as the basis for "localization" when using GPS derived coordinates on local sites. Being familiar the advantages and limitations of a map projection and associated plane coordinates can be very important for many civil engineers – especially those who work with GPS, LIDAR, or machine control.

René Descartes (1596 – 1650) was a noted philosopher and mathematician. As a philosopher, Descartes is best known for the quote "I think, therefore I am." However, Descartes (who gave us the rectangular Cartesian coordinate system) also made huge contributions in mathematics by systematically organizing geometry concepts and publishing his "Discourse on the Method of Reasoning Well and Seeking Truth in the Sciences" in 1637 (Aczel, 2005). Even today, rules of solid geometry, analytical geometry, and calculus are routinely studied and used within the context of Cartesian coordinates. There is little to get excited about in engineering so long as the use of 3-D rectangular Cartesian coordinates is limited to assumptions of a flat-Earth (spatial data). But, as everyone knows, the Earth is not flat and, over the past 400 years, methods of triangulation and geodetic surveying have been employed to perform rigorous latitude/longitude computations. Geospatial data (geodetic) computations are conducted at a higher level of complexity and geospatial data considerations now include issues of ellipsoids, map projections, datums, coordinate systems, geoid modeling, and spatial data accuracy.

DIGITAL REVOLUTION

The digital revolution of the past 50 years has had an enormous impact on many facets of life – one being the collection, manipulation, and use of 3-D spatial data. In years past, survey measurements were recorded in field books, computations were performed by hand (often using logarithms), drawings were created on a drafting board, and original maps were stored in flat files for use and re-use. The analog map was both the end product of the survey and the storage medium for the information. All that changed with the advent of the digital computer, the invention of electronic measuring devices (EDM), refinement of photogrammetric mapping

processes, organization of spatial data in geographic information systems (GISs), the arrival of GPS positioning, and integration of sensors/microprocessors into elaborate 3-D measurement, imaging, processing, and data storage systems. Laser scanning, LiDAR, machine control, point clouds, Google Earth, and 4G networks are currently riding the technology wave. In all cases, spatial data are characterized as digital and 3-D and stored in electronic files. The current challenge is realizing geometrical consistency in the manner in which 3-D spatial data also include geospatial data and are used in various disciplines all over the world. The 3-D global spatial data model (GSDM) described by Burkholder (2008) is built on geometric/mathematical fundamentals, supports existing horizontal/vertical applications, accommodates modern 3-D digital measurements, and offers significant benefits for standardization and interoperability for the global community of spatial data users. The difference between spatial data and geospatial data can become significant in practice. But, given an appropriate tie between them, the GSDM accommodate can both.

TRANSITION – ANALOG TO DIGITAL

The transition of practice from analog to digital with regard to use of spatial data has not been instantaneous or without glitches. It has taken time to evolve from using journals and field books to using recorders and electronic data collectors. Once analog maps were meticulously drafted by hand or compiled on a photogrammetric plotter and printed to exacting specifications on large printing presses. The importance of high-quality maps is not to be discounted and a collection of maps can be a valuable investment. On the other hand, maps are now generated on a computer screen from a file of digital data. A disposable map is used and discarded. Or if hard-copy is needed, a map can be run off on a color printer by the user.

Mapping procedures have been automated over the years. Efficiency and productivity have both soared accordingly. During the transition, existing maps have been scanned and/or digitized so that analog data previously stored on a map can be shared in digital format. Although costly by some measures, the benefits of such conversion justified the expense. **Impressive as the analog-digital transition for spatial data has been, a final significant step involves the adoption and use of an integrated 3-D spatial data model.** Traditionally, horizontal and vertical data have been modeled separately – even so far as maintaining separate horizontal and vertical datums – a practice which fails to exploit fully the wealth of data available. As stated in the Foreword (Burkholder 2008), "In a sense, the spatial data user community continues to put new (digital) wine into old bottles. The global spatial data model (GSDM) is a new bottle model that preserves the integrity of 3-D spatial data while providing additional benefits. . ." A recent paper by Burkholder (2012) describes the development of spatial data models and compares the features of a low distortion projection (LDP) with those of the GSDM.

LESSONS FROM THE GRINTER REPORT

Published over 50 years ago, some of the issues discussed in the 1955 Grinter Report are dated but the big-picture view of educational concepts emerging from the

report remains relevant and can help avoid "re-inventing the wheel" when looking for the best way forward with regard to meeting the current challenges of adapting to the digital spatial data world. Gibson (2009) correctly notes that the Grinter Report recommends that "engineering education should leave the hands-on practical approach and adopt the highly mathematical and scientific approach." Gibson also notes that surveying was considered "hands-on and practical" and identified for elimination in a 1959 meeting of CE Department Chairs. As noted in the Introduction of this paper, the surveying profession has matured considerably over the past 50 years as a separate distinct profession and makes huge contributions to society. Without detracting from the value of existing surveying programs, the fact remains that civil engineers also need and use spatial data concepts in the conduct of civil engineering practice. There is a lot of overlap in the use of spatial data and everyone should understand that the practice of surveying and engineering are not mutually exclusive. An important point in this paper is that while the Grinter Report fails to anticipate the impact of the digital revolution, it does accommodate current justification for including spatial data modeling and concepts in civil engineering education.

In summary, among others, the Grinter Report (ASEE, 1955) emphasizes that:

- Engineering education should focus heavily on science and math.
- New areas of knowledge (i.e. characteristics and use of digital spatial data) should be included.
- Information theory (spatial data management) is an area showing significant promise.
- Developing frontiers based on new concepts (GPS) give increased vitality to older fields.
- Measurements and their analysis are essential elements of the laboratory experience.
- Mathematical proficiency is a must and learning to learn is paramount.

It seems, given the pervasive role of spatial data in most civil engineering applications and the benefits associated with efficient use of digital spatial data, that effort and attention devoted to exploiting the fundamental characteristics of digital spatial data has the potential of paying enormous dividends to the civil engineering profession.

Differences between spatial data and geospatial data were discussed earlier. But, there is more. Many design activities involve use of local spatial data in which 3-D flat-Earth computations competently accommodate sound engineering principles and the thought processes of the design engineer. In that case, it can be argued that a bigger picture of 3-D geospatial data concepts is not necessary. On the other hand, a Geomatics engineer has the responsibility of insuring competent use of 3-D spatial data in a broader context that includes geo-referenced (geospatial) data – whether those data are related to a GIS, a project tied to state plane coordinates, or any project containing elevation data. A broad statement is that geospatial data are those referenced by a well-defined global coordinate system while spatial data are taken to be coordinate differences within the same system. Viewed that way, the use of

spatial data is subordinate to the larger context of geospatial data. The reverse argument could also be made to insist that, with respect to rules of solid geometry, geospatial data are a subcategory of spatial data. In either case, an extension of the concepts described in the Grinter Report supports the argument for at least one or two Geomatics courses in every civil engineering BS program.

3-D GLOBAL SPATIAL DATA MODEL (GSDM) IS A SOLUTION

The global spatial data model (GSDM) is an arrangement of time-honored solid geometry equations and proven mathematical procedures. In that respect, it contains nothing new. But, the GSDM is built on the assumption of a single origin for three-dimensional (3-D) geospatial data and formally defines procedures for handling spatial data that are consistent with digital technology and modern practice. In that respect, the GSDM is a new model (Foreword, Burkholder 2008)." Stated differently, the GSDM provides a well-defined connection between applications of spatial data and geospatial data. The GSDM can preserve the 3-D geometrical integrity of any/all 3-D computations on a global scale while simultaneously accommodating simple 3-D flat-Earth computations.

Details of concepts, algorithms, and computational procedures associated with use of the GSDM are in the public domain and readily available by reference. Relevant sources include:

- During early stages of formulating the concepts, the author had an opportunity to make a presentation to the "First Congress on Computing in Civil Engineering" June 20-24, 1994 in Washington, D.C. (Burkholder 1994).

- A formal definition of the GSDM is given by Burkholder (1997) and is available on the Global COGO web site.

- More recently, the author was privileged to make a presentation to the ASCE Texas Section Meeting in October, 2010, in El Paso on Spatial Data Considerations for Civil Engineers (Burkholder 2010).

- A more comprehensive source is a book by the author, "The 3-D Global Spatial Data Model: Foundation of the Spatial Data Infrastructure" published in 2008 by CRC Press (Burkholder 2008).

- A more philosophical big picture challenge was written for spatial data users worldwide and is posted on the Global COGO, Inc. web site (Burkholder 2007)

- Spatial data users use map projections extensively. However, instead of projecting features to a flat map, the GSDM provides a "user view" of any/all data (point or cloud) from an origin selected by the user. This game changing concept is described in an article "Contrasting a Low Distortion Projection

(LDP) with the Global Spatial Data Model (GSDM)" posted on the Global COGO web site (Burkholder, 2012).

CONCLUSIONS

We (society and our professions) are where we are because of where we came from. No apologies are needed for that. With regard to use of spatial data, many disciplines and professionals have become accustomed to long-standing practices of conceptually separating horizontal and vertical concepts in the way spatial data are used. That is our real world experience. So long as simple flat-Earth assumptions remain valid, those spatial data practices remain legitimate. However, with advent of the digital revolution and modern measurement systems, spatial data are now characterized as digital and 3-D. When attached to a global reference system, such 3-D data are best called geospatial data. Much of the existing software used in civil engineering practice still treats horizontal and vertical data separately – even in terms of geospatial considerations. The purpose of this paper is to present a forward looking view and to advocate transition to an integrated 3-D spatial data model which provides a "user view" of the world (whether the data are point data or cloud data). That model is built on the assumption of a single origin for 3-D data and accommodates real-world modeling and visualization much better than do existing models. It all has to do with computing.

In order to stay abreast of these technological innovations, ASCE should:

1. Develop and sponsor workshops/seminars/webinars on 3-D computing.

2. Promote the idea of including high-level spatial data concepts in all BS civil engineering programs.

3. Lobby for enhanced EAC surveying engineering criteria in the ABET accreditation process.

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Prediction of the In-asphalt Temperature for Road Construction Operations

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ABSTRACT

During the construction of new asphalt roads, compaction is the final step. Proper compaction is crucial for the road's lifetime. The temperature of the asphalt mixture directly impacts on the compactability and therefore the construction process strategy. Ideally compaction should be done within a certain in-asphalt temperature window, with lower and higher temperature boundaries, to achieve high quality road surface. But, as there are no available systems to predict in-asphalt temperature, roller operators have to guess the actual temperatures. This paper describes a method and proposes an implementation of this method to predict in-asphalt temperature at any given position. Calculations are based on an initial asphalt mix temperature during paving operations and the automated computing of a cooling function for a specific mix within certain ambient weather conditions. The implementation of the method was tested using position and temperature information collected by following a real paving project. Outcome of the method - the resulted visualization - aims to provide information about in-asphalt temperature to support decisions of machine operators when to start and stop rolling process to obtain the high quality road surface more reliable.

INTRODUCTION

Road infrastructure is a vital component of any transportation system. As growth of the economy is accompanied by increasing travel demand (WSDOT, 2011), there is a clear need for continuous improvement of road systems. Therefore, construction companies introduce new materials and require new working methods from the personnel on site. The changes often require an asphalt team to perform paving operations under new conditions, where lack of previous experience can make the results of the paving process uncertain (Ter Huerne, 2004). Despite these changes, the current asphalt paving process still heavily relies on the skills and experiences of people working on the construction site and depends on personnel craftsmanship often without instruments to monitor key process parameters (Miller, 2010). Therefore additional instruments to support road construction professionals in their working tasks are needed.

Once a paving job has begun, operators deal with the issues of temperature and cooling by adjusting the lag time between the paver and the roller (Chadbourn, 1996). Ideally, the compaction process takes place when the asphalt mix temperature is within a certain temperature window - with high and low boundaries depending on

the mixtures' characteristics. To the authors' best knowledge, currently there are no systems, available to predict in-asphalt temperature during road construction. To address this gap, this paper introduces a method to predict in-asphalt temperature at any given location.

The proposed method is based on combination of the document temperature of the asphalt mixture during lay-down phase (Fig. 1, a) and cooling of the mixture (Fig.1, b) according to the ambient conditions. In the next section, we outline the role of the temperature during road construction operations. Later, we describe current state of technology in documenting temperature and calculating the cooling rate and, then, propose a method to predict in-asphalt temperature.

ROLE OF THE TEMPERATURE IN ROAD CONSTRUCTION OPERATIONS

The paving or finishing machine lays the hot-mix asphalt mixtures (HMA) at temperatures between approximately 225°-300° F (~110°-150° C) depending on the mixture characteristics, layer thickness and ambient conditions (MAPA, 2011). The deployed mixture normally does not have homogeneous temperature due to truck delays, discontinuity of the paver movement and paver characteristics (Figure 1, a). The material should be compacted before the mix temperature falls below a lower bound compaction temperature. The temperature window is determined according to a particular mixture (Wise and Lorio, 2004). Moreover, recommendations by the mix designers can include pre-determined temperature windows for more than one roller (Sullivan, and De Bondt, 2009). Those recommendations should be considered by the roller operators during the compaction process and this task requires understanding of the in-asphalt asphalt temperature. Although currently available systems do document and inform machine operators about surface temperature of the asphalt layer, there are no solutions to predict in-asphalt temperature at any given location. To make operational decisions more well-founded a system to predict in-asphalt temperature of the asphalt mixture during road construction operations is needed.

AVAILABLE SOLUTIONS TO DOCUMENT TEMPERATURE OF THE ASPHALT MIX

Documenting the laydown temperature of the asphalt mixture provides opportunity to verify homogeneity of the temperature and, later, to predict in-asphalt temperature at any location of the paved layer. Technologies like infrared cameras and temperature linescanners (Vasenev et al., 2011) are able to provide essential information of the asphalt surface temperature during compaction - without direct contact with the asphalt layer. Different schemes for utilizing such devices were recently developed. For example, a sensing device can be fixed on a paver (Baker et al., 2004) to collect and deliver information about surface temperature to the operator's cabin. In a more advanced approach temperature of the deployed mixture is obtained using sensors on pavers and, later, the expected cooling model is refined by sensor readings from rollers (Glee et al., 2009). Several industrial solutions to visualize and record the asphalt temperatures are created by asphalt machinery producers. To record temperature of the paved layer temperature readings can be

obtained from an infrared bar in combination with geographic coordinates using the PAVE-IR system, located on a paver (Swaner, 2010). Also, the compaction control system (CCS900) for rollers, introduced by Trimble manufacturer, in addition to compaction information provides readings from temperature sensors on a roller. Another approach, available in scientific literature, is based on the general prediction of the cooling in a form of a generic formula (Miller et al., 2011). One must keep in mind that while all these devices measure and provide only surface temperature, the mix behavior highly depends on the inner temperature of the layer.

The above described available visualization methods do document machine movements, but are not applicable to predict in-asphalt temperature, as they do not take asphalt cooling inside the layer into consideration. Therefore, utilization of these systems by machine operators to adjust their work is questionable, as the in-asphalt temperature is the dominant factor in compaction. To be able to predict in-asphalt temperature it is needed not only to document the initial temperature of the asphalt mixture, but also predict the in-asphalt cooling rate.

EXISTING APPROACHES TO CALCULATE THE ASPHALT MIXTURE COOLING RATE

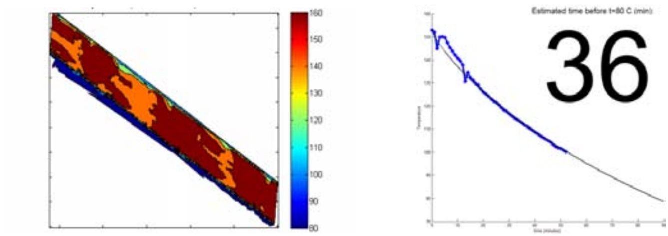
The information about a cooling rate of the deployed asphalt mixture is a valuable characteristic of the paving process. The cooling rate significantly depends on ambient weather condition, such as wind, air temperature, humidity and solar radiation. To assist paving teams by providing expected cooling rate, specialized software programs were developed recently. For example, cooling rate for a single layer can be calculated with the PaveCool program (Chadbourn et al., 1996). PaveCool consists of a user interface, a pavement cooling model and a knowledge-based expert system. The cooling models were further developed in the CalCool software. CalCool extends the single layer solution to multi-layers based on theoretical heat transfer considerations (Timm et al., 2001). Also, an additional research on asphalt cooling in special conditions was conducted, such as cooling during night road constructions (Chang et al., 2009). In particular, night construction is usually combined with low ambient temperatures and high wind speeds, thus creating adverse conditions for hot-mix asphalt paving.

Although specialized software and mathematical modeling can calculate the asphalt mixture cooling rate, it demands entering a number of parameters and, thus, additional tasks for personnel on site. Moreover, the prediction is highly dependent on accuracy of the measurements, such as wind speed and the latitude of the paving job, entered to the simulation software. Another approach is to utilize temperature sensors in real-time and calibrate the mixture cooling rate based on obtained readings. For those purposes we developed (Vasenev et al., 2012) an Automated Temperature Unit (ATU) to:

- measure surface- and in-asphalt temperature real time;
- predict the cooling rate and;
- provide information to the operators.

The implemented system can predict asphalt cooling based on previously obtained readings. In particular, readings from thermocouples and infrared sensors are stored

and used to find a fitting function to predict further temperature changes. We utilized a formula (Bossemeyer, 1966) for the asphalt cooling rate, where two variable characterize cooling rate of the mixture. The automatically calculated variables, called time factor and pole value incorporate thermal conducting ability, thickness of the layer, thermal conduction and thermal transition coefficients. Example of sensors readings and a predicted fitting function are represented on Fig. 1, b. With increasing number of readings the prediction of cooling rate is changing according to the accumulated sensors data. Using the ATU it is possible to predict the time interval, before the asphalt mixture will cool down to a certain temperature at the given location.



a b

Figure 1. a. Asphalt temperature as measured during laydown; b. Readings from ATU's thermocouples and prediction of the mixture cooling rate

The automatically calculated cooling rate of the asphalt mixture at a particular sport, calculated by the ATU, can be used to predict in-asphalt temperature at other points, if their initial temperature and paved time are known. By combination of the calculated cooling rate and previously documented temperature of the asphalt mixture it becomes possible to predict in-asphalt temperature of the asphalt layer.

THE PROPOSED METHOD TO PREDICT IN-ASPHALT TEMPERATURE DURING COMPACTION OPERATIONS

By combining the documented temperature of the asphalt mixture during lay-down phase and the calculated cooling rate of the mixture by ATU, it is possible to predict in-asphalt temperature at any given location (Fig. 2). Firstly, information from location and temperature sensors is used to document temperature of a newly paved layer. Then, the temperature of the placed asphalt layer is combined with automated prediction of the asphalt cooling to predict in-asphalt temperature within the layer. To represent temperature of the placed asphalt and the predicted in-asphalt temperature in a convenient form we utilized temperature contour plots.

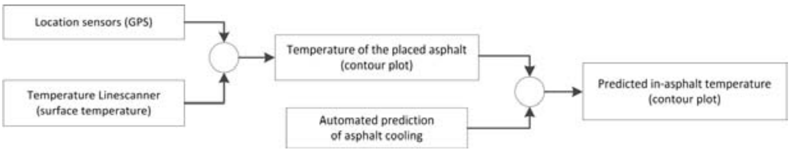


Figure 2. The proposed method to predict in-asphalt temperature

To be able to predict the temperature of the asphalt mixture we assume that the thickness of the asphalt layer is constant within the area of interest and only one layer is paved. Furthermore we assume a constant temperature over the height of the layer at moment of laying the asphalt mix. In this way we consider the obtained temperature readings during the asphalt laydown not only as a surface temperature, but also as an initial temperature distribution at any depth of the freshly constructed layer. Next, when the thickness of the asphalt layer is constant, the cooling process is assumed to run similar at any given location. Within the scope of this paper we limit the explication to construction of a single layer.

The proposed method is to be implemented as follows. All the sensors reading, related to the asphalt temperature and paver location are collected during the road construction project. In particular, the asphalt laydown temperatures are documented and visualized by combining GPS and IR-linescanner data from instruments located on a paver (Fig. 1, a). Also, temperature readings from the thermocouples, injected into the newly paved asphalt layer at a particular depth are used to predict cooling rate of the mixture (Fig.1, b). The thermocouples' readings are used to predict the cooling rate by ATU. With the predicted cooling rate we can predict in-asphalt temperature at other locations and times. The automatically calculated values can be applied to every other point to calculate the expected temperature, with [a] the given initial temperature and [b] time interval passed after the mixture deployment.

To verify the described method for the in-asphalt temperature prediction we developed and tested data collection and processing infrastructure to computing in-asphalt temperature. The infrastructure includes sensing devices to collect data, computers to pre-process readings and transfer data to a database, a server which stores the sensor readings and a visualization client. The communication between sensors can be described as follows. An IR-Linescanner, located on a paver, is connected to a computer, that transmits the real-time information to a server by wireless connection. Also, another computer sends the thermocouples' readings in real-time to the server. Sensors readings are stored at the server in MySQL database and are accessible to a client computer with the visualization software. Calculation and visualization components are implemented using Matlab.

The initial tests of the described method were based on real sensor readings, collected in cooperation with Dutch road-building contractors. By applying the proposed method we created visualization of in-asphalt temperature contour plots from the documented temperature of the asphalt mixture during the laydown phase and predicted cooling rate. An example of the visual representation of in-asphalt temperature, based on information collected during a real paving project near the Dutch city of Alkmaar, is represented on Fig 3 and 4.

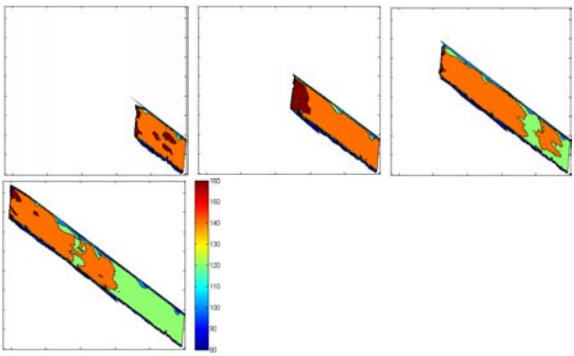


Figure 3. In-asphalt temperature after 4, 8, 12 and 16 minutes after paver started moving.

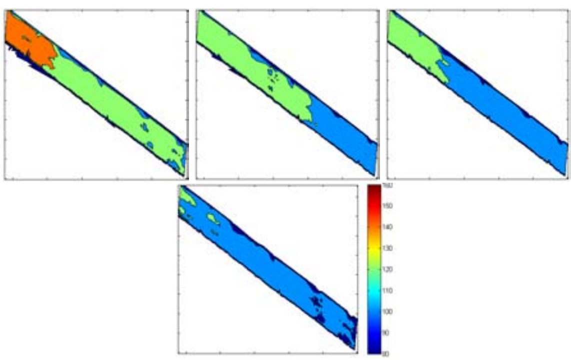


Figure 4. In-asphalt temperature of the paved area after 5, 10, 15 and 20 minutes

The obtained visualization showed applicability of the proposed method to automatically predict in-asphalt temperature during paving processes. As the main advantage of this method we see the automated prediction of in-asphalt temperature, that incorporates numerical parameters of the physical process, such as temperature differences within the freshly paved layer and discontinuity of the paver speed, into a clear visualization. The resulted visualization can be used to analyze the paving process in retrospective, or, when used in real-time, to support machine operators in decisions when and where to compact the asphalt layer.

CONCLUSIONS AND FUTURE WORK

Understanding of in-asphalt temperature by roller operators is needed to perform compacting within a desired temperature limits. Nevertheless, according to the authors' best knowledge, in the current paving practice there was no possibility to

automatically predict in-asphalt temperature. To address this gap we developed a method to predict in-asphalt temperature based on documenting the initial temperature during lay-down phase and the asphalt cooling using specialized sensors. The method incorporates information collection and processing from different sensors: GPS, temperature (linescanner) and thermocouples, deployed within the asphalt layer. The temperature contour plots can be used to analyze the paving project and to assist roller operators in their decisions when and where to roll, according to the asphalt mixture characteristics. The proposed method was tested on the data from a real paving project to obtain in-asphalt temperature contour plots.

Currently, the described implementation incorporates solution to predict cooling rate only for a single paved layer. Nevertheless, we believe that with additional information, such as readings from thermocouples at the bottom and at the top of the asphalt layer it is possible to predict temperature changes for more than one paved layer. Further research effort will also be devoted in analyzing visual representation of the temperature to assist machine operators in their tasks during road construction operations.

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Three Dimensional Displacement Response Study of a Rubble-House Using a 3D Laser Scanner

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ABSTRACT

After the devastating earthquake that hit Haiti in January 2010, a number of non-profit organizations started building cost effective replacement homes for the needy using the rubble from collapsed buildings. Rubble-Houses are environmentally friendly structures with walls comprised of recycled loose rubble placed in welded wire baskets. Rubble-Houses are assumed to be earthquake resistant structures due to their improved damping and ductility characteristics arising from the rubble and welded wire basket, respectively. However, the response of such structures under static and dynamic loads has not been studied in detail. In order to have a better understanding of its behavior, a full-scale rubble-house was built in the middle of Southern Polytechnic State University campus and subjected to a series of in-plane and out-of-plane static loads. Wall displacements were recorded using a 3D laser scanning technique in addition to total station and displacement gauge measurements. 3D laser scanning is an effective and efficient approach for precise and dimensionally accurate as-built documentation. This paper presents and discusses the use of 3D laser scanning technique in measuring the displacement response of a rubble-house under static loads.

INTRODUCTION

A 7.0 magnitude earthquake struck Haiti on January 12th, 2010. The Haitian government estimates that 200,000 have died as a result of this sad incident, 2,000,000 people have been left homeless and 3,000,000 people are in need of emergency aid. The United States Geological Survey (USGS) reported that the earthquake was the strongest earthquake to hit the area since 1770.

Shortly after the earthquake, relief organizations from around the world joined forces to support the devastated communities in carrying out rescue operations and supplying food, shelter, medical aid and providing sanitation, etc. The most challenging issue was proving shelter to millions of people who lost their homes. Conscience International, a non-profit humanitarian and advocacy organization, started building homes for the Haitian out of the destroyed concrete, or rubble. Rubble-Houses are environmentally friendly structures that recycle the broken

concrete from destroyed buildings to build the walls and are assumed to be earthquake resistant. The earthquake left huge quantities of rubble that could be used in the reconstruction of Haitians' homes.

Rubble-Houses' walls comprised of welded wire baskets filled with loose rubble seemed to be an inexpensive and immediate solution for the needy. Such structures are assumed to be earthquake resistant structures due to their improved damping and ductility characteristics arising from the rubble and welded wire basket. In August 2011, a collaborative research effort between Southern Polytechnic State University and Conscience International initiated to assess the seismic resistance of such rubble houses. A full-scale structure (14 ft. wide, 20 ft. long and 8 ft. tall), as shown in Figure 1 below, was built in the middle of Southern Polytechnic State University' campus and subjected to series of in-plane and out of plane static loads.

Figure 1. Rubble-House

In order to understand the mechanical behavior of the rubble walls, the displacement response map of the walls was recorded using a 3D laser scanning technique. 3D laser scanning is a very effective and efficient approach for precise and dimensionally accurate 3D as-built documentation. 3D laser scanning is a process of collecting the spatial coordinates of millions of points of an object by using lasers. The point clouds generated in this process are useful for measurement and visualization applications. This approach reduces errors and rework during documentation and enhances the productivity in a construction process.

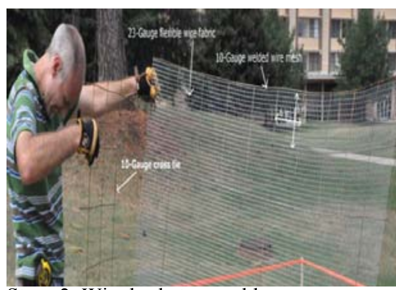
3D laser scanning technique has been successfully used for various architecture, engineering and construction applications (Shin and Wang 2004; Olsen et al. 2010; Jaselskis 2005). Walters et al. (2008) used laser scanners to determine the thickness of concrete pavement. Tsakiri et al. (2006) calculated the deformations through usage of surface reconstruction and deformation extraction techniques from laser scanner data. Gordon and Lichti (2007) used laser scanner data for modeling to calculate the precise structural deformation. Chang et al. (2008) used 3D laser scanner data for deformation calculations for evaluating the structural safety.

This paper presents and discusses the usage of the 3D Laser Technique in measuring the displacement response of structures under static loads.

RUBBLE HOUSE CONSTRUCTION

Rubble Homes are inexpensive and easy to build without power tools and skilled labor. A 6-in. deep foundation was first excavated and filled with rubble and concrete as shown in Figure 2, Stage 1. Next, a single wire basket was prepared for each wall separately. A wire basket consists of 10-Gauge 6-in. x 6-in. welded wire mesh and 23-Gauge flexible wire mesh fabric. As shown in Stage 2 of Figure 2, the sides of the basket are formed by tying 10-Gauge and 23-Gauge wire mesh together, then the sides are connected to each other by a 12-in. wide 10-Gauge cross tie at every foot along the length of the wall. Such an assembly creates 8 ft. tall compartments with 12 in. by 12 in. cross-sectional area. After erecting all four wire baskets, they are filled with crushed concrete, or rubble. Finally, the walls are covered with 1.5-2.0 in. thick cement finish as shown in Stage 5 of Figure 2. Each rubble house measures 14 ft x 20 ft. in foot print area and contains no bathroom, which is not uncommon in Haiti.

Stage 1: Foundation



Stage 2: Wire basket assembly

Stage 3: Wire basket erection

Stage 4: Pouring the rubble into the Basket

Stage 5: Finishing *rubble walls*

Figure 2. Construction Sequence of the Rubble House

RUBBLE HOUSE TESTING

The rubble houses are assumed to be earthquake resistant because of the ductile behavior of the wire baskets and the ability of the rubble to relocate its position without damaging the wall. However, behind its simplistic look and construction technique, a rubble wall possesses a highly complicated mechanical behavior due to its composite structure. Therefore, this experimental study was intended to be a preliminary research phase to gain a better understanding of Rubble-Houses. The objectives are: 1) evaluate current construction techniques and propose cost-effective improvements; 2) perform static load testing on a full-scale rubble-house; and 3) draft construction and design guidelines based on experimental and numerical findings. To achieve these objectives, the rubble house was subjected to a series of in-plane loads (Test-1), out-of-plane loads (Test-2) and a destructive test (Test-3) as shown in Figure 3.

Test 1: In-plane loading (North Wall)

Test 1: In-plane loading (South Wall)

Test 2: out-of-plane loading (West Wall)

Test 3: Destructive Test (South Wall)

Figure 3. Rubble House Testing

3D SCANNING RESULTS

3D scanning converts physical objects into digital 3D data. These scanners capture xyz coordinates of millions of points all over an object to recreate a digital

image. In this project, FARO laser scanner Photon 20/120 was used for documenting the wall displacements for Test 2 and Test 3. It is a high accuracy, high resolution scanner. It scans at the rate of 976,000 points per second. It has range resolution of 0.07 mm. It has systematical distance error of ±2mm at 25 m. It has 320^o and 360^o field of view in vertical and horizontal directions, respectively (FARO, 2010). A 3D scanning for the house was performed after each loading step at three different locations. A total of 5 spheres have been used during the scanning process. These spheres were used for registering different scans during post data processing. FARO SCENE LT software is used for processing the scanned data. In order to determine the displacement response of each wall, a number of points on the wall were selected as shown on the West Wall in Figure 4. The displacement responses of the selected points were traced through the xyz coordinates. Mathematica software was used to fit the best surface between the scattered xyz displacements data points. Because of the limited space of this paper, only the results of Test 2 and Test 3 will be presented.

West Wall. The west wall was subjected to a series of out-of-plane loading at the mid point of the wall as shown in Figure 4. The selected mean points are also shown in the same figure. Figure 5 shows the displacement response of the wall for the load case of P=5000 pounds where Figure 5a shows the 3D scanning response of the wall compared to the original unloaded condition. In addition to the 3D scanning technique, the displacement response of the south wall was measured using displacement gauges placed inside the house. The displacement map of the inside surface of the wall using the displacement gauges and the outer surface using 3D scanning is shown in Figure 5b. The displacement map of the inner surface and the outer surface were overlapped as show in Figure 5c. Both maps are in great agreement.

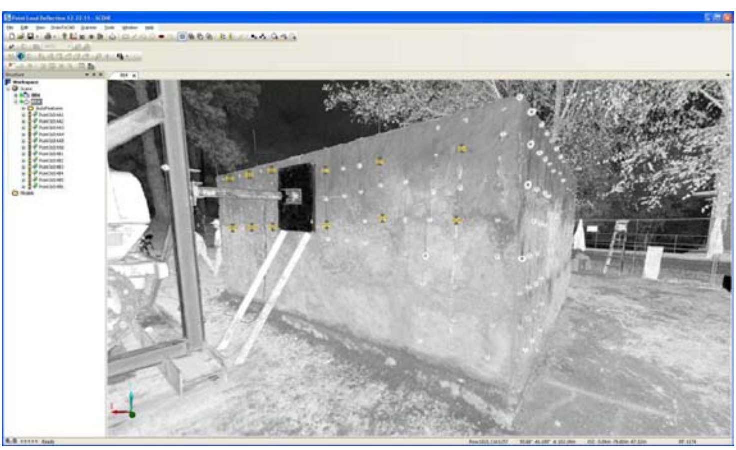


Figure 4. West Wall Mean Points

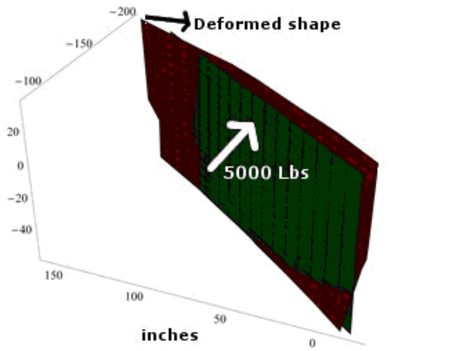


Figure 5a: Deformed shape vs. undeformed shape

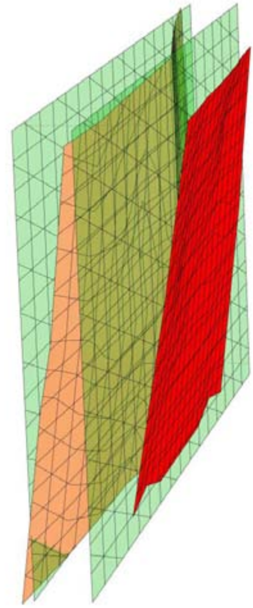


Figure 5b: 3D scanning results (outer surface) vs. displacement gauge results (inner surface)

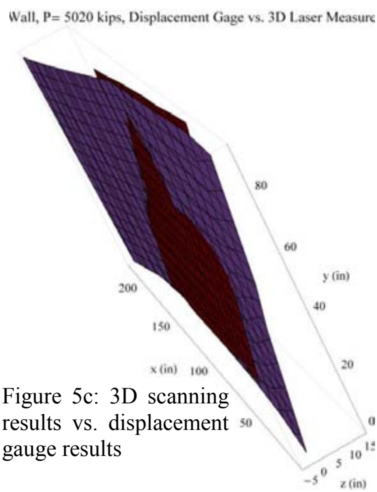


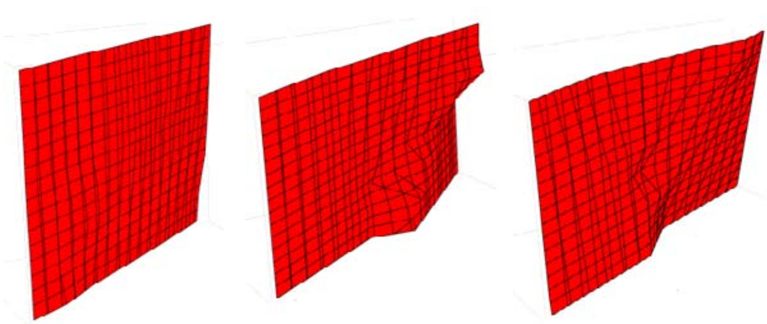
Figure 5c: 3D scanning results vs. displacement gauge results

Figure 5. Displacement response of west wall

South Wall. In the destructive test, the south wall was subjected to a pull from behind loading up to the collapse level. The displacement responses were recorded at three loading levels, namely 6 kip, 12 kip, and 15 kip (just before failure). Figure 6 shows the test setup and the selected mean points. The Displacement map is shown in Figure 7 for the three loading conditions. The walls of the rubble house sit on the foundation. A number of dowel rebars were embedded in each side of the foundation

and extended inside the wall and that explains the out-of-plane displacements once the wall starts to slide.

Figure 6: South Wall Mean Points



P = 6 Kip **P = 12 Kip** **P = 15 Kip**

Figure 7. Displacement response of south wall

CONCLUSION

This paper presented the usage of 3D laser scanning technique to record the displacement response of a rubble-house under static loading. 3D scanning of an object produces millions of points stored in xyz coordinates format. To extract the deformed shape of each wall, sample area mean points were selected on each wall. After each loading, the displacements of the mean points were calculated by comparing the xyz coordinate of the current scan with the previous scan. Mathematica software was used to fit the best surface between the scattered xyz displacements data points. In one case, the displacement of 3D scanning was compared with the displacement obtained using simple displacement gauges. Although 3D scanning seems to be a very accurate technique in measuring the displacement response of structures, more work needs to be done to simplify the data extraction and manipulation.

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Intelligent Building Hazard Detection Using Wireless Sensor Network and Machine Learning Techniques

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ABSTRACT

Research and innovation in the design of sustainable intelligent buildings has gained much interest recently. Among various technologies, wireless sensor network is a promising option that enables real-time building monitoring and control. In addition to utilizing the collected data points for building operation management, it is attractive to analyze the real time building information for hazard detection. In this paper, the authors implemented an indoor wireless sensor network that transmits the sensed nearby air temperature. A machine learning algorithm is developed to analyze the collected data and automatically generate early warning signals for hazards. Experimental results validate the proposed algorithm and the effectiveness of using a wireless sensor network for early detection of building hazards.

INTRODUCTION

Nowadays the design of energy-efficient intelligent buildings is an active area of research. Among a series of emerging technologies, the wireless sensor network (WSN) has been paid growing attention. A wireless sensor network, which consists of distributed tiny sensors, can monitor physical or environmental conditions (e.g., air quality, humidity, temperature) within a building (Denial, 2009). The sensed parameters of building conditions are sent to a control computer through wireless data transmission. Then, the control computer can dynamically adjust actuators (e.g., fans and chillers) to achieve energy-efficient HVAC operation (Osterlind, 2007). The diagram of a typical building monitoring and management system is shown in Figure 1. Several design examples have already been implemented and tested (Osterlind, 2007) (Shu, 2009). It was revealed by Castello (2009) that WSN based building automatic control systems can result in roughly 20% savings in energy usage. Consequently, a wireless sensor network can play a crucial role in energy-efficient intelligent buildings.

Conventional WSNs in existing structures are typically powered by batteries. Due to the space limitations for battery integration in modern miniaturized sensors and the fact that battery energy will be quickly drained after a few months of operation, use of state-of-art wireless sensor networks is constrained by a need for inexhaustible power to each sensor node for infinite lifetime operation (Lu, 2010) (Lu, 2011). A potential approach to resolve this challenge is to utilize an energy harvesting technique that converts electrical energy from ambient energy sources,

such as natural light, artificial lighting or heat flow that exists in a building. Lu (2010) summarized the electrical power densities of household energy harvesting sources. It was estimated in Lu (2011) that ambient energy harvesting is capable of powering wireless sensor nodes without battery integration. Huang (2010) experimentally verified the feasibility of powering wireless sensor network by harvested indoor light energy alone. In this way it is feasible to operate a WSN system without the necessity for human maintenance (e.g., battery replacement). Thus, the use of energy harvesting technique significantly reduces the labor cost for deployment of WSN systems.

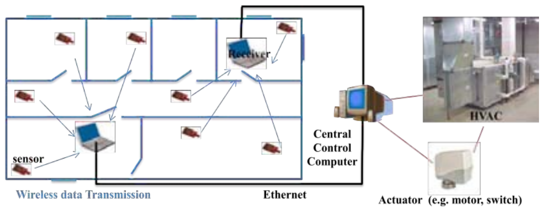


Figure 1. WSN based Building Monitoring and Management System

In addition to using WSN for intelligent building, in this paper the authors investigate the feasibility of a WSN for building hazard detection (i.e., overheat/fire warning). Thus, the expense for purchasing dedicated overheat/fire detectors can be eliminated. As the quantity of collected data from a wireless sensor network is extremely large, it is impossible for humans to quickly conduct data analysis to extract essential data features. As a result, it is hard to generate an early warning signal for building hazard detection. As will be shown later, the machine learning technique enables rapid and efficient processing of the collected data. The use of both techniques results in a cost-effective rapid building hazard detection. To validate this idea, a machine learning algorithm was developed and coded using Python language. An experiment was conducted. The experimental results validate the machine learning approach and the effectiveness of using wireless sensor network for building hazard detection.

RELATED WORK

Overheat and fire hazard detection systems are crucial parts of a building. Billions of dollars are annually spent on detection systems to assure safety from unwanted fires (Osterlind, 2007). There are several references in literature about utilizing WSN for overheat/fire detection applications. In Sarkar (2010) and Yu (2005), the researchers proposed the use of a wireless sensor network to realize early detection of forest fires. Liu et al. (2001) reviewed the research progress of fire detection systems developed for intelligent building. It was predicted that a wireless sensor network is an appealing technique among other techniques. Derbel (2003) presented a smoke detection system using a WSN.

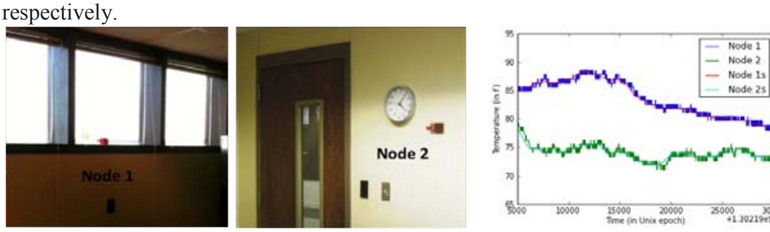
Machine learning is an advanced data analysis technique. Its concept is designing algorithms that allow a computer to learn from past experience or data. The basic operating methodology is described as follows. First, unknown properties or characteristics of interest are extracted from the collected training data. Then, in

Melhem (2003) these essential data features are applied to analyze and examine the future collected data. Machine learning algorithms have been developed to predict and estimate the remaining service life of bridge decks. In Fang (2010) and Ganguly (2007), wireless sensors were used to collect data with machine learning applied to characterize normal patterns for real-time anomaly detection. Results in Boggia (2008) and Iyer (2011) showed the effectiveness of a statistical method based machine learning algorithm for forest fire hazard detection.

From the above discussion, it is evident that there is still one unaddressed gap: how to develop practical machine learning algorithms used for early detection of indoor overheat/fire hazards. Verification of machine learning algorithms using experimental measurement data is lacking. This issue is the focus of this paper.

PROPOSED HAZARD DETECTION APPROACH

Sensor Data. A wireless sensor network was implemented at Knoy Hall of Purdue University. The sensor network was composed of two sensor nodes developed by Texas Instruments. Room light energy powered the operation of the sensor network. The nearby air temperature data were collected for 18 days (i.e., from April 7th to April 24th, 2011). Node 1 was placed near a window so that outdoor light could radiate to this node, and hence it was powered by outdoor sunlight and indoor artificial lighting. Node 2 was installed in a printer room without any window to outside world, so only nearby fluorescent light provided power to its operation. The placement of both sensor nodes in this experiment represents typical deployment positions in an office or residential building. Figure 2(a) and 2(b) show the deployment of wireless sensors and the collected sensor data on April 10th of 2011, respectively.



(a) (b)

Figure 2(a). Placement of Two Wireless Sensor Nodes in the Experiment, and 2(b) Plot of Sensor Data on April 10th of 2011

Data Preprocessing. As is frequently experienced when collecting real-world data, the observed temperatures from the sensors contain a significant quantity of noisy and unreliable data. There also exist some missing values due to sensor malfunction or various other reasons (e.g., wireless channel block). A moving average method with a window size of 10 minutes to smooth the data was used. Specifically, the unweighted mean of the previous data points in 10 minutes as the sample at time *t* was taken. Figure 3 plots the transformed sensor data on April 10th of 2011. Node 1 and Node 2 are the raw data, and Node 1s and Node 2s are the corresponding smoothed data. The proposed machine learning algorithm is based on the smoothed data.

Proposed Machine Learning Algorithm. Fire hazards can be viewed as one type of anomalies which are patterns in data that do not conform to a well defined notion of normal behavior. Therefore, the task of detecting fire hazards can be formulated as the anomaly detection problem. Anomaly detection has been extensively studied in the machine learning and data mining community. Various techniques have been specifically developed for certain application domains in Fang (2006) and Fang (2008). There are three key ingredients in a typical anomaly detection algorithm: 1) learn the normal behavior from a set of observed training data; 2) define a deviation metric that can characterize an anomaly from the normal behavior; 3) generate an alarm when a new observation yields a large value in the deviation metric. In this section, we will present our learning algorithm involving these three ingredients. The proposed machine learning algorithm has two phases: i.e., training and testing. In the training phase, a set of sensor data is collected over a period of time to learn the normal behaviors of the building temperatures from this training data. Later, in the testing phase, the learned model is applied to the new observations. The hazards are then characterized by how far the given observations are deviated from the normal behaviors. In particular, the normal behavior is learned from both individual sensor nodes and the correlation between them. The deviation metric is defined based on the confidence interval of Gaussian distributions.

Anomaly from Individual Sensor Nodes. This section introduces the methodology of detecting anomalies from individual sensor nodes. The machine learning approach assumes a parametric statistical model describing the distribution of the data. We adopt the Gaussian/Normal distribution model as we assume that the temperature from any given sensor node at a specific time (e.g., 1:00 pm) over an extended period (e.g., 10 days) is Gaussian distributed. This is a valid assumption as it has been investigated in a study by The National Climatic Data Center. In fact, Gaussian distribution is often assumed for underlying probability in many applications involving statistical analysis of data in Fang (2006) and Fang (2007).

Under Gaussian assumptions, about 68.27% of the values lie within 1 standard deviation (σ) of the mean. Similarly, about 95.45% of the values lie within 2 standard deviations of the mean. Nearly all (99.73%) of the values lie within 3 standard deviations of the mean. This is often referred to as *three-sigma rule* in Statistics. Anomalies are observations whose characteristics differ significantly from the normal profile. Therefore, a data point falling outside the 2 standard deviations range is deemed as a rare event and can be flagged as a hazard. The limit (or confidence interval) can also be adjusted to be 3σ or even higer. In this experiment, 2σ was chosen to be conservative. The goal is to detect as many potential hazards as possible while tolerating false alarms to some extent.

Anomaly from Correlation of Multiple Sensor Nodes. To learn normal patterns, we not only look at the individual sensor nodes, but also investigate how one sensor node is correlated with the other node. The underlying assumption is that: under normal conditions, the temperatures from the two sensors should be related because they are located in the same building and have a similar environment. If one sensor has an increased temperature, it is likely that the temperature at another sensor node is also increasing. In other words, without any fire hazard present, the difference between the temperatures from two sensor nodes should not vary significantly over

time. On the other hand, in the case of fire hazards, the sensor closer to the fire location would show a much higher temperature value than that of the sensor faraway, which is unusual from their historical correlation. If the observed temperatures from two sensors do not follow their normal correlation, it is very likely that something unusual happening.

We can learn the correlation between the two sensors from training data. As shown in Section 3.3.1, at a given time for a specific sensor, the temperature is assumed as Gaussian distributed. We use P_1^t and P_2^t to denote the temperature distributions at time t for Sensor 1 and Sensor 2, respectively. To compute the correlation or difference between P_1^t and P_2^t, we adopt the Kullback-Leibler (KL) divergence. It is the natural statistical measure of difference between two probability distributions and defined as:

$$D_{KL}(P_1^t||P_2^t) = \sum_{x \in A} P_1^t(x) \log_2 \frac{P_1^t(x)}{P_2^t(x)}$$

where $x \in A$ is the set of all possible temperature observations (for continuous variables, the summation becomes integration). While KL divergence is not considered a true distance metric as the divergence between two probability distributions (because it is generally not symmetric and the triangle inequality is not satisfied), it has a number of desirable theoretical properties and has been widely used in machine learning study.

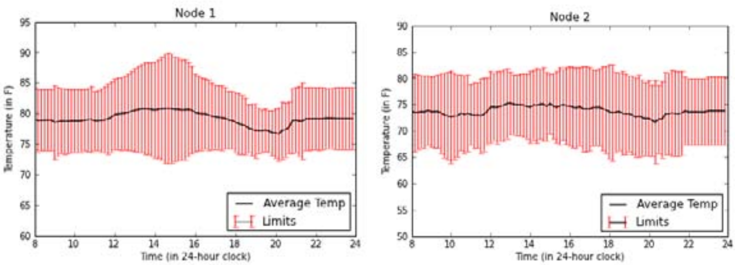
Once we compute the KL divergence $D_{KL}(P_1^t||P_2^t)$ for each time t, we also assume that it is Gaussian/Normal distributed over t. We can then build a Gaussian distribution model by computing the mean and standard deviation (σ). In the testing phase, we compute the KL divergence from the new observations of the two sensors and compare it against the learned Gaussian distribution model. The hazard is then determined in a similar fashion with that in Section 3.3.1 (by looking at whether the deviation exceeds the established limits (i.e., 2σ)).

Our proposed hazard detection approach combines two methods by looking at both anomalies from individual sensor nodes and anomalies from correlation of multiple sensor nodes. As long as any observation falls outside of the limits determined by either method, an alarm will be generated.

EXPERIMENTAL RESULTS

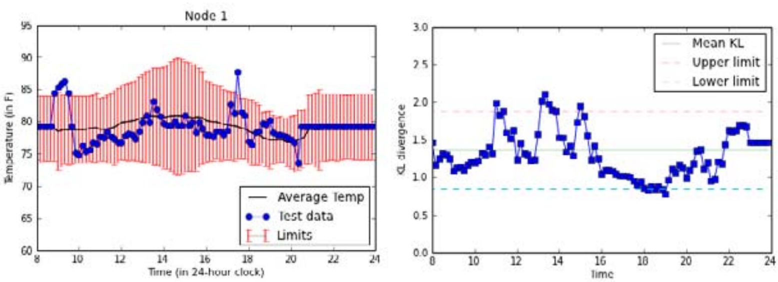
Experimental Setup. During the first 12 days (i.e., April 7th - April 18th) of experimental measurement, the sensed temperature values of both nodes were used for training purpose. The data collected during the next 6 days (i.e., April 19th - April 24th) were used to test the performance of our proposed machine learning algorithm. For these 6 days, in order to evaluate the performance of our propose hazard detection algorithm, we randomly increased the surrounding air temperatures of both sensor nodes on purpose by moving a heat fan close to them (mimicking the occurrences of overheat/fire hazard). There were a total of 30 artificial overheat events created. The total number of collected data points for the 18-day experiment is 87106, which is sufficient to extract the normal patterns of temperature characteristics for training and testing the machine learning algorithm.

Experimental Results. Figure 3 shows the upper and lower alarm limits for any particular time of a day. They are represented by the error bars in red. The black solid line denotes the mean temperatures. Both mean and limits are identified from the 12-day training data by the proposed machine learning algorithm in Section 3.3.1. Once we have completed training the model, we can use it to monitor new sensor observations in real-time and detect potential hazards if any of the observations exceeds the limits.



(a) (b)

Figure 3. The average temperature (solid line), and upper and lower warning limits (error bars in red) for a particular time of a day over a period of 12 days for two sensor nodes: a) Node 1; b) Node 2.



(a) (b)

Figure 4. Exemplar test data monitored by two methods: a) Gaussian distribution model for Node 1 on the test day of April 22nd; 2) KL divergence for the correlation of two nodes on April 23rd.

Figure 4(a) demonstrates an example that utilizes the measured temperatures on April 22nd. There were two alarms generated: one was around 9:00 am and the other was around 6:00 pm. In fact, these two alarms were coincident with the overheat hazard events that we intentionally made by moving a hot heat fan close to node 1. For the rest of time, no artificial overheat hazards were created. Moreover, all other collected data points were located between the upper and lower limits, thus, no hazard warning signals were generated. The above results illustrate the effectiveness of the proposed detection method. Regarding overheat/fire related hazards, the temperatures exclusively exceed the upper limits. Note our approach is also well

applicable to detection of other types of hazards in which lower limits may be violated.

Figure 4(b) shows the limits established by the KL divergence method (Section 3.3.2). The test data are from April 23rd. According to Section 3.3.2, we know that the KL divergence between two nodes should remain relatively stable over time in no hazard conditions. If a large deviation from the expected KL divergence is observed (which means exceeds the upper or lower limits in Figure 4(b)), an alarm should be generated. Figure 4(b) indicates 4 alarms, which were also consistent with the intentionally created overheat occurrences.

Overall, the experimental results on the test data demonstrate that the proposed method is quite effective for the detection of overheat hazards. For the 6-day testing, the proposed algorithm successfully detected all the occurrences of artificial overheat created. Two occasions during the test period false alarm warnings were observed. This phenomenon may be explained as follows. As the upper and lower limits of our hazard detection algorithm are based on the Gaussian assumption that is targeted for 95% confidence, there is still a small probability that the detection algorithm treats a normal condition as a hazard. To measure the performance of the proposed algorithm more precisely, we can use the standard metrics: *Precision (P)*, *Recall (R)* and F score. *Precision* is the fraction of generated alarms that are correct, while *Recall* is the fraction of correct alarms that are generated. F score is the combination of both defined by *2PR/(P+R)*. Therefore, the *Precision* in the experiment is 93.8%, the *Recall* is 100% and F score is 96.8%. This high accuracy indicates the potential for application of the proposed detection.

CONCLUSION

In this work, the use of wireless sensor network and machine learning techniques to detect overheat/fire hazards inside buildings was investigated. A wireless sensor network has been installed to collect temperature data of interested positions. A new machine learning algorithm to intelligently analyze these collected data by considering the information from both individual sensors and their correlations was developed. Using the machine learning algorithm, the underlying normal patterns are discovered from training data and the hazards are then captured by measuring the deviation of new observations from the normal behaviors. The proposed process is fully automatic and requires no human intervention. The proposed machine learning algorithm has been verified using an experimental test with real-world sensor data and shows a potentially valuable hazard detection capability.

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A Taxonomy for Depicting Geospatial Deviations of Facilities Extracted through Comparisons between Point Clouds and Building Information Models

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ABSTRACT

Building components are subject to diverse changes throughout their lifecycles. Several tasks, such as construction quality control and structural health monitoring, require accurate information of the existing condition, and they involve comparing the current status of the building with the models to identify possible discrepancies. However, there is a lack of formalisms for representing the identified deviations so that they can be easily understood, evaluated and addressed by engineers and managers. Accurate and complete understanding of how, and the extent to which, buildings deviate from models is necessary for a number of decisions made throughout the building's lifecycle. This paper addresses this need by proposing a taxonomy for depicting geospatial deviations identified through comparison of as-is data (i.e. laser scanned point clouds in this paper) and building models. This taxonomy is an initial step toward formalizing the representation of geospatial deviations and communicating them in a machine-interpretable manner to support data-model comparison, and model evaluation tasks.

INTRODUCTION AND PROBLEM STATEMENT

Building components are subject to many different types of changes throughout their lifecycle. It is possible that components are built differently from the specified designs, either due to construction errors, or changes during construction process (Akinci et al. 2006). Beyond construction, the geometry of the components also changes during their service lives due to deformations, degradation, deteriorations, modifications, retrofits or renovations (Cotts 1999). A number of tasks in the Architectural, Engineering, Construction and Facility Management (AEC&FM) domain, such as construction quality control and lifetime performance evaluation, require accurate as-is geospatial information. Referring to out-of-date and inaccurate geospatial information that might be contained in building models can lead to wrong decisions. Building models deviating from the real status of the building may lack the necessary reliability to predict the behavior of the building and support accurate decisions. As-is data are needed for evaluating the quality of building models, and for updating them when deviations from the reality exceed the specified tolerances. For this to be

accomplished, accurate and complete understanding of how, and the extent to which, building models deviate from real condition is needed.

Different reality capture technologies are being used to acquire as-is geospatial condition of a building and its components. For example, the application of 3D laser scanners in the AEC&FM domain is increasing, mainly due to their higher accuracy and wider coverage compared to traditional measurement methods. As-is geospatial data, depicted as point clouds, are compared to as-designed/built models in order to extract deviations that are critical for a particular task.

Several previous research studies have focused on developing efficient data collection plans to ensure the acquisition of the needed data associated with the important features of a facility (e.g. Akinci et al. 2006). Many commercially available software packages support the processing of the captured data and their comparison with models. Also, a number of research studies have attempted to streamline such processes for particular objectives, such as quality assessment of 3D city modeling (e.g. Boudet et al. 2006), structural assessment and health monitoring of building components (e.g. Takhirov 2010), construction defect detection (e.g. Tang et al. 2011), and construction progress monitoring (e.g. Bosche et al. 2008).

Through these approaches and existing software systems, it is now possible to identify a variety of possible deviations between point clouds, depicting the as-is conditions, and building models. However, without a clear categorization and formal depiction of these deviations it becomes cumbersome, or even impossible, to have a comprehensive understanding of the deviations and identify the important ones to be addressed. A formal taxonomical representation of geospatial deviations can address this need. Taxonomies provide structured sharable representations of such knowledge (El-Diraby and Briceno 2005). Such a taxonomy would be the initial step toward achieving formalisms to support building geospatial model evaluations. Such a taxonomy needs to be representative of possible geospatial deviations addressed in different ACE&FM domain tasks. It should also be re-usable for different objectives.

The approach taken here consists of a detailed motivating case study through which a building information model (BIM) of structural and architectural components of a facility is compared with laser scanned data. By analyzing the identified deviations, a taxonomy is generated and is further analyzed and validated through literature review and another case study. Finally, discussions and paths for future work are summarized.

MOTIVATING CASE STUDY

The motivating case study involved the comparison of as-is laser scanned data captured from a 3,530 m^2 facility located in Philadelphia with its as-built BIM. The building was built on 1942 as an athletic facility, and was later abandoned. The as-built BIM was developed from 69-year old as-built drawings; hence, it did not accurately reflect the existing condition. The objective was to identify deviations of all structural and architectural components in the as-built BIM compared to scanned data captured in 2011. One Time of Flight (TOF) scanner and one Phase Based (PB) scanner were used to scan each building zone.

This case is a suitable choice for studying different types of geospatial deviations because a large number of deviations were expected, mainly due to two reasons:

a) A large number of deviations were expected, mainly due to two reasons: 1) as-built drawings were generated using traditional methods of 1942 which were more error-prone, and 2) the building has been subject to many changes during its 69 years of operation.
b) The components were to be analyzed for every possible geospatial deviations, rather than specific deviation types critical for a particular objective.

The process of comparing laser scanned point clouds to the BIM started with transforming the 68 separate scans captured from the building to a single coordinate system to create a complete view (i.e. registration). Generally, this process is an optimization problem to minimize the distance among some control points common in adjacent scans. Such an optimization process introduces some errors. For this building, a 1 cm registration error could be achieved. The next step was to transform the as-built BIM to the same coordinate system as the registered point clouds, for geospatial comparison purposes. The metric used to measure the geospatial deviations was the Euclidean distance between the points in the scanned data and their pairs in BIM. By color-coding the Euclidian distance associated with each point pairs, a deviation-map was generated for better visualization of the analysis results.

Components analyzed in this case consisted of walls (including external and internal), columns (including columns and their footings, where visible), windows (including windows, skylights and openings), doors, and floors. Discrepancies in any feature of a component (e.g. width, location, sill height, etc.) that were beyond a pre-defined threshold for that feature were detected as deviations. Such thresholds should be small enough to prevent missing important deviations, and big enough to prevent erroneous identification of deviations caused by registration errors or noises in the data. Also, these thresholds may vary for each component, since the quality of building model has different level of sensitivity to deviations of different components. In this case, based on the project objectives and designer requirements, thresholds of either 10 or 5 cm were selected. For example, the threshold of 10 cm was chosen for location deviation of a wall.

Table 1. An aggregated summary of the identified deviations

Type of Deviation	No. of Deviating Components
Was not modeled in the as-built BIM	7 walls, 2 windows, 12 doors (in point cloud)
Did not exist in the as-is data	12 walls, 8 doors, 3 columns (in BIM)
Was in a different location	16 walls, 17 windows (sill height), 2 windows (along the wall), 4 doors (along the wall), 8 columns, 5 floors (elevation)
Was in different orientation	1 wall
Dimension was different	11 walls (thickness), 6 walls (length), 3 walls (height), 7 windows (height), 1 window (width), 2 doors (height), 4 doors (width)

In total, 141 deviations were identified. The difficulties faced during reporting and communicating all these deviations, with different types and magnitudes, showed the need for a formal approach for their representation. Otherwise, it becomes very time-consuming and difficult, if not impossible, for an

end-user to have a comprehensive understanding about the nature and precision of all the 141 deviations identified. As a first step toward such formalization, all 141 deviations were numbered and reported in a tabular form and marked on the as-built drawings, with narrative descriptions of the deviations, and with values necessary to quantify each deviation. Table 1 summarizes the list of the identified deviations and total number of components associated with each deviation. This approach facilitated the communication of the identified geospatial deviations to the end-users (e.g. designers) by reducing ambiguities.

DEVIATION TAXONOMY

Different types of features needed to be compared to extract geospatial deviations of different components. Moreover, different parameters, and their corresponding values, needed to be reported. However, as shown in Table 1, these deviations share common aspects that can be used to formalize a taxonomy of deviations and can be grouped into three high level classes:

- **Content Deviation:** Refers to the *completeness* of the model. For instance, a wall that is not modeled in the as-built BIM exemplifies a *content deviation* and affects the *completeness* of the available BIM.
- **Geospatial Deviation:** Refers to the *position* and *placement* of the modeled building/components. For instance, a floor that is modeled at a different elevation than the actual position falls under this category.
- **Geometry Deviation:** Refers to the *geometric compatibility* of the modeled building/components with as-is data. An example can be different dimensions of a column that result in deviations in its cross section, hence, *geometry*.

Further studies on the identified deviations revealed that two major types of deviations can be classified as content deviation, namely *missing components* and *spurious components*. Missing components are those existing in the as-is data but not in the building model; while spurious components are those additionally modeled in the model, and do not exist in the as-is data.

Figure 1 shows some examples of the *geospatial deviation* type. Studying components with geospatial deviations revealed that they are either located in a different position in the model (Figure 1a, b & c) and/or are oriented differently (Figure 1d). Therefore, the geospatial deviation class can be disaggregated into *location deviation* and *orientation deviation*. Further analysis showed that location deviation can be either *absolute* or *relative*. *Absolute location deviation* refers to deviations in the location of components, independent from the alignment of the as-is data and the model. For instance, differences in the sill height of a window in the as-is data and in the model, independently, shows that the window is positioned in a different absolute location. On the other hand, *relative location deviation* is affected by the overall alignment of the as-is data and the building model. For instance, in the aligned BIM with the as-is data, deviations of other components, such as floors, may cause the *relative deviation* in the location of windows to be different from their *absolute location deviations* (Figure 1b).

Figure 2 illustrates some examples of *geometry deviation*. Geometry deviation of a component occurs in cases where at least one of the geometric features of the component deviates from the as-is data. Examples of geometric features are width, length, and surface. Deviation in these features results in deviations in at least one of the cross-sections of the components. Therefore,

cross-section deviation was chosen as one of the sub-classes of geometry deviation. On the other hand, there are cases in which the geometry of the component deviates, but not due to cross-section deviations. A column that is not built perpendicular to the floor can be an example of such situations. This case occurs when an axis in the component deviates from what is modeled. The *Baseline deviation* sub-class addresses such deviations. Figure 3 summarizes the identified deviation classes in a hierarchical taxonomy. Each and every one of the 141 deviations identified throughout the motivating case study falls under one of the deviation sub-classes represented in the proposed taxonomy.

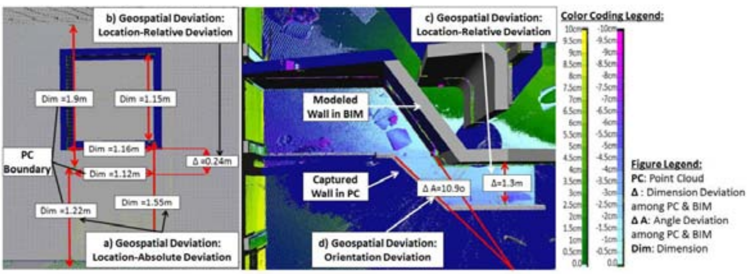

Figure 1. Geospatial deviation: a) Absolute difference in the sill height of the window, b) Relative deviation in the location of the window, c) Relative deviation in the location of the wall, d) Deviation in the orientation of the wall

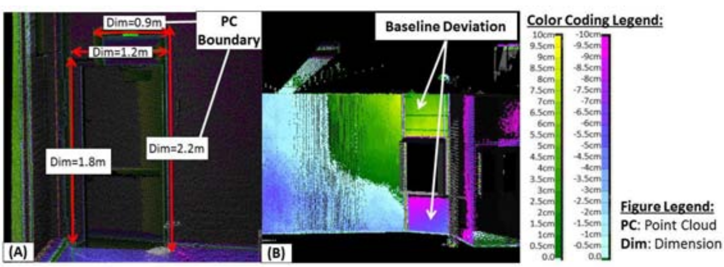

Figure 2. Geometry Deviation: A) Cross-section deviation due to different door dimension, B) Baseline deviation: different axes of top and bottom of wall

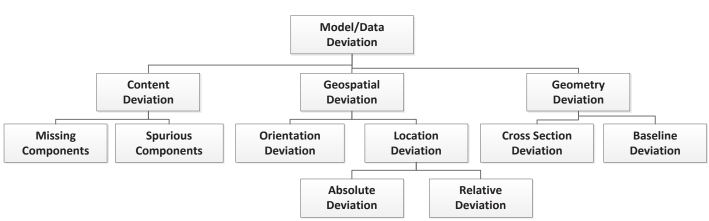

Figure 3. Geospatial Deviation Taxonomy

FOUNDATIONAL LITERATURE

Background research in the areas needing geospatial deviation analysis showed that the results have been rarely represented in a formal and unambiguous

manner. For instance, Takhirov (2010) addresses out-of-plane deformation of a wall as *displacements* in X direction of the coordinate system that is assigned to the building with an origin fixed in a corner of the wall. However, by addressing this deformation as "*displacement*", one cannot infer that the upper part of the wall has had different displacement than its lower part; hence, the nature of the deviation is not clear. In the proposed deviation taxonomy, however, the movement of the whole wall would be addressed as *location deviation*, since the wall is displaced. Different displacements of portions of the wall, however, would be addressed as *baseline deviation* from the original axis.

Moreover, it was identified that geometric deviations with the same nature are referred to differently or vice versa. For example, increase in the length of an anchor bolt of a column plate is referred to as *vertical displacement* in the study conducted by Takhirov (2010). However, Gorden et al. (2004) uses a similar term, *vertical deflection*, to address bending of a beam due to addition of loads. Tang et al. (2011), on the other hand, have used the term *vertical alignments* to address the out-of-plane deviation of walls and columns. Although these phenomena are referred similarly, the natures of the deviations are different. The increase in the length of the bolt is actually referring to deviations in one of the geometric features of the component (i.e. length). Hence, it would be studied under *cross-section deviation* in the generated taxonomy. However, the nature of the deviation in the case of deflections of beams, columns and walls, from their original axes, is different and is generally referred to as *baseline deviation*.

City model evaluation is another area in which data-model comparisons have been widely studied. Although some studies have addressed representation of the deviations, there is still a lack of formal representations that can be reused in different applications. For example, Boudet et al. (2006) have studied model deviations under three headings and the corresponding sub-categories:

1) *Non-existence of the* building: This category addresses the *content deviation* of the model at the building-level, but only for *missing* content.
2) *Shape description incorrectness*: 2.1) *under-modeling*, and 2.2) *over-modeling* This category addresses the model *content deviation* at the component-level.

The *content deviation* class in the proposed taxonomy and its two subclasses (i.e. *missing* and *spurious components*) covers the objective of both categories above.

3) *Geometrical inaccuracy*: 3.1) *slope inaccuracy*, 3.2) *altimetry location, and* 3.3) *planimetric delimitation*

Although grouped under the same category, these sub-categories refer to different natures of deviations: *Slope deviation* of a component such as roof from its original axis would be studied under *baseline deviation*, which is a *geometric deviation*, in the proposed taxonomy. However, *altimetry location* is related to the *spatial deviation* of the component, and would be studied either as *relative* or *absolute location* deviations. *Planimetric delimitation* refers to deviations in the dimensions of the building boundaries, that is, deviations in geometric features, and would be studied under *cross-section* deviation sub-class of the proposed taxonomy.

Similar ambiguities were observed in classifications offered in other studies, but were not included due to space constraints.

EVALUATION OF THE DEVELOPED TAXONOMY

Achieving a comprehensive taxonomy which completely covers all the concepts is impossible (El-Diraby and Briceno 2005). In fact, because their main role is to represent a theoretical structure of the concepts, taxonomies are incomplete by nature (Jones and Wilson 1995; El-Diraby and Briceno 2005). This reasoning also applies to the data-model deviation analysis area: “no complete taxonomy of deviations is possible” (Ragia and Forstner 2007). However, taxonomies have been widely evaluated for their *representativeness* and *re-usability* in the AEC&FM domain (e.g. El-Diraby and Briceno 2005). These two metrics ensure whether the taxonomy captures the knowledge created through model-data deviation analysis. A case study was conducted to validate these features of the taxonomy.

The case is a progressive laser scanning of the renovation process of a laboratory with a total area of 32.5 m^2. During the 70 days of renovation process, a total of 16 scans were captured. To validate the taxonomy, the as-designed BIM was compared with the as-built scanned data. Since different components were captured in different scans, each and every scan was compared to the model to ensure comparison of all components. The same comparison and deviation analysis methods as those in the motivating case were applied. Figure 4 reports the number of components in the as-designed BIM deviating from as-built scanned data. Deviating components include architectural elements, structural components, and HVAC elements. The comparison results show that the taxonomy can represent all of the geometric deviations in this case. No deviation was identified that cannot be studied under the classes of the proposed taxonomy. However, as illustrated in Figure 4, no component was identified with the deviation type of *orientation deviation* and *baseline deviations*.

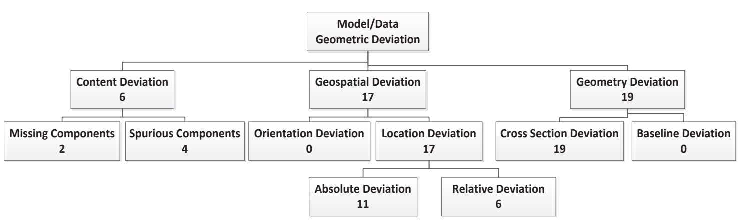

Figure 4.Validation results: Number of components deviating from as-built data

CONCLUSION

Geometry and spatial characteristics of building models need to be compared with existing condition for variety of tasks in AEC&FM domain. Although the comparison process is widely addressed by research studies in the domain, representation and communication of the identified deviations to the end-users have not been well addressed. In this study, a taxonomy of the possible geospatial deviations is structured through a detailed motivating case study. The formalism applied in this case for representing the deviation analyses’ results facilitated the knowledge-transfer process to the end-users by reducing ambiguities. Accuracy of the decisions made throughout the building’s lifecycle, and reasoning about the reliability of the models to predict building behavior, are

dependent on the comprehensiveness and accuracy of our understanding of how, and the extent to which, real condition of the buildings deviate from the reality. A taxonomical representation of the geospatial deviation revealed to be an effective initial step toward a formalism to address such needs. It is notable that geospatial information is only a portion of building deviations. Variations in different aspects of buildings, such as material thermal performance, structural capability and functional performance call for more inclusive formal frameworks for model evaluation, which are the future steps of this study.

ACKNOWLEDGEMENT

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Efficient Processing Algorithm for Large 3D Scan Dataset of NATM Tunnels

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ABSTRACT

Tunnel surveying requires fast and accurate data processing because a tunnel excavation pattern and its work sequences are dependent on the surveying result in the field. While a total station is widely used for measuring reference points in tunnel projects, the data from the total station are too limited in implementing some of the functions required for project control. Recently, 3D laser scanners have been tested in some tunnel projects, because they generate high-density data within several minutes. On the other hand, software development to facilitate processing the resulting large dataset is essential for its wide adoption on tunnel projects. We propose efficient data processing algorithms to accelerate continuous data processing and to facilitate downsizing data points, considering the characteristics of tunnel projects using The New Austrian Tunneling Method.

INTRODUCTION

The New Austrian Tunneling Method (NATM) uses the inherent strength in the rock mass to support the roof during excavation. The self-supporting capability helps to achieve economy, flexibility in uncovered ground conditions, and dynamic design variability, and as a result, NATM is widely applied for underground structures. NATM tunnel excavation is largely dependent upon the tunnel's diameter and types of support and ground conditions such as shear strength, deformation, and groundwater level. Therefore, fast and accurate measurements of ground conditions are important in deciding an appropriate excavation pattern (Kim and Lim, 2007). Until recently, an electronic theodolite called a total station has been widely used for surveying in tunnel projects. While the total station provides rapid reference data points, data from it are too limited in allowing implementation of some of the functions required in project control.

A 3D laser scanner generates high-density of data having several million points within a few minutes, providing an efficient way to acquire accurate and dense 3D point clouds of object surfaces. Such data have been widely tested in various construction fields including profile surveying, 3D modeling, volume computations, estimating shotcrete quantity, and detecting defects such as under-break, over-break, cracks, leakage, and efflorescence (Lee et al., 2011). Precise modeling of tunnel structures gives users an efficient control tool for project management during construction and for facility management after completion. Every 3D laser scanner uses its own hardware system to generate the scanning data and software system to process the data. However, the equipped software cannot fully support the diverse requirements of project management. To allow efficient processing of large volumes of data for rapid decision making and to convert scanning data into meaningful data for project control, independent software development appropriate to specific functions is essential. Several software applications equipped with commercial laser scanners have already been developed; they provide specific functions appropriate to construction management in tunnel projects. For efficient data processing, performance criteria of the software applications might include data processing speed and efficiency, measurement accuracy, economic feasibility, user-friendly interface, and automatic documentation. Several independent software systems have been increasingly developing to implement specific functions more efficiently. However, their data processing algorithms have been rarely discussed in the industry and it is therefore difficult to improve algorithms through comparisons among them.

Research Scope, Purpose and Methodology. A customized software application processing large 3D scan datasets of tunnel projects is under development in the Korean construction industry. Under ongoing software development, this paper proposes new data processing algorithms appropriate the various functionalities of tunnel management. The main purpose of this paper is to provide algorithms for improvement of processing large datasets from the 3D scanning data. This paper includes literature reviews on general 3D scanning data processing algorithms, analysis on the characteristics of tunnel projects, and algorithms development against the characteristics in the search for more efficient data processing methods.

ANALYSIS ON LARGE POINT CLOUDS FROM 3D SCANNER

General data processing of 3D scanning data. 3D laser scanners and their data processing algorithms have undergone extensive research and development for over decades. A 3D scanner system consists both hardware to register point clouds and software to process the data according to the required the functionalities. In the overall data process to complete a 3D profile: 1) a single scan generates a data set such as a patch, frame, image, or shot; 2) several scans from different measurement points build a field view coverage of the tunnel surface; and 3) the data sets from scans are processed by a software application. Data processing of 3D scans involves data acquisition, registration, decimation, averaging, overlap removal, zipping, merging, and visualization. While data

processing calculations are implemented using a combination of the processing methods mentioned above, the following processes are widely used:

1) Acquisition > Registration > Averaging > Overlap Removal > Zipping;
2) Acquisition > Registration > Merging.

While averaging, overlap removal, and zipping generate new data sets, the merging process integrates multiple range images to maintain consistent data points. This paper adopts the second method as a data processing algorithm for large point clouds from a 3D scanner.

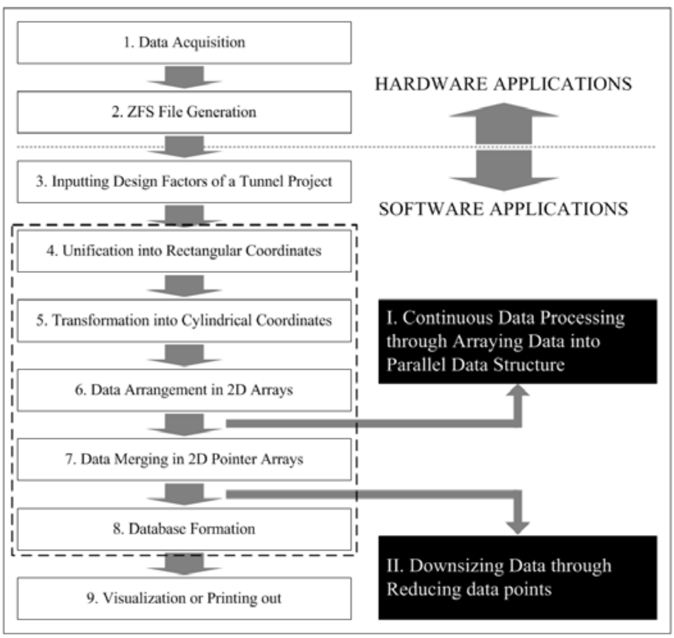

Figure 1. Data processing in 3D scanner systems

Overall Processing of scanning data. The Z+F Imager 5003 scanner is our data source for analyzing 3D data processing algorithms. It supplies high-resolution results with a maximum range of 360° horizontally and 310° vertically; data acquisition rate of 500,000 pixels per second; and data range from 40 to 5,350 cm. Hardware applications supplied with the scanner generate roughly 160 MB of ZFS files (raw data format) for every measurement section. The files contain both header information containing the horizontal and vertical resolutions per minute (RPM) and point locations of data elements; and data section information consisting of the distances of points and their signal strengths. The overall data processing for 3D scanning data in the hardware and software applications is illustrated in Figure 1.

In Step 3, the software applications in the Z+F Imager 5003 scanner open ZFS files for the respective measurement sections, and the local shape descriptors supplied in the software define tunnel characteristics such as transverse section, longitudinal section, and slope. Steps 4 and 5 assign numerical values to coordinate points in the files. Steps 6 and 7 represent data structure transformations for efficient processing of the large dataset. Table 1 describes the respective file structures and formats according to the step number. The remainder of this paper focuses on describing the continuous data processing algorithm and the downsizing data algorithm, including Steps 4-8 as described in Figure 1.

Table 1. File structures and format according to data processing steps

Step	*File format*	*Structure*	*Point size*
2	Coordinates, signal strength	Header + data section	3-4 bytes
4	x, y, z, c	Coordinate values	12-13 bytes
5	r, θ, z, c		
6	S (θ, z), z, c	2D arrays	
7	S (θ, z), r, c	2D pointer arrays	
9	Image	BMP 256 color map	Flexible
	Geo file	Point data	

Characteristics of tunnel projects. Three characteristics of tunnel projects related to 3D scanning data are analyzed within the research scope. First, tunnel surveying using 3D scanners requires several profile scans because of the tunnel's horizontally long and linearly repetitive structure. Large point clouds create a considerable computer workload in both memory and hardware system. Second, the semicircular shape of a tunnel is well suited to cylindrical coordinates. Local shape descriptors are a popular method of providing guidelines and detecting range points efficiently (Gong and Caldas, 2008). As shape templates, the descriptors represent design factors including transverse sections, longitudinal sections (straight or curved line), and slope at the measurement points of the 3D scanner. Third, high resolution of accuracy might not be necessary for these large structures, compared with other industry areas. For example, accuracies better than one millimeter are not important in calculating shotcrete quantity. In other word, data processing might be made more efficient by adjusting the density of the scanning data according to the required application. In summary, development of appropriate data processing algorithms is essential to handle large volumes of data, and the current algorithms have much room for improvement, considering the characteristics of tunnel projects (Chung, 2006). The three major characteristics of tunnel projects are applied to the algorithms to access more efficient data processing methods.

DEVELOPMENT OF DATA PROCESSING ALGORITHMS

Data unification into coordinates. Distributed data points in files require a unification process that assigns numerical values to rectangular coordinates using a unitary benchmark in Step 4 in Figure 1. The transformed coordinates involve *x, y, z* (vector values) and *c* (color value). Because cylindrical coordinates are better for representing tunnel shape, the rectangular coordinates are transformed into cylindrical coordinates having *r, θ, z,* and *c* values. The following equations are used in the transformation process, illustrated in Figure 2.

$$\mathrm{r} = \sqrt{x^2 + y^2},\ \tan\theta = \frac{x}{y}\ (\theta \text{ from y-axis, } \frac{\pi}{2} \geq \theta \geq \frac{-\pi}{2})$$

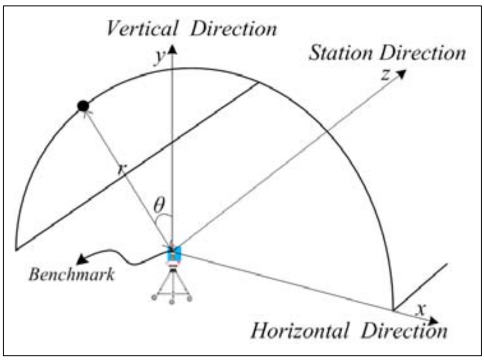

Figure 2. Unification data points into coordinates

Data Structure transformation. The length of a measurement station can vary depending on the requirements for scanning data. In empirical tunnel scanning, roughly 100 m is an appropriate length of a station for scanning data only and 40 m is appropriate for a high-quality image file. A point record in a 40 m scan occupies 12-13 bytes of memory and the measurement data for one section consists of roughly 50 million points requiring 600 MB. Several stations of scanning data are required for a survey profile. It is almost impossible to process all the data at once in the memory of a typical desktop computer.

Two-dimensional array structures are better for arranging data on a virtual grid; the concept of the virtual grid is useful for defining the adjacency of neighboring laser point data and to speed up processing (Cho et al., 2004). The 2D array structure algorithm using a virtual grid accelerates data efficiency by processing data in parallel. Data points are simultaneously arranged on the virtual grid of the respective measurement stations. Two-dimensional array structures for parallel processing of data are illustrated in Figure 3. This algorithm can reduce the workload of the computer considerably and facilitate data processing at more than 50 measurement stations at once.

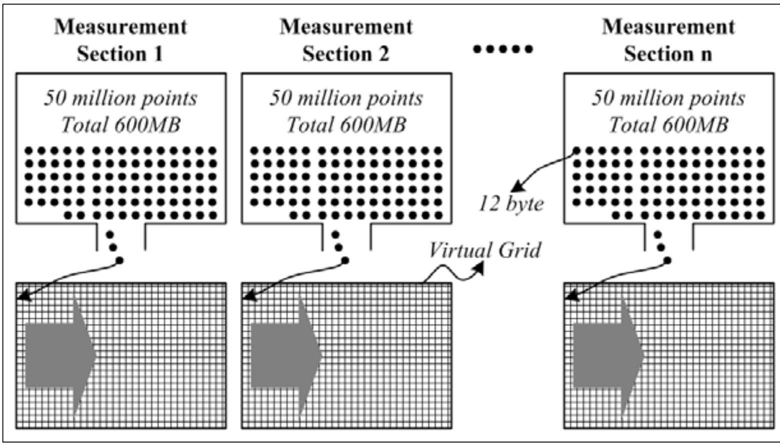

Figure 3. Continuous data processing through arraying data in parallel

In Step 7, the two-dimensional point algorithm is used to merge multiple data points into a single point using an averaging method. This can reduce the number of data points while while maintaining data density. The algorithm reorganizes the data array structure from (r, θ, z, c) to ($S(\theta, z), r, c$) for efficient representation of the characteristics of tunnel shape. An $S(\theta, z)$ value indicates a location on a virtual grid; the r value indicates the distance between the benchmark and a point of the virtual grid; and the c value saves color data as a second layer.

At the detailed level of point clouds, the r_m at the first layer is calculated by averaging values of r_1, r_2, r_3, …, r_l that have the same $S(\theta, z)$ values. The two-dimensional pointer array structure contains roughly 40% of less data than the data array of Step 6. The overall process of creating the two-dimensional pointer array structure is illustrated in Figure 4. Clearly, the algorithm facilitates downsizing data by merging multiple data points into a single point in the software application.

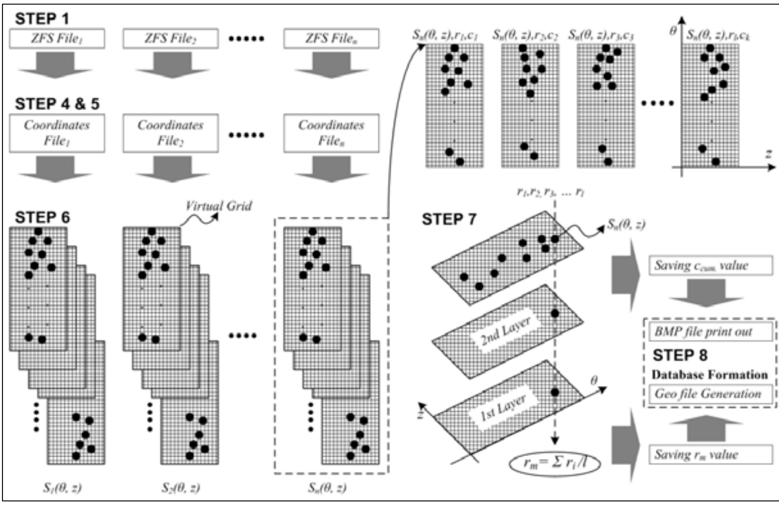

Figure 4. Data transformation processes

CONCLUSIONS

Digitization of real objects into 3D models is a rapidly expanding field, with an ever increasing range of applications. Underground construction in tunnel projects includes many risk factors that can cause unexpected accidents and schedule delays. Therefore, efficient and accurate measurements of ground conditions are important tasks in reducing potential accidents and verifying smooth transitions among complex operations. Based on our analysis of the characteristics of tunnel surveying, this paper introduces data processing steps for 3D scanning data and proposes two major algorithms: the two-dimensional parallel data structures and the two-dimensional pointer arrays. The algorithms this paper provides are expected to accelerate continuous data processing and to facilitate downsizing data points.

A customized software application is being developed for efficiently processing the large volume of scan datasets. A further investigation needs to be made as to whether or not the proposed algorithms improve data volume and processing speed. As a future study area, volume computations estimating under-break and over-break are designed to verify quantitative improvement, through the comparison between raw datasets from the scanner and transformed datasets from the algorithms.

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Automated Benchmarking and Monitoring of Earthmoving Operation's Carbon Footprint Using Video Cameras and a Greenhouse Gas Estimation Model

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ABSTRACT

Benchmarking and monitoring are critical steps toward improving operational efficiency of earthmoving equipment and minimizing their environmental impacts. Despite the importance, the relationship between operational efficiency and total pollutant emissions of these operations has not been fully understood. To establish such relationship and find ways to minimize the excessive environmental impacts due to reduced operational efficiencies, there is a need for an inexpensive and automated benchmarking and monitoring method. This paper presents a novel cost-effective method for monitoring carbon footprint of earthmoving operations using a vision-based equipment action recognition method along with pollutant emission inventories of construction actions. First a site video stream is represented as a collection of spatio-temporal features by extracting space-time interest points and describing each feature with a histogram of oriented gradients. The algorithm automatically learns the probability distributions of the spatio-temporal features and action categories using a multiple binary support vector machine classifier. Next, using a new temporal sliding window model, the equipment action categories are classified over a long sequence of video frames. The recognized time-series of equipment actions are placed in an emission and carbon footprint estimation model where based on the amount of emission for each equipment action, the overall Green House Gas emissions are analyzed. The proposed method is validated for several videos collected on an on-going construction project. The preliminary results with average action recognition accuracy of 85% reflect the promise that the proposed approach can help practitioners understand operational efficiency of their construction activities and minimize excessive environmental impacts due to reduced operational efficiencies.

INTRODUCTION

The construction industry is the third highest contributor of Green House Gas (GHG) emissions among all industrial sectors (EPA 2010). Twenty percent of this total emission is produced only in the first few years of the construction phase, while the remaining 80 percent is produced during the entire lifecycle of the project

(Skanska 2011, Ramesh et al. 2010, Ahn et al. 2010). The relatively large amount of emissions produced in a short period of time reveals the importance of reducing this source of emission. In the United States, although new regulations support carbon footprint reductions, yet they are rapidly becoming a concern for the construction industry (AGC 2011, ENR 2010). While these regulations should mainly focus on improving the efficiency of onsite construction and offsite operations as a means to reduce the excessive environmental impacts of performance deviations, instead they are focused on putting tighter controls on construction equipment. As a result, most projects are now subject to costly and time-consuming upgrade requirements. In the case of construction equipment, instead of finding ways to benchmark and monitor efficiency of their operations, the alternatives for reducing GHG emissions are purchasing new equipment and/or upgrading older machineries. These alternatives are challenged by their high initial capital cost. Furthermore, non-compliance with these new standards can cause penalties such as the loss of funding for future highway projects for heavy civil contractors. The controversial issues associated with such regulations have required Associated General Contractors of America (AGC) and the California Air Resources Board to postpone enforcements of any emission regulations until 2014 (AGC 2010). Proper enforcement of any carbon footprint reduction policies requires 1) techniques that can support practitioners to benchmark and monitor carbon footprint, and 2) availability of validation data to help adopt the best carbon footprint reduction practices.

Despite the benefits, there are a number of challenges associated with benchmarking and monitoring construction GHG emissions which include: 1) limited available field data for the analysis of non-road diesel construction equipment fuel use and emissions during construction operations (Rasdorf et al. 2010), and 2) the lack of established relationship between the active duty cycles versus fuel use and emission (Frey et al. 2010). Without a systematic monitoring during the construction phase, performance deviations' excessive GHG emissions cannot be minimized.

There is a need for a solution that can help practitioners reduce the excessive environmental impacts of their operations without affecting productivity and the final cost of project delivery. Low-cost and easily accessible benchmarking and monitoring methods can support wide implementation of pollutant emission and carbon footprint reduction policies at project level. To address these needs, a new method for monitoring emissions and carbon footprint of construction operations is presented. First, using a network of fixed cameras and a novel equipment action recognition method, operations are remotely monitored and a time-series of construction actions is generated. Based on the recognized actions and an emission model, the overall pollutant GHG emissions are measured. In the following sections, first the state-of-the-art techniques in carbon footprint monitoring and automated monitoring of construction equipment are reviewed. Next, the new developed method is discussed. The experimental results are presented and perceived benefits of the proposed approach and limitations are discussed in detail.

BACKGROUND AND RELATED WORK

In recent years, several studies have focused on estimating GHG emissions of construction operations. Ahn et al. (2010) presented a method which estimates

construction emission using a Discrete Event Simulation model. Peña-Mora et al. (2009) presented a framework on estimation and visualization of GHG emissions and recommended application of portable emissions measurement systems. Lewis et al. (2009b) discussed the challenges associated with quantification of non-road vehicle emissions and proposed a new research agenda that specifically focuses on air pollution generated by construction equipment. Artenian et al. (2010) demonstrated that lowering emissions could be achieved through an intelligent and optimized GIS route planning for offsite transportations of construction equipment. A common link among these studies is the lack of automation to further support benchmarking and monitoring of construction GHG emissions. Without a '*continuous*' monitoring program, minimizing excessive environmental impacts is practically challenging.

Several researchers have evaluated application of sensor-fusion approaches for monitoring construction carbon footprint (Lewis et al. 2011). These studies use portable emissions monitoring systems (PEMS) to collect the equipment engine performance data which in turn helps measuring the GHG emissions of construction equipment. The results provide a valuable insight on the effects of operational efficiency on GHG emissions of construction equipment. Nonetheless, these systems have a high initial capital cost (each PEMS is about $10-100K), typically require 1-2 hours for installation per equipment, and need expertise for installation, operation and maintenance. Considering the number of equipment per project, their wide implementation might be limited for all projects. There is also limited available field data for the analysis of non-road diesel construction equipment fuel use and emissions during construction operations (Rasdorf et al. 2010). Furthermore, those that exist are not quality assured nor are they all available for public use (Frey et al. 2010). Without established relationship between the active duty-cycles versus fuel use and emission (Frey et al. 2010), excessive impacts due to low productivity cannot be monitored. Hence, practitioners are unable to analyze the environmental impacts of different construction operation alternatives. There is a need for an automated and cost-effective monitoring tool that instead of using onboard measurements can provide a remote assessment of construction GHG emissions.

Over the past few years, several techniques for monitoring earthmoving construction operations are proposed which include application of RFID tags, GPS, or both (e.g., Moon and Yang 2010, Grau et al. 2009), in addition to site video cameras (Brilakis et al. 2011, Yang et al. 2011, Gong et al. 2011). These techniques primarily focus on tracking construction operations and do not provide detailed insight about the actions performed by the equipment. Among these sensing solutions, video cameras can provide detailed information about construction operations (Gong et al. 2011) and help establish relationship between operational efficiency and GHG emissions. Despite the potential, there is no existing vision-based research in the Architecture/Engineering/Construction community that can identify different construction actions and measure production and emission rates. Automated and continuous monitoring of construction operations, identifying sequence of equipment actions, and determining idle/non-idle periods can determine actual operational efficiency and GHG emissions. Timely and accurate operational details bring awareness and empower practitioners to take corrective actions, avoid delays, and minimize the excessive environmental impacts of their operations.

METHODOLOGY

The proposed methodology involves analyzing a sequence of site video streams and recognizing multiple actions of all onsite equipment. Once a time-series of actions per equipment is formed, the GHG emissions and carbon footprint associated with that equipment can be measured. In the following, the action recognition method is presented. Next, the action recognition over long sequences of video stream and emission modeling are discussed in detail.

Automated Video-based Action Recognition

In the proposed method (Figure 1), first a video containing several equipment, is represented as a collection of spatio-temporal features by extracting space-time interest points using Gaussian and Gabor filters, and describing each feature with a Histogram of Oriented Gradients (HOG). The algorithm automatically learns the probability distributions of the features by clustering HOG descriptors using *K*-means clustering, generating spatio-temporal feature histograms, and learning action categories using a multiple binary Support Vector Machine (SVM) classifier. This strategy handles noisy feature points arisen from typical dynamic background of construction sites (More details can be found in Heydarian et al. 2012). Once these actions are learned, they will be applied to long sequences of site video streams in which the starting point and an approximate duration of each action is known.

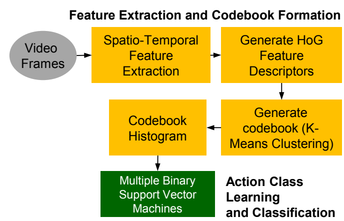

Figure 1. Action Recognition (Adapted from Heydarian et al. 2012)

Action Recognition for Long Sequences of Site Video Streams

Recognizing equipment actions in long sequences of video is a difficult task as 1) the duration of actions are not pre-determined, and 2) the starting point of actions are unknown. The action recognition algorithm presented in the previous stage is only capable of accurately recognizing actions when the starting point and duration of each action is known as *priori*. To automatically and accurately recognize the starting point and the duration of each equipment action with 96% confidence on a long video sequence, a new temporal sliding window algorithm is developed. Figure 2 illustrates the concept of the temporal sliding window:

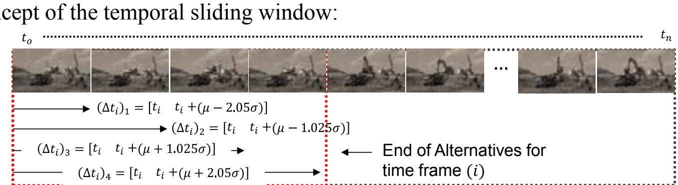

Figure 2. Temporal Sliding Window to Identify Start and Duration of Each Action

In this algorithm, the average (μ) and standard deviation (σ) of the expected duration of each action is calculated using the training dataset. Due to the need for

accurate prediction of the actions and their durations, each temporal sliding window (overall duration of $\mu \pm 2.05\sigma$ representing the 96 percent confidence interval) is divided into four separate time frames. These time intervals, all starting from frame (t_i) have sequential terminating points, such that the first time frame ends at $[t_i + (\mu - 2.05\sigma)]$, the second one ends at $[t_i + (\mu - 1.025\sigma)]$, the third ends at $[t_i + (\mu + 1.025\sigma)]$, and finally the last one ends at $[t_i + (\mu + 2.05\sigma)]$. For each time frame, the spatio-temporal features are first extracted and the probability of their distribution is automatically learned by clustering their HOG descriptors using K-means clustering algorithm. The outcome is a histogram per each time frame. The histograms for all time frames are then placed into the SVM classifier, and for each time frame, the action category plus classification score are stored. The time frame which its detected action category has the highest score will be used to determine the duration of the detected action and identify the starting point for the next iteration. This process is repeated until the last frame is visited.

Estimating the Overall GHG Emission and Carbon Footprint per Equipment

From the analysis of equipment's actions, the total amount of each pollutant emissions (E_T) will be calculated according to the following equation:

$$E_T = \sum_{\rho} e_\rho \times \Delta t_\rho \tag{1}$$

where e is the average emission rate for different actions of the equipment (Kg/sec) (e.g., excavator actions: digging, swinging, dumping, moving, and idle), Δt is the duration of each actions, and ρ is the different action modes. The total emission is calculated for all pollutants (i.e., CO, NOx, HC, PM). Emission rates for construction equipment, specific to particular types of equipment and engine size are extracted from Lewis et al. (2011), Lewis (2009) and Abolhasani et al. (2008). The Carbon footprint equivalent (CO_2e) rate is calculated using EPA's CO_2e formula (EPA 2012).

EXPERIMENTAL SETUP

The video streams required for validation were collected from five ongoing construction projects. More than 100 hours of useful excavation operation videos were recorded. Using this comprehensive set of videos, 1200 short action videos are assembled which two third of those are used for training and the rest for individual video testing. These videos contain four different types of excavators and three different types of trucks. The emission rates for the trucks were directly extracted from (Lewis et al. 2011, Lewis 2009). Due to the absence of actual emission rates for excavators, we assumed they generate the same level of emissions as dozers.

EXPERIMENTAL RESULTS AND DISCUSSION

The Following presents the validation experiments conducted in this study:
Accuracy of Equipment Action Recognition – The following confusion matrices (Figure 3) represent the average precision of each action classification for both excavator and truck datasets. Our classification results for trucks are very promising,

yet in the case of excavators, there are still several instances which may cause confusion between digging and dumping classes. This is attributed to the presence of noise in the dataset, and symmetrical characteristics of HOG descriptors which capture similar spatio-temporal feature points around the bucket for both digging and dumping action classes.

Figure 3. Confusion Matrices for Excavator (Left) and Truck (Right) Action Classes

Forming Time-Series of Actions for Multiple Equipment – A total of 3 videos with duration of 3, 4, and 6.5 minutes were chosen for generating time-series of actions per equipment. For these cases, we assumed the approximate 2D location of each equipment is known. An automated technique for recognition and 2D tracking of equipment is presented in another paper in this conference (Memarzadeh et al. 2012). Figure 4 shows eight snapshots from one of the testing videos wherein the actions for both excavator and the truck are recognized. In this case the spatio-temporal features detected in the overlapping sections of the detector windows are used for action recognition for both equipment types. The time-series of actions recognized for the earthmoving operation for both excavator and truck categories, for one of the videos, is presented in Figure 5 wherein the actions are illustrated using different gradient hatchings.

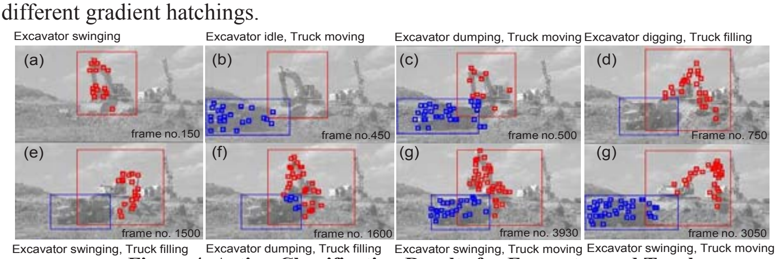

Figure 4. Action Classification Results for Excavator and Truck

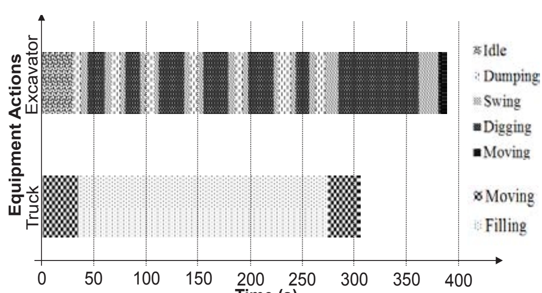

Figure 5. Time-Series of Actions per Equipment

Pollutant Emission and Carbon Footprint Monitoring Results

Using the detected time-series of equipment actions plus the pollutant GHG model, the released emissions and carbon footprint are compared with the average of the expected emissions and carbon footprint rates. Figure 6 illustrates the curves of the released PM, HC, and NOx, plus CO2e, CO emissions of an excavator's operations in comparison to the average expected emission levels. In this figure, (f) shows the released vs. expected carbon footprint for the entire operation including both the excavator and the truck.

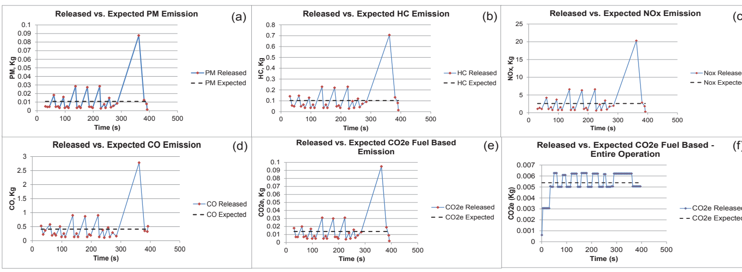

Figure 6. The Released vs. Expected Emission Comparisons.

CONCLUSION

In this paper we presented a new method to automatically monitor carbon footprint of earthmoving construction activities using emerging and already available video cameras, in addition to GHG inventories of construction operations. An average accuracy of 85% on individual video action recognition categories is achieved. The preliminary results of hold the promise that the developed method can help minimize the excessive environmental impacts due to reduced operational efficiency. Future work includes developing simultaneous tracking and action recognition algorithms for analyzing video streams of more variety of earthmoving equipment, generating a more comprehensive pollutant and carbon footprint inventories of construction actions per equipment, and finally a simulation model for benchmarking expected pollutant emissions and carbon footprint. These are all part of ongoing research and the outcomes will be presented soon.

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A Hybrid Model-Free Data-Interpretation Approach For Damage Detection During Continuous Civil-Infrastructure Monitoring

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ABSTRACT

A hard challenge associated with infrastructure monitoring is to extract useful information from large amounts of measurement data in order to detect changes in structures. This paper presents a hybrid model-free approach that combines two model-free methods - Moving Principal Component Analysis (MPCA) and Robust Regression Analysis (RRA) - to detect damage during continuous monitoring of structures. While a merit of MPCA is the ability to detect small amount of damage, an advantage of RRA is fast damage detection. The objective of this paper is to exploit these two complementary advantages through an appropriate combination. The applicability of this hybrid approach is studied on a railway truss bridge in Zangenberg (Germany). Its performance is compared with that of individual methods in terms of damage detectability and time to detection. Results show that the hybrid approach has higher damage detectability and identifies damage faster than individual applications of MPCA and RRA.

INTRODUCTION

Structural Health Monitoring (SHM) is an emerging research field in civil engineering since it has the potential to prevent catastrophes due to structural failure and save maintenance cost through early detection. In last decades, many large structures have been equipped with sensors to measure ambient parameters (such as temperature, pressure, wind speed) and structural response characteristics (such as acceleration and strain). However, interpreting such measurement data to assess structural conditions remains a challenge.

To overcome this challenge, tens of data-interpretation methods have been presented (Deraemaeker et al. 2008; Goulet et al. 2010; Jaishi and Ren 2006; Koh and Thanh 2009; Lanata and Grosso 2006; Magalhães et al. 2009; Morassi and Tonon 2008; Ni et al. 2008; Omenzetter and Brownjohn 2006; Yang et al. 2009).

In general, these methods are classified into two classes - model-based and model-free methods - based on the presence of behavioral (physics-based) models (ASCE 2011). Behavioral models are typically expensive to build. In addition, although model predictions might exactly match observations, due to modeling and measurement errors, the best matching model is not necessary the right representative of a structure (Goulet et al. 2010). Alternatively, model-free methods focus on analyzing only measurements without the use of behavioral models. The main idea behind the model-free method is to identify changes in the patterns of measurements that may signify the occurrence of damage. For example, Hou et al. (2000) proposed Wavelet-based approach for structural damage detection. Omenzetter & Brownjohn (2006) proposed an Autoregressive Integrated Moving Average method (ARIMA) to detect damage from measurements. Lanata & Grosso (2006) applied a proper orthogonal decomposition method for continuous structural monitoring using static measurements. For vibration-based SHM, Yan et al. (2005a; 2005b) proposed local Principle Component Analysis (PCA) for damage detection. Posenato et al. (2008; 2010) performed a comparative study and results showed that the performance of MPCA and RRA for damage detection were better than those of other methods (Wavelet packet transform, Discrete wavelet transform, ARIMA, Box-Jenkins, Instance based method, Short Term Fourier Transform and correlation anomaly scores analysis) when dealing with typical civil-engineering challenges such as significant noise, missing data and outliers.

It is also found that temperature has a significant effect on the overall behavior of structures (Brownjohn 2009; Catbas and Aktan 2002; Peng and Qiang 2007). Laory et al. (2011a) evaluated the performance of MPCA and RRA under traffic and temperature variations. Results showed that while MPCA is better than RRA in terms of damage detectability, RRA is better than MPCA in terms of time to detection. These two methods were found to be complementary and hence, synergy between both methods may result in a better overall methodology for damage detection (Laory et al. 2011b). Thus, this paper presents a novel data-interpretation approach that combines these two model-free methods to detect damage during long-term monitoring of structures. The applicability of the proposed approach is demonstrated on a railway bridge in Zangenberg (Germany).

METHODOLOGY

The new approach interprets measurement data in two steps (Figure 1). The first step is to transform measurement data into time series of principal components (PCs) using MPCA. It is carried out by using a fixed-size window that moves along the measurement time series to extract datasets. The data within the window are employed to compute a covariance matrix and then solve the eigenvalue problem of the covariance matrix to obtain time series of principal components (eigenvectors). These time series are further interpreted using RRA in the next step.

The main idea behind the second step is built on an assumption that when damage occurs in structures, the correlations between the principal components will be changed. Thus, damage can be detected by tracking changes in these correlations over time. The second step explores the correlations between PCs by developing regression functions using the robust regression analysis. For long-term monitoring of structures, the regression functions are then used to predict a

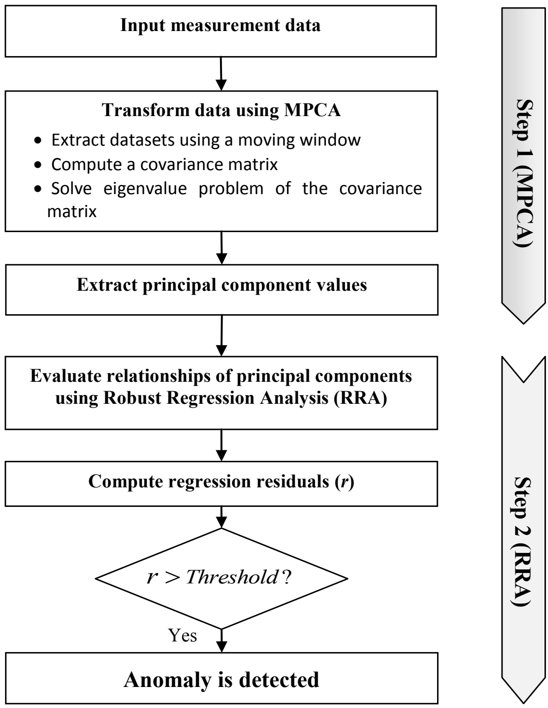

Figure 1. Flowchart of the hybrid model-free data-interpretation approach

principal component at one measurement location using the known principal component at another location. If the difference between the predicted principal components obtained from regression functions and the known values exceeds a pre-defined threshold bound, damage is detected. The performance of the approach is demonstrated in the following case study.

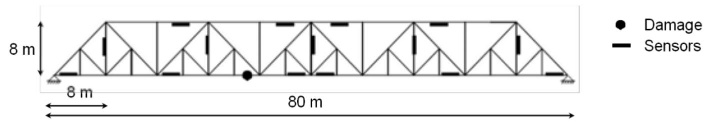

Figure 3. A 80-m railway steel truss bridge with sensors and damage locations.

A CASE STUDY

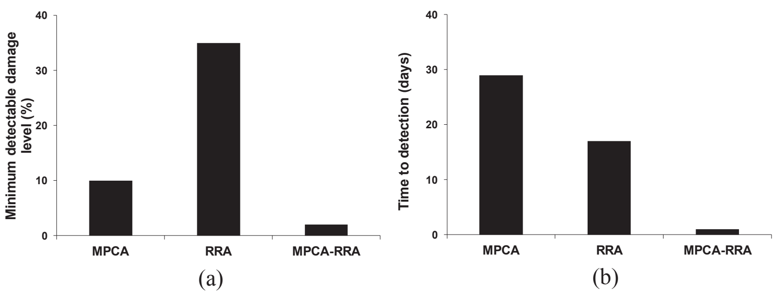

Figure 2. Minimum detectable damage level (a) and time to detection (b) of MPCA, RRA and the hybrid approach for a case study using a truss bridge.

A numerical simulation for a railway truss bridge in Zangenberg (Germany) is carried out to obtain its responses under temperature variation as well as traffic loading. The responses are used as long-term continuous measurement data. One truss of the bridge is modeled using finite element analysis (Figure 2). Traffic loading is simulated by applying a vertical load of random values (0-19 tonnes) at each node in the bottom chords. A load of 19 tonnes is equivalent to an axle load of a railway locomotive. Daily and seasonal temperature variations are simulated as thermal loads. Damage is simulated as a reduction in axial stiffness of each member.

The performance of the hybrid approach is compared to that of applying each individual model-free method. Comparison criteria are damage detectability and time to detection. Damage scenarios with varying damage levels are generated to evaluate damage detectability and time to detection. Damage detectability is the capability of the methods to detect damage. It is determined through evaluating the minimum damage-level that can still be detected. Time to detection is the time interval from the moment damage occurs to the one when damage is detected.

Results of the comparative study are shown in Figure 3. As mentioned in the introduction, MPCA is better than RRA in terms of damage detectability. Figure 3(a) shows that the hybrid approach is able to detect damage that is much smaller than that to be detected using MPCA alone. The minimum detectable damage level is reduced from 10% for the hybrid approach to 2% for MPCA. It

demonstrates that the hybrid method performs better than each individual method in terms of damage detectability. As for time to detection, a scenario with 50% damage level is studied. For this damage scenario, MPCA requires 29 days from the moment damage occurs until detection and 17 days for RRA. Figure 3(b) shows that while MPCA and RRA need more than ten days to detect damage, the hybrid approach detects damage immediately.

This study also compares the performance of the hybrid approach with other model-free methods such as Multiple Linear Regression (MLR), Support Vector Regression (SVR) and Random Forest (RF). It is observed that the hybrid approach have better damage detectability and smaller time to detection than that of the application of each individual methods.

CONCLUSIONS

The hybrid model-free data-interpretation approach that integrates two complementary advantages of Moving Principal Component Analysis (MPCA) and Robust Regression Analysis (RRA) is able to improve damage detectability as well as reduce time to damage detection for continuous monitoring of structures. A follow-on study is evaluating the potential of combining MPCA with other linear and non-linear regression analysis methods.

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A Novel Method for Non Intrusive Load Monitoring of Lighting Systems in Commercial Buildings

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ABSTRACT

In the U.S., buildings account for 42% of the total energy consumption - half of which is consumed by commercial buildings. Knowledge of electricity use patterns in buildings has several applications in demand side management. In commercial buildings, acquiring energy consumption information with high granularity requires consuming node level sub-metering, which is prohibitively expensive. Accordingly, a cost effective, non-intrusive energy metering is needed to provide room level and personalized energy consumptions. This paper proposes a vision for an alternative non-intrusive load monitoring approach in commercial buildings. As part of the overall vision, the feasibility of non-intrusive lighting load monitoring using single wireless light intensity sensors has been explored. The experimental results show the feasibility of the vision introducing area of the room, the fluctuation amplitude of the captured signal, and the daily variation trend of the signal as some of the parameters and features that could be applied for machine-learning training purposes.

INTRODUCTION

Detailed energy consumption information is essential for both utility companies and end users in order to efficiently manage the supply-demand chain. Providing detailed information of spatiotemporal energy consumption facilitates informed decisions for future investments in distribution systems, and reduces the costs (Yu Yi-xin et al. 2008). Moreover, the availability of detailed energy consumption enables more accurate load forecast for power system planning. More importantly, the availability of this information provides the ground for managing distribution of the energy demand uniformly on the grid by load scheduling and peak shifting.

Smart grid addresses some of the above-mentioned needs for efficient energy management. Smart grid is an electric network that records the actions of its users to deliver sustainable, economic and secure electricity supplies (Sianaki et al. 2010). Smart meters are one of the main components of the smart grid for obtaining energy consumption patterns. These meters provide almost real-time remote access to the energy consumption information. Smart meter facilitates the application of dynamic demand management strategies such as dynamic pricing. On the other hand, users can be informed of their inefficient energy consumption patterns at a high level so that they can take actions towards reducing the energy consumption.

Building occupants have a major role in the success of the smart grid implementations. In the U.S., buildings account for about 42% of total annual energy consumption, which is higher than industry and transportation sectors (Department of

Energy 2009). Forty percent of total energy consumption in the U.S. is used for electricity generation. Commercial and residential buildings, with 35% and 39%, respectively, contribute almost equally in the total electricity consumption (Energy Information Administration, 2011). Research studies show that the consumers are ready to change when they are presented with the appropriate information; however, they still lack the tools to obtain detailed and personal energy consumption information (Torriti et al. 2010). Although smart meters provide continuous energy information, the information represents the building or unit as a whole and smart meters do not provide the occupants with the decomposed information, necessary for detecting the source of the consumed load.

To provide decomposed and personalized electricity consumption information, non-intrusive load monitoring (NILM) approaches have been the subject of various research studies since its introduction in late 80's (Hart 1989; Hart 1992). Using NILM techniques, the sensed load at the main feed are decomposed to individual appliances' loads using signal processing and machine learning techniques, which provide the electricity consumption with high granularity for occupants. For this purpose, the individual appliance power consumption patterns (appliances' signature) are used as features in the training process. The majority of NILM studies focused on residential buildings due to the complexity of the appliances' signature in residential buildings and also the fact that residential buildings' occupants are motivated to take actions in order to reduce energy consumption. In commercial buildings, occupants are not directly in charge of electricity consumption costs, and therefore, they are not aware and motivated to improve energy related behavior in order to increase energy efficiency, which poses interesting research questions. On the other hand, although the diversity of appliances' signatures is limited in commercial buildings, the conventional NILM approaches cannot correlate signatures with spaces in the building. This is due to the fact that signatures may be very similar, which make training infeasible. For commercial buildings, energy consumption information should be provided in higher granularity such as room level to inform occupants of their actions and their consequences.

In this study, an alternative approach for real time load monitoring in commercial buildings is introduced in the form of a vision for load monitoring of various devices including lighting, office appliances and HVAC system components. Moreover, the proposed approach for load monitoring of the lighting systems as one of the sub-components is presented.

LOAD MONITORING BACKGROUND

To increase the awareness about energy consumption patterns, different commercial electricity metering devices have been developed. These devices include solutions for building/unit level metering such as TED (The Energy Detective, 2011) or plug level metering such as "Kill-a-watt" (P3 International,2011) and "Watts up?" or "Watts up? Pro" (Electronic Educational Devices, 2011). These devises can show the electricity consumption of the appliances over the time on an LCD screen and in some cases they can be connected to a computer (wired or wirelessly) and record the data. The use of these devices makes the plug level sub-metering possible for each appliance in a building, however the implementation is prohibitively expensive.

Building/unit level monitoring devices offer a relatively inexpensive solution in concomitant with NILM algorithms for decomposing.

NILM uses overall voltage and current measurements at the circuit level (main feed) to deduce individual loads for appliances. In the last three decades, various research efforts have been made to improve the process of load monitoring at the appliance level. Since appliances might have similar power consumption profiles, some of the research studies introduced the application of additional metrics such as reactive power (Hart 1992) and power harmonics (Laughman et al. 2003) for improving appliances' signature detection. In more recent studies, the application of NILM was explored for contemporary appliances (Shaw et al. 2008; Berges et al. 2009); in addition, practical developments for using NILM in residential buildings as a feedback system have been explored (Berges et al. 2011). The detection of the temporal energy consumption in the circuit is based on On/Off status of the load, but some of the appliances have several load profiles due to their multiple internal components. Moreover, in recent years many advanced devices are using electronic controllers for adjusting power consumption and increasing efficiency, which resulted in non-linearity of the electricity consumption patterns. Accordingly, part of the research efforts have focused on addressing these challenges - e.g. (Akbar and Khan 2007; Jin et al. 2011).

Although significant progress has been made in the field of NILM, the application of this approach in commercial buildings, specifically for providing room level energy consumption (as a criterion for commercial buildings' occupants' personal energy consumption) is still very challenging. The approximate similarity of the appliances in commercial buildings, difficulty of decomposing the electricity consumption for appliances in each room, and time intensive training processes are major barriers for practical application of NILM in commercial buildings.

PROPOSED VISION

Occupants in commercial buildings are individual stakeholders, who need to know their personal energy consumption to be motivated in taking actions toward energy efficiency in buildings. Accordingly, for load monitoring approaches in commercial buildings, location of the consumption is also important in addition to time and level of consumption. In this paper, an alternative approach that uses multiple sources of data from different databases, sensors, and IFC models is presented.

In recent years, the adoption of building information modeling (BIM) has increased dramatically. The BIM models comprise of virtual 3D geometry of a building, whose components have semantic data associated with them as well as their relative locations. IFC models are the data models for interoperability provision between different computing systems regardless of the tools used for development.

This vision proposes to use IFC models to extract device location and characteristics. In commercial buildings, major components, which play the main role in energy consumption, are lighting systems, appliances such as computers and printers, and HVAC systems. These are also the main systems, which provide occupants with functionality and comfort. Accordingly, these components are the main subjects of interest in the proposed vision. The overall vision has been depicted

in Figure 1. In this vision, appliances are trained to communicate their consumption over computer networks; and IFC and other facilities management data sources are proposed to be used for HVAC energy consumption monitoring through data fusion.

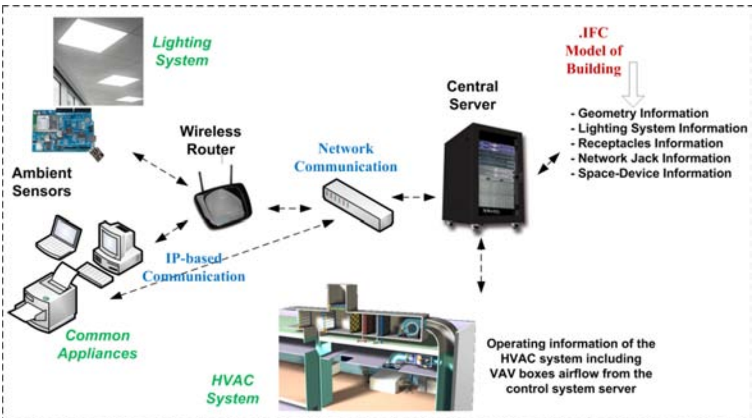


Figure 1. System architecture of the proposed vision for fusing data from multiple databases for load monitoring in commercial buildings

This study focuses on the use of ambient sensors for lighting system load monitoring by using light intensity sensors for detecting events (i.e. turning on/off the lights or dimming the lights) and correlating the intensity with the energy consumption of the lighting systems. In an analogy with NILM, in the vision for lighting load monitoring, the event is the changes in light intensity, which is labeled for identification. Moreover, the general trends in captured signals would be used as features for detecting the event and correlating the events with the physical phenomenon - the changes in the number of light bulbs in use or dimming the light intensity. Finally, machine-learning approaches would be deployed for training a model for autonomous detection of the events and correlating them with energy consumption. Although the deployed sensors can be referenced by room numbers and operate independently from the IFC file information, integrating the building characteristics from the IFC file such as room area, number of bulbs, and type of bulbs can provide complementary data. In order to explore the feasibility of using light intensity sensors for non-intrusive lighting load monitoring, and to define the characteristic features of the captured signals for training autonomous detection model, and to investigate challenging conditions, an experimental study was carried out.

EXPERIMENTAL SET UP

Sensing Devices. Light sensors that are capable of detecting variation in the light intensity due to changes in number of bulbs in use were deployed. The sensors wirelessly communicate the light intensity readings to a database. Linksprite

DiamondBack® microcontrollers, equipped with a WiFi module, were selected. AMBI® light intensity sensor, connected to the analogue pin of the microcontroller, was used. This AMBI light intensity sensor maps the voltage between 0 to 5 volts to a number between 0 to 1023 - an indicator of the light intensity. In this study, the relative variation of the light intensity is adequate therefore no calibration process is required to correlate the actual light intensity with the sensor readings.

Objective. Investigating the feasibility of developing a solution that has the ability to sense the intensity of light for different light levels, in different geometry/size of rooms with different types of light sources (i.e. fluorescent and incandescent), and the ability to detect the effect of natural light was the main objective of this study.

Experiment Test Bed. Considering the above-mentioned objective, different rooms in university buildings were considered as the study test bed. All the rooms were equipped with fluorescent lighting fixtures. For incandescent light source, portable lighting fixtures were used. Since sub-metering the lighting electricity consumption requires intrusive approaches, the nominal value of the power consumption was used for electricity measurements. Although this approach does not detect the malfunctioning devices, it addresses the objective of providing decomposed spatiotemporal electricity consumption information.

RESULTS AND DISCUSSION

The results of the experiment are used as a proof of concept for the ambient light intensity sensor for non-intrusive lighting system load monitoring.

Sensor Sensitivity. The most important factor is the sensitivity of the sensor in detecting slight changes in light intensity. Figure 2 shows the sensor readings for six rooms of different sizes. The results are depicted in one graph to provide the ground for comparison. In 200 level rooms the lighting fixtures are similar with three fluorescent bulbs (with nominal power of 32 watts per bulb) per fixture. The selected rooms have the capability of setting lights in three different levels of 1 bulb, 2 bulbs, and 3 bulbs per fixture. The lighting fixtures in 100 level rooms have two bulbs per fixture and they are equipped with dimmers; in the experiments the dimmers were set to highest and lowest levels. As it can be seen in Figure 2, the light intensity sensor is sensitive to variations in changes while it is an inexpensive sensor (~$5). Although, the results in Figure 2 are all related to fluorescent bulbs, the sensor is also sensitive to variation in light intensity using the incandescent bulbs.

Room Area. Since the number of bulbs in use is the metric for measuring lighting electricity consumption, the area of the room can be used as another parameter for correlating the intensity and the energy consumption in the training process. As it is seen in Figure 2, although the number of bulbs in room 226 is less (9 bulbs total) than the number of bulbs in rooms 209 and 203 (18 bulbs in each), the captured intensity is higher, which is related to the room's area considering that other characteristics such as room color are the same in these rooms. In all these cases the sensor was placed in a room corner on a table and the change in the location of the sensor does not show considerable changes in the acquired light intensity. Moreover, the captured intensity levels in rooms 203 and 209 (with the same area) are almost the same.

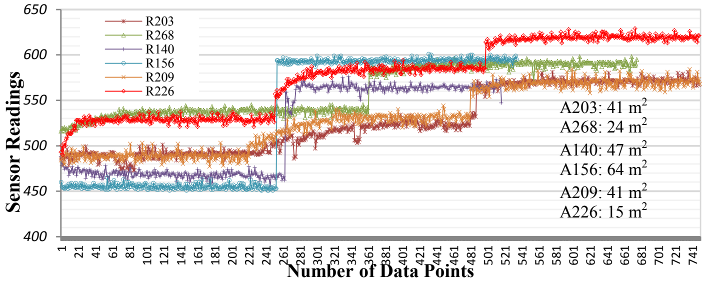
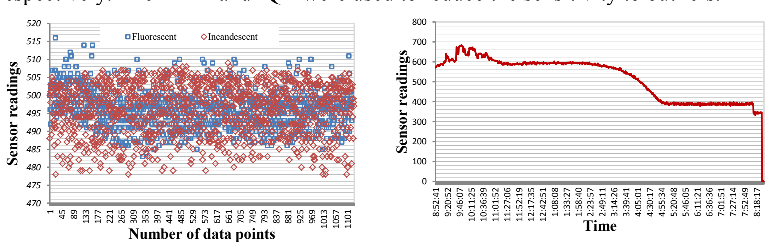


Figure 2. Light sensor sensitivity to variation of lighting intensity in different rooms

Identification of Light Sources. One of the features that can be taken into account for distinguishing between fluorescent and incandescent light sources is the light color. However, sensors, capable of detecting the difference between the colors of light are very expensive and infeasible to be used for the purpose of non-intrusive load monitoring. Therefore, the same light intensity sensor was used for different sources of light in order to find the proper features for identifying the light source. Captured data using incandescent and fluorescent bulbs under the same space and time condition shows that regardless of the magnitude of the light intensity (i.e. regardless of bulb's power), the signal fluctuation amplitude is higher in case of incandescent bulbs. In Figure 3-a, a sample of the captured data using both incandescent and fluorescent bulbs has been depicted. The dispersion analysis of the sample data shows the median absolute deviation (MAD) values of 6.1 and 3.8 and Interquartile ranges (IQR) of 11 and 6 for incandescent and fluorescent bulbs, respectively. The MAD and IQR were used to reduce the sensitivity to outliers.



a) Sample data showing the signal fluctuations of different light sources

b) Variation of sensor readings over a day in the presence of natural light

Figure 3. The captured data under different conditions

Effect of Natural Light. One of the potential limitations is the presence of the natural light, which can interfere with sensor readings. The experiments' results show that as long as the sensor is not under the direct influence of natural light, it is capable of detecting even the slight changes related to artificial lighting (even the addition of a 25 watt incandescent bulb was detected although sensor was located almost close to the window). By keeping the sensor out of the direct influence of natural light, the detection sensitivity increases. In Figure 4, variation of the sensor readings for two

different locations of sensors have been presented. Also in this figure, the detection of events is evident. As it is seen in this figure, the presence of artificial light, especially, when the sensor is kept far from the window keeps the sensor readings in the steady state, which can be used as a feature in detecting events. Another feature that can also be taken into account for detecting the presence of the natural light is the specific trend of the captured signal (as presented in Figure 3-b) during the day. Repeated test over several consecutive days show that the trend could be used as a feature for detecting the presence of the window. However, this trend is dependent on the relative location of the window (Figure 3-b is for a window facing east and Figure.4 is for window facing west) and the specific season and month of the year.

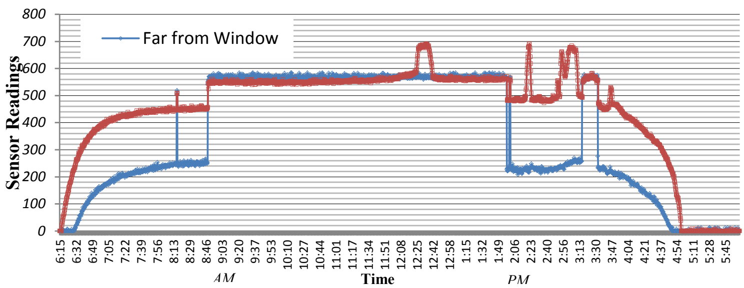


Figure 4. Variation of sensor readings during a day detected by sensors in two different locations in the same room

CONCLUSION

This paper presents the vision for an alternative approach in non-intrusive load monitoring in commercial buildings with an objective of providing room level decomposed electricity consumption to building occupants and managers. An experimental study was carried out for exploring the feasibility of the approach in non-intrusive lighting system load monitoring by using light intensity sensors. The results show that the deployed inexpensive light intensity sensor is capable of detecting the events (specifically, the variation in the lighting intensity) and useful features are extractable for training machine learning algorithms. Area of the room, the fluctuation amplitude of the captured signal, and the daily variation trend of the signal are some of the parameters and features that could be applied for training purposes. Also, it is been observed that even in the presence of the natural light, the sensor is capable of detecting variations of artificial light intensity. Trending the daily patterns of the data in different conditions and applying the identified features in using machine learning algorithms for autonomous estimation of room level lighting system energy consumption are the next steps that are pursued by authors.

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A Novel Vision-Based Crack Quantification Approach by Incorporating Depth Perception for Condition Assessment of Structures

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ABSTRACT

Cracks are important defects that can cause catastrophes if neglected. Visual inspection is currently the predominant method for crack assessment. This approach is labor-intensive, yet highly qualitative. Although several non-destructive evaluation methods have been proposed for inspection purposes, they cannot quantify crack thickness reliably. In this paper, a new contact-less crack quantification methodology, based on computer vision and image processing concepts, is introduced and evaluated. The proposed approach utilizes depth perception to quantify crack thickness.

INTRODUCTION

In many applications (e.g., bridge inspection), crack thickness is measured visually by an inspector. In the case of inaccessible remote regions (e.g., nuclear power plant structures), an inspector uses binoculars to detect and quantify crack thickness. It is a subjective process that relies on an inspector's experience and mental focus, making it highly prone to human error. In this study, a quantitative approach for estimating crack thicknesses, based on depth perception, is introduced.

Although in the past two decades efforts have been made to implement image-based technology in crack detection methods, very few studies are dedicated to quantification of crack thicknesses using image-processing approaches. The most recent effort in this regard is done by Zhu et al. (2011) who developed a system to retrieve the concrete crack properties, such as length, orientation and width, for automated post-earthquake structural condition assessment. These properties were reported as relative measurements related to the dimension of the structural elements.

In this study, a contactless crack thickness quantification approach (i.e., estimating the crack thickness in unit length) based on depth perception is introduced. Such a quantitative approach has been lacking in previous studies. The procedures under discussion involve several steps. First, the depth perception is obtained through 3D scene reconstruction. Subsequently, a morphological crack segmentation operator

is used to segment the whole crack. In this study, a novel method is introduced to extract the tangent and the thickness orientation at each crack centerline. Then, for each centerline pixel, the pixels in the segmented crack that are aligned with the corresponding thickness orientation are counted in the horizontal and vertical directions. Finally, the computed thickness is converted to unit length. Furthermore, a method to compensate for the perspective error is introduced. Validation tests are performed to evaluate the capabilities, as well as the limitations, of these methodologies.

CRACK QUANTIFICATION

To quantify a crack thickness using the proposed approach, the entire crack has to be segmented from the background. In this study, an adaptive crack detection approach that can segment the whole crack from its background is used for crack extraction (Jahanshahi and Masri, 2012).

The Proposed Approach. In the proposed approach, the segmented crack was thinned using morphological thinning. The remaining pixels were considered as the centerlines of the cracks. In order to measure a crack thickness, the perpendicular orientation to the crack pattern at each centerline pixel had to be identified. To reach this goal, the thinned segmented crack was correlated with 35 kernels, where these kernels represent equally-incremented orientations from 0° to 175°.

For each centerline pixel, the kernel corresponding to the maximum correlation value represents the tangential orientation of the centerline. Thickness orientation was then defined as the perpendicular orientation to the detected tangential direction. Next, for each centerline pixel, the pixels in the original segmented crack that are aligned with the corresponding thickness orientation were counted in the horizontal and vertical directions. Using these two values, the hypotenuse was computed and considered to be the crack thickness in pixels. Finally, the crack thickness was converted to a unit length by knowing the camera-object distance and the focal length of the camera. Figure 1 shows an example of the thickness quantification method described above. The white squares are crack pixels of a larger crack image. The blue squares represent the centerline obtained by thinning the crack object. The kernel corresponding to 45, centered at the red square, has the highest correlation with the thinned pixels. Consequently, the green squares, which correspond to 135° direction, indicate the thickness orientation at the red square. It is seen that the number of the thickness pixels in the horizontal and vertical directions are both 6 pixels, and the crack thickness at the red square is estimated as 8.5 pixels.

Unit Length Conversion Using 3D Scene Reconstruction. Using a simple pinhole camera model, the crack size represented by *n* pixels can be converted to unit length by:

$$CS = \frac{WD}{FL} \times \frac{SS}{SR} \times n, \quad (1)$$

where CS (mm) is the crack thickness represented by n pixels in an image, WD (mm) is the working distance, FL (mm) is the camera focal length, SS (mm) is the camera sensor size, SR (pixels) is the camera sensor resolution.

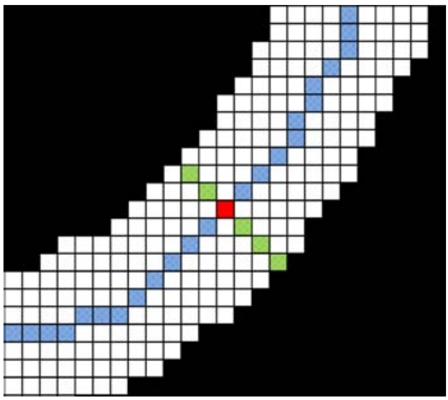

Figure 1. An example of the proposed approach for thickness quantification: the white squares are crack pixels of a larger crack image; blue pixels are centerline obtained by thinning the crack object; green pixels are thickness orientation at the centerline pixel (dark red square).

The approximate focal length can be extracted from the image Exchangeable Image File Format (EXIF) file; however, the working distance should be given. Usually, measuring the camera-object distance is not always an easy or practical task. Thus, the reconstructed 3D cloud and camera locations from the Structure from Motion (SfM) problem are used to estimate the working distance and the focal length. To reach this goal, first, several overlapping images of the object are captured from different views. The SfM approach aims to optimize a 3D sparse point cloud and viewing parameters simultaneously from a set of geometrically matched keypoints taken from multiple views. The SfM system developed by Snavely et al. (2006) is used in this study. In this system, SIFT keypoints are detected in each image and then matched between all pair of images. The RANSAC algorithm is used to exclude outliers. These matches are used to recover focal length, camera center and orientation, and radial lens distortion parameters (two parameters corresponding to a 4^{th} order radial distortion model are estimated) for each view, as well as the 3D structure of a scene. This huge optimization process is called bundle adjustment.

The SfM problem estimates the relative 3D point coordinates and camera locations. By knowing how much the camera center has moved between just two of the views, there constructed 3D points and camera locations can be scaled. To obtain the absolute camera-object distance, a plane is fitted to the 3D points seen in the view

of interest. This can be done by using the RANSAC algorithm to exclude the outlier points. By retrieving the equation of the fitted plane, one can find the intersection between the camera orientation line passing through the camera center and the fitted plane. The distance between this intersection point and the camera center is computed as the camera distance.

Perspective Error Compensation. The above approach is valid if the camera orientation is perpendicular to the plane of the object under inspection. If this plane is not perpendicular to the camera orientation (i.e., the projection surface and the object plane are not parallel), a perspective error will occur. In order to overcome the perspective error, the camera orientation vector and the normal vector of the object plane are needed. The camera orientation vector was already retrieved using SfM, and the normal plane can be computed by fitting a plane to the reconstructed 3D points, seen in the corresponding view, by excluding outliers using the RANSAC algorithm. For each centerline pixel, the number of pixels that are aligned with the corresponding thickness orientation are counted in the horizontal and vertical directions. Next, the perspective error compensation for each component is computed. For each centerline pixel, the resultant of the two perspective-free components is the crack thickness.

EXPERIMENTAL RESULTS AND DISCUSSION

In order to evaluate the performance of the proposed thickness quantification approach, an experiment was performed as follows: Synthetic cracks with thicknesses of 0.4, 0.6, 0.8, 1.0, 1.2, and 1.4 mm were drawn by a human operator using AutoCAD®, and printed using a 600 dpi HP LaserJet printer. Eighteen images with different camera poses were captured from the printed crack-like patterns to form six image sets. These images were in color, and they contained regular image noise. The crack edges were tapered in the captured images. Each image set consisted of three views, where the distance between two of the camera centers was known. The images were captured by a Canon PowerShot SX20 IS with a resolution of 2592 × 1944 pixels. For each image set, the SfM problem was solved and the camera-object distance was retrieved. The working distances in this experiment varied between 725 mm to 1,760 mm. First, the cracks were extracted by a multi-scale crack detection approach (Jahanshahi and Masri, 2012). More than10,000 measurements for each of the above thicknesses were carried out. A total of 94,390 thickness estimations were performed. To increase the robustness of the proposed thickness quantification system, thicknesses within a 5 × 5 neighborhood of each centerline were averaged.

Table 1 shows the mean and standard deviation of the estimated thicknesses, as well as the mean and standard deviation of relative errors. As can be seen, except for the 0.4 mm thickness, the mean errors fall below 20%. As the measured thickness increases, the mean errors fall below 10%. This is due to an increase in the number of the pixels representing a specific thickness. The higher the number of pixels representing a thickness, the higher the achieved accuracy. In some of the estimations in this experiment, a 0.4 mm thickness is represented by only two pixels. Consequently, the mean error for the 0.4 mm thickness is relatively high. In order to improve estimation accuracy, either the working distance can be decreased, the focal

length can be increased (zoom), the image resolution can be increased, or a combination of these actions can be applied.

Based on the results from Table 1, the mean error of thickness estimations, for cracks that are represented by at least 6 pixels, is less than 10% (i.e., crack thicknesses of 1 mm and greater). The mean and standard deviation of relative error for the above 94,390 estimations are 12.24% and 12.64%, respectively.

There are many sources of error when quantifying a crack thickness using the above procedure, including bundle adjustment errors, scaling errors, crack orientation errors, and pixel representation errors (i.e., the number of pixels representing a thickness); however, the results of this study indicate that the errors are quite reasonable, and they are amenable to improvement. Due to some rare irregularities in an extracted pattern, a small portion of the thinned image might not represent the exact centerline, which causes errors too. Averaging the neighboring thickness values will help get rid of these outliers.

Table 1. Comparison between the actual and estimated thicknesses obtained from the proposed method

Ground truth thickness (mm)	Mean estimation (mm)	Std. estimation (mm)	Mean relative error (%)	Std. relative error (%)
0.40	0.52	0.09	32.0	18.7
0.60	0.71	0.08	18.5	11.9
0.80	0.90	0.09	13.9	9.1
1.00	1.08	0.09	8.7	5.3
1.20	1.22	0.10	6.3	5.3
1.40	1.55	0.11	6.0	5.3

SUMMARY

In this study, a crack quantification procedure was introduced. First, images of a scene are captured from different views. By solving the SfM problem, the sparse structure of the scene as well as the camera position, orientation, and internal parameters for each view are determined. By scaling the reconstructed sparse 3D model of the scene, the depth perception of the scene is obtained. A crack detection algorithm is used to extract cracks.

To quantify crack thicknesses, the thickness orientation at each crack centerline is determined. Then, for each centerline pixel, the pixels in the original segmented crack that are aligned with the corresponding thickness orientation are counted in the horizontal and vertical directions. The hypotenuse length, computed based on these two values, is considered as the crack thickness. In order to obtain more realistic results, an algorithm is proposed to compensate for the perspective errors. The depth perception, obtained from 3D scene reconstruction, is used to present the thicknesses in unit length. Validation tests, under ambient light, were performed to evaluate the capabilities, as well as the limitations of the methodologies discussed in this paper.

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Application of Classification Models and Spatial Clustering Analysis to a Sewage Collection System of a Mid-Sized City

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ABSTRACT

Improving asset management of infrastructure systems has been an ongoing issue in the United States. Oliveira et al. (2010, 2011) developed several approaches to better understand the nature and location of pipe breaks in a drinking water distribution system. In this paper, we applied these two approaches to another infrastructure system—the pipe network of a sewage collection system. We first applied several classification approaches to analyze factors associated with higher density regions of deteriorating pipes in the sewage collection system. Relevant attributes that cause poorly conditioned sewer pipes could be found using this approach. We then applied the network version of a density-based clustering algorithm created by Oliveira et al. (2010), used to detect clustered regions of pipe breaks in water distribution systems, to detect hierarchically clustered regions in one of the high density regions of pipe deterioration in the same pipe network. This latter approach was found to provide useful information and additional insight about the local attributes that might be related to the high-density of pipe deterioration.

INTRODUCTION

Improving asset management of infrastructure systems has been an ongoing issue in the United States. Oliveira et al. (2010, 2011) developed several approaches to better understand the nature and location of pipe breaks in a drinking water distribution system. In the analysis described by this paper, we first explored the application of several classification approaches to the data we had related to pipe deterioration problems in a sewage collection system. The goal of this classification analysis was to determine if there are any correlations among the available attributes within the higher density regions of pipe deterioration events, and to extract any relevant factors that are associated with the pipe deterioration process. Then, a

density-based clustering algorithm, adapted for networked domains, was applied to observe if applying the hierarchical clustering approach would provide additional insight into the local attributes that might be related to the higher densities of pipe deterioration events in parts of the sewage collection system.

This paper is organized as follows. The next section briefly presents the approach used in this paper that applies both classification and density-based clustering to better understand the correlations between local attributes and the clusters of pipe deterioration events. The section entitled "Case Study" then discusses our application of this approach to data collected from a specific sewage collection system provided to us by RedZone**,** which develops robotics and software technology to perform condition assessments of wastewater collection systems. This section first describes the data collection process and how the dataset was prepared. In addition, it describes the selection and application of the classification models applied to that data and the application of the network-OPTICS approach. The last section provides conclusions.

OVERVIEW OF APPROACH

There have been numerous approaches that have been explored for developing deterioration models to predict pipe breakage rates based on several factors (Piratla and Ariaratnam 2011). For instance, Clair and Sinha (2011) developed the weighted factor and/or fuzzy logic model to prioritize or predict the performance of water pipes. Chua et al. (2008) developed and evaluated the Proactive Rehabilitative Sewer Infrastructure Management (PRISM) model, which uses a Logistic Regression approach to determine the deficiency probability of sewer pipes. Oliveira et al. (2010, 2011) applied several different classification models, such as C4.5 Decision Tree, Logistic Regression, Boosted Decision Stump, etc. to identify relevant factors associated with abnormal regions of drinking water pipe failures.

In the research described in this paper, two classification models were applied to data provided by RedZone concerning the pipe network of a sewage collection system. During inspection, RedZone uses the Pipeline Assessment and Certification Program (PACP) developed by NASSCO to record the condition of the sewer pipes being inspected. Grades of 4 and 5 are the pipes of 'immediate attention' and 'poor' respectively. Thus, in our dataset, only pipes that are structurally graded as 4 or 5 were labeled as "Pipes with Defects" while the others were labeled as "Pipes with No Defects". Two classification models were applied to determine attributes that can be associated with clusters of pipes with defects and pipes with no defects: 1) a Bayesian Network Approach was applied to explain the distribution of the sewage collection system pipe deterioration data; and 2) Decision Trees were used to identify the relevance of particular attributes associated with the high density regions of pipe defects. This process was not used to indicate any cause-effect relation, but to identify factors that influence pipe deterioration or that may be good predictors of pipe deterioration (Oliveira 2010). After these two classification approaches were applied to the data, we then applied the density-based spatial clustering approach developed by Oliveira et al. (2010), referred to as Network-OPTICS to determine whether more specific relationships between attributes and the pipe defect classes could be discovered.

CASE STUDY

In this section, the process of preparing the dataset is presented. Then, the application of the two classification approaches and the application of Network-OPTICS are discussed in detail.

Data collection. Data used in this study were provided by RedZone Robotics. The data were collected using a Solo(R) robot, an autonomous self-operating inspection device, and RedZone's ICOM3 software to manage this inspection data and link each inspection result to a GIS-represented sewer asset tool. The data used in this research was from one of the cities that RedZone has inspected. The inspection data are recorded as the robot moves along the pipe, so the data contains the distance along each pipe and the corresponding structural condition grades. The data also contains physical characteristics of the pipes, all the information about inspection results, and additional pipe characteristics. Among the available attributes captured in the data, many of them could not be utilized, because they were not relevant for the prediction task or the data set was missing too many values for that attribute. Thus, in the end, only the attributes of pipe diameter and material were able to be drawn from the collected data. Geographical attributes, such as soil type and elevation, were collected from other sources and used. The soil type data was collected from the Natural Resources Conservation Service and the elevation data from the "County" Fiscal Office GIS (2004). We recognize this is an incomplete set of attributes and that if available, more attributes, such as traffic, age, demographics, usage, and many others that are possibly good indicators of deteriorating pipes should also be considered.

Data preparation. The number of defect points in the dataset was comparably very small, because pipes with defects can be thought of as 'abnormal' events that do not occur very often. In addition, every pipe of the network has not yet been inspected by RedZone such that applying the classification models and the clustering algorithm over the entire network was not appropriate to obtain any useful information. Thus, this case study was based on the four different dense areas of the defect points, as shown on the left of Figure1.

Because of this seriously skewed distribution of the dataset, several techniques had to be considered to address this issue. In this analysis, the two most common techniques, i.e., sampling and cost-sensitive classification were examined before applying the frameworks. There are several types of sampling, e.g., over-sampling and under-sampling. In Weka (Hall et al.. 2009), which is a collection of machine learning software tools, there is a sampling method, SMOTE, where the minority class gets over-sampled by creating synthetic examples rather than by over-sampling with replacement (Nitesh et al. 2002). Another technique, called cost-sensitive classification penalizes misclassification of anomalies more than misclassifying normal examples (Neill 2011). Both techniques would cause a bias towards the minority class, but since the number of pipes with defects was comparably very small, at least one of these techniques was necessary to observe any underlying relationships between the attributes and the target class.

Each high-density region has a different number of pipes and defect points, which means a different ratio of the number of members in the majority class to those in the minority class. In addition, selecting the sizes of the datasets was subjective; thus, even though the same technique was used, the number of times this technique was applied to each region had to vary in order to solve the class imbalance problem . In this study, SMOTE was used, because its precision and recall rates were higher than the cost sensitive classification approach. The SMOTE sampling was applied twice to region A (i.e., 200%), three times to B, once to C and twice to D, before applying the classification approaches. The ratio of the positive instances, or pipes with defects, to the negative instances, or pipes with no defects, was then better balanced. While each dataset was ensured to have a smaller number of pipes with defects than that of normal pipes, the percentage difference between the two classes was less than 50%. The skewness of the data tends to cause high false negative rates, resulting in falsely high overall accuracy. Thus, to evaluate classifiers with a skewed class distribution, either precision or recall must be assessed, instead of accuracy. In this case study, a high recall rate would be preferred to a high precision rate, because whenever there are seriously deteriorating pipes, it would be preferable to recognize all such situations.

Application of two classification algorithms to case study data. There are numerous classification algorithms available, so the choice of algorithms would be subjective. However, properties of the data, characteristics of the models, and the objective of the analysis were carefully considered to see which algorithms would be the most appropriate to perform the classification of the deteriorating pipes in the sewage collection system investigated in this case study.

Application of Bayesian Networks. Bayesian networks provide a useful graphical representation of the probabilistic relationships between many variables (Neill 2011). Thus, this algorithm was first applied to see dependencies between the variables and their relationships with the class variables, i.e., "Pipes with Defects" and "Pipes with No Defects" (Weka was used with "global score metrics" and the Hill Climbing search algorithm with a maximum of two parents.)

The Bayes Network created using the approach described above (as shown on the right of Figure 1) showed no direct dependencies between the class variables and the elevation. However, it did show dependencies among the other variables, i.e., the material, the diameter and the soil type. From this observation, it can be concluded that the elevation of the pipe is not a good indicator of pipe deterioration. The only variable that depended on the elevation was the soil type. R. Scharf states in the "Soil and Formation" website that "changes in elevation of only a few feet produce major changes on soil properties of the region, all attributable to the topography's effect on soil water". This statement enhances our result, which showed the dependency between the elevation and the soil type.

In the Bayesian Network, the diameter and the material of the pipe were found to be dependent on each other in every region. For example, in region A, the probabilities of 8 in. vitrified clay pipes (VCP) being in the "Pipe with Defect" and "Pipe with No Defect" classes were 0.764 and 0.957, respectively. Even in the other regions, the probabilities of 8 in. VCP pipes being in these two classes were relatively

higher than the combinations of other diameters and materials. In this dataset, VCP pipes dominate the entire dataset, and so do 8 in. pipes, so it was not surprising to see this result. Thus, we cannot simply conclude that "diameter = 8 in." and "material = VCP" are the most relevant factors in classifying the deteriorating pipes. However, this result would be enhanced if correlated with other variables, e.g., the age of the pipes. For instance, the 8 in. VCP pipes might have been installed in a similar time frame, which means there could be some trends in the installation of particular sizes or types of pipes.

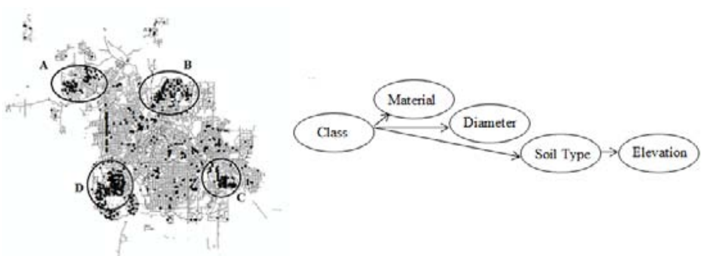

Figure 1. (Left) A network of the wastewater collection system where the points on the network indicate the defects (Right) The Bayes Network graph for Region A

Application of Decision Trees. Decision Tree creation is a widely known classification algorithm that creates a set of rules by assigning each attribute to a decision node of the tree. Depending on the value of the attribute, a different path in the tree is followed towards one class or another. Another advantage of the Decision Tree algorithm is that it is easy and simple to interpret its results. Since we were interested in interpretability of results, a Decision Tree algorithm was appropriate for application to our case study data.

The most widely known Decision Tree algorithms are ID3 and C4.5, created by Quinlan. An extension of ID3, the C4.5 algorithm has a pruning ability, so it was used instead of ID3 (in Weka, the J48 algorithm implements C4.5). The output of the J48 algorithm provides a sense of which variables are important in predicting the target class, because more important variables are located toward the top of the tree while unimportant variables get pruned (Neill 2011). The recall rates of "Pipes with Defects" in the four regions came out to be very similar except for the region C. They were 93.3%, 96.1%, 79.3% and 95.2% respectively. In most of the regions, diameter and/or material seemed to be the most important attributes, because they were the root nodes of the trees. The root node of the region A, for example, was the diameter of 8 in., and the subsequent nodes were the soil types followed by the elevations and materials, respectively. In region A, there were three different soil types that seemed relevant given the 8 in. pipes. Based on Table 1, while the soil type 'S1' has the moderate potential for frost action, 'S2' and 'S3' have high potential. However, it cannot be simply concluded that this soil property is always relevant. Other regions, for example, had soil types that have low potential for frost action. In addition, even though overall properties in the region are still the same, soil properties around the

pipe can be altered due to soil manipulation during pipe installation (Oliveira et al. 2011). There are likely complex combinations of factors that need to be considered before relating properties to deteriorating pipes. Thus, the interpretation of the soil data relating to the pipe deterioration may change as more available attributes are brought into this analysis. Nonetheless, it would be still worthwhile to be aware of the characteristics of the soils when predicting the conditions of the pipes.

Table 1. Examples of Soil Features

Soil Type	Potential for Frost Action	Corrosion Steel	Corrosion Concrete
'S1':	Moderate	Moderate	Moderate
'S2':	High	Moderate	Moderate
'S3':	High	High	High

Application of Network-OPTICS: In this analysis, the Network-OPTICS algorithm (Oliveira et al. 2010) was applied to the pipe deterioration events in region C to determine if different levels of clusters would provide any additional insight on the dataset. Region C was chosen because it had the most balanced distribution of pipes with and without defects out of the four regions, which means there is less bias. As can see be seen from Figure 2, the application of Network-OPTICS to the data from region C generated four levels of clusters, and levels 2 and 3 displayed the most interesting outputs. Since the variations among the physical characteristics of the pipes were very small, only the elevation and the soil data were compared between these two levels. As shown in Figure 2, clusters C9, C13, C5 and C7 are in level 2. Defect points that were part of cluster C7 are no longer part of any cluster at level 3, and several defect points of cluster C5 are also not part of cluster C3 at level 3. Moreover, cluster C13 disappears at level 3, while C9 was further broken down into C8 and C10.

Because the soil type varied so greatly geospatially, this clustering analysis was used to determine if a relationship between the soil types and the clusters at level 3 could be discovered. Figure 3 shows that C7, which is uniquely in level 2, has a different soil type from the clusters in level 3. The higher density clusters, i.e., clusters that remained up to level 3, are located on the same soil type, 'S4', as shown in Figure 3, and cluster, C7 on level 2 is located on soil type, 'S1'. This shows that the clusters in the different levels have different soil type. Thus, even though it might have been a coincidental result, analyzing the soil properties of these two areas and possible changes of their characteristics over time might be useful to determine if particular soil types are more likely to cause these pipes to deteriorate.

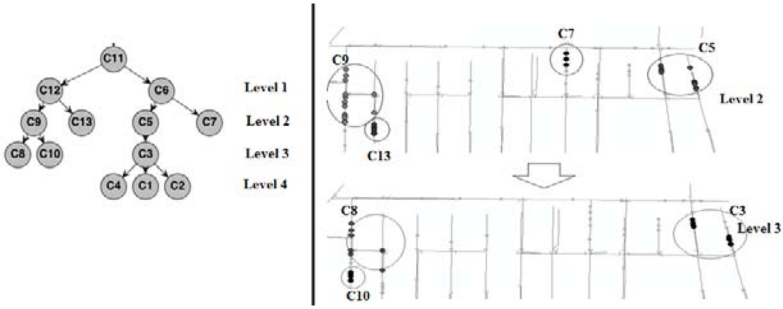

Figure 2. Left: the hierarchical clusters generated by the network-OPTICS for Region C. Right: comparison of the level 2 and level 3 clusters

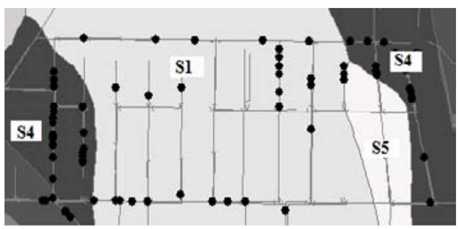

Figure 3. Soil types labeled in the part of the network for Region C

CONCLUSIONS

Bayesian Networks and Decision Trees were created for the data collected from a pipe network in a sewage collection system to see if there were any important local indicators of that deterioration. The performance of these two classification algorithms was assessed using the precision and recall rates and both seemed to perform reasonably well based on these metrics. Relevant factors associated with the pipes with defects, and the dependencies among the attributes, could be found. After the classification analysis, a density-based clustering algorithm was applied to one of the high-density regions of pipe deterioration. This exercise showed the value of examining the hierarchical clusters to get more meaningful associations between more dense clusters and local attributes that might explain the pipe deterioration. These results, however, need to be further explored because of the limited data availability and quality.

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Mobile Terrestrial Laser Scanning for Highway Inventory Data Collection

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ABSTRACT

A variety of roadside objects along state highways contribute to a complex infrastructure system that needs to be efficiently managed by state departments of transportation (DOTs). State DOTs routinely collect data on roadside objects using a variety of sensing methods to meet regulation requirements, to evaluate road conditions, and to optimize their operations. Significant challenges exist in collecting and maintaining highway inventory data of sufficient detail and quality. There are thousands of miles of highways in each state. Collecting road inventory data along these highways often incurs significant cost. This research reviews mobile terrestrial laser scanning (MTLS) as an emerging highway inventory data collection method. The objective is to analyze the system components of MTLS systems and to investigate MTLS's data accuracy and data collection effort relative to the need of implementing a cost-effective highway asset management system.

INTRODUCTION

To efficiently manage highway systems, State DOTs often collect a variety of geospatial data to support their management programs. These programs include, but are not limited to, bridge clearance measurement, asset inventory and management surveys, as-built surveys, engineering topographic surveys, corridor study and planning surveys, Americans with Disabilities Act (ADA) compliance surveys, deformation surveys, environmental surveys, sight distance analysis surveys, earthwork surveys, coastal zone erosion analysis, crash prediction and response, and construction inspection. The collection of geospatial data to support these programs incurs costs of hundreds of millions of dollars. Crews are often exposed to dangerous road traffic during data collection. Considering the vital role of highway systems for the nation's economy, methods that can collect higher quality geospatial data in a safer manner and with lower cost are immediate needs.

The recent emergence of Mobile Terrestrial Laser Scanning (MTLS) systems for land-based geospatial data collection methods has the potential to greatly improve existing DOT geospatial data collection practices (Graham 2010). As the MTLS technology and market quickly evolves, MTLS has become one of the most anticipated breakthroughs in geospatial data collection for State DOTs. There are multiple recent studies at both the state and national level on evaluating the capability of MTLS systems for meeting state DOTs' geospatial data needs (Yen et al. 2011a &b; Uddin 2011). Several industry and standardization bodies are diligently working on data standards for MTLS systems (such as The American Society of

Photogrammetry and Remote Sensing). This paper provides an overview of the latest developments in this exciting and dynamic research field. The particular focus of this paper is on MTLS's applications for highway inventory data collection. The rest of this paper starts with a brief description of existing methods that have been used for geospatial data collection by state DOTs. We present documented cost figures of some of these DOT programs. We then present an analysis of MTLS systems relative to State DOTs' highway inventory data needs from the perspectives of system configuration, data accuracy, and data collection effort and cost, and discuss challenges and opportunities in this dynamic and young field.

OVERVIEW

Existing Highway Inventory Data Collection Methods. Many techniques for collecting highway inventory data have been used by state DOTs and local agencies. These techniques include field inventory, photo log, video log, integrated GPS/GIS mapping systems, aerial photography, satellite imagery, structure from motion, terrestrial laser scanners, mobile mapping systems (i.e. vehicle-based LiDAR), and airborne LiDAR. The brief definitions of each method are given in Table 1.

Table 1. Common Highway Inventory Data Collection Methods

Field inventory	Using conventional optical and GPS survey equipment to obtain desired information in the field.
Photo log/Video log	Driving a vehicle along the roadway while automatically recording photos or videos to produce a visual record which can be examined later to extract information
Integrated GPS/GIS mapping systems	Using an integrated GPS/GIS field data logger to record inventory information and store such information into GIS database simultaneously
Aerial photography/Satellite imagery	Analyzing high resolution images taken from aircraft or satellite to identify and extract highway inventory information
Structure from Motion (SFM)	Using detailed 3D models reconstructed from a set of unstructured roadway photos (triangulation of cameras not required) for extraction of highway inventory data
Stationary Terrestrial laser scanners	Using direct 3D precision point information (3D point clouds) acquired from stationary 3D laser scanners to extract highway inventory data.
Mobile mapping systems	Driving an instrumented vehicle while collecting direct 3D precision point information using either land-based LiDAR systems or photogrammetry systems while traveling at highway speeds
Airborne LiDAR	Using direct 3D precision point information acquired from aircraft-based LiDAR systems to derive highway inventory data

Implementation of Highway Inventory Data Collection Methods

Highway inventory data collection methods vary in equipment used, time requirements, and costs. Each of these techniques has its specific advantages, disadvantages, and limitations. To date, many state DOTs have elected to use one or more techniques to collect their highway inventory data. Table 2 lists ten different

techniques used by state agencies in the United States. The type of data collected in road inventory programs varies significantly from state to state. In some cases, certain types of road inventory data may be collected multiple times by different divisions in the same state. Table 3 shows typical road inventory data collected by state DOTs and its associated cost.

Table 2. Available Techniques for Highway Inventory Data Collection

Data Collection Method	Equipment Utilized	State Agency Implementation
Field Inventory (Khattak et al. 2000)	GPS, distance measuring tools, laptop	Alaska, Colo., Conn., Del., Hawaii, Ky., La., Mass., Mich., Minn., N.Y., N.D., Okla., Ore., Pa.
Photo Log (Jeyapalan 2004; Wang et al. 2010)	Vehicle, GPS, and camera	Ariz., Del., Ga., Mich., Wash., Ohio
Video Log (Gunaratne and Sokolic 2003)	Vehicle, GPS, video cameras	Ala., Idaho, Ind., Md., Nebr., N. J., Okla., Pa.
Integrated GPS/GIS Mapping Systems (Caddell 2009)	GPS and GIS data-logger combination	Ala., N.H., Ohio, S.D., Utah, Wash.
Aerial Photography (Veneziano 2001)	Airplane, GPS, digital camera	Iowa, Nebr.
Satellite Imagery (Ravani et al. 2009)	N/A	Iowa
Virtual Photo Tourism (Uslu et al. 2011)	Digital Camera	
Terrestrial Laser Scanner (Jaselskis et al. 2005)	Terrestrial Laser Scanner	Iowa, Caltrans, Wash.
Mobile Mapping Systems (Khattak et al. 2000; Graham 2010;Turner and Comport 2007)	GPS, vehicle, distance measurement indicator, inertia measurement system, digital cameras, LiDAR	FHWA, City of Charlotte, Ind., Wis., Nev., Tex., Tenn., Hawaii
Airborne LiDAR (Shamayleh and Khattak 2003)	Airplane, GPS, LiDAR	Iowa, Nebr.

ANALYSIS OF MOBILE TERRESTRIAL LASER SCANNING SYSTEMS

Most of the above highway inventory data collection methods use one or more visual sensing methods to capture road inventory information. These visual sensing methods include land, air, and space-based imaging systems as well as air and land-based LiDAR systems. GPS, IMU (Inertia Measurement Unit), and DMI (Distance Measurement Indicator) are often used to provide accurate positional data for these visual sensing systems. Mobile Terrestrial Laser Scanning is essentially a land-based LiDAR system which competes with satellite imaging, aerial imaging, air-borne LiDAR, and land-based mobile photogrammetry systems. In the following sections, the latest MTLS systems are described, common workflows used in MTLS applications are explained, and data accuracy and collection effort are discussed.

MTLS Systems. A LiDAR system typically consists of a motorized spinning mirror with encoder and a Time-of-Flight (TOF) or phase-based LiDAR sensor. Common parameters for benchmarking the performance of LiDAR sensors include scan rate,

measurement rate, range accuracy, and maximum range. The resolution of a point cloud (the number of points in a unit area) depends heavily on the scan rate and the measurement rate. The measurement rate (points measured per second) refers to the number of points measured in a single sweep of the LiDAR scanner mirror. The scan rate is the LiDAR scanner's mirror rotational rate. Therefore, a high LiDAR measurement rate produces small point spacing within each scan line from a single sweep. The vehicle speed divided by the scan rate determines the spacing between lines of points. The Optech Lynx, Riegl VMX-250, and Trimble MX8LiDAR sensors are capable of scanning at 100-200 HZ frequency, measuring 300,000 to 500,000 points per second, delivering range measurement at a maximum distance of 75 meters and with accuracy of less than one centimeter. Figure 1 shows the scan line spacing that can be achieved under different scanning settings and driving speed, demonstrating the importance of the scan rate.

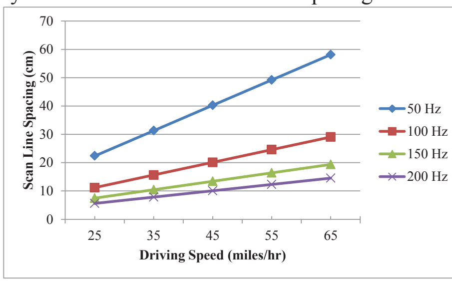

Figure 1 The Impact of Driving Speed and Scan Rate on the Scan Line Spacing

Table 3. Example State DOT Road Inventory Programs

State DOT	Inventory Techniques		Inventory Data	Cost (if available)
	Collection	Storage		
Washington State	Photo Log, Integrated GPS/GIS Mapping	GIS	Cable barrier, concrete barrier, culvert, culvert end, ditch, drainage inlet, glare screen, guardrail, impact attenuator, misc. fixed objects, pipe end, pedestal, roadside slope, rock outcropping, special use barrier, support, tree, tree groupings, wall	$16.44/Feature $2,179/Mile
Michigan	Integrated GPS/GIS Mapping Systems, Field Inventory	GIS	Guardrail, pipes, culverts, culvert ends, catch basin, impact attenuators,	$4.34 per mile per year with an initial investment of $26/mile/year
Ohio	Photo Log, Integrated GPS/GIS Mapping Systems	GIS	Wetland delineation, vegetation classification	N/A
Iowa	Airborne LiDAR, Aerial Photography	GIS	Landscape, sloped areas, individual count of trees, side slope, grade, contour	N/A
Idaho	Video log	MS Access	Guardrail	
FHWA Baltimore-Washington Parkway	Mobile Mapping	Point Cloud Software, GIS	Corridor, Sign inventory	Collecting:$3,500 /day @ 20-60 MPH Processing: $100/per hour

MTLS Workflow. Most MTLS applications employ a typical workflow as shown in Figure 2. The data collection starts with mission planning and staging, which is mainly concerned with GPS outage-related planning. Systems shall be calibrated prior to the actual driving. Upon finishing data collection, most MTLS systems provide 3D point clouds, GPS/IMU data, and camera data. These data need to be extensively post-processed to meet highway inventory data requirements. The typical steps in data post-processing include creating geo-referenced point clouds and photographs, extraction of road inventory features from the geo-referenced data (point clouds and photos), generating derived products, and quality control. The

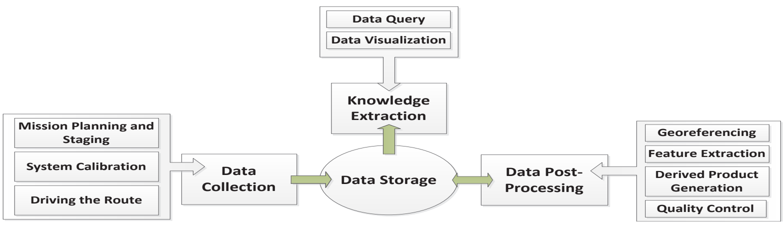

Figure 2 A Common Work Flow in Highway Inventory Data Collection

typical derived product includes digital elevation models (DEM), digital terrain models (DTM), vectorized contour lines, track geometry, etc..

MTLS Data Accuracy and Inventory Program Requirement. Commercially-available MTLS systems can be classified into two types of systems: mapping-grade and survey-grade systems. Mapping-grade systems are used for mapping and inventory applications, providing absolute and relative accuracy in the range of 1 foot and 0.1 foot respectively. Survey-grade systems can produce centimeter-level absolute accuracy. The system's absolute accuracy refers to the position accuracy of a point in a point cloud in a global coordinate system, and the relative accuracy refers to the position accuracy of a point relative to other neighbor points. Among the most common LiDAR sensors used in survey-grade MTLS systems are Optech Lynx, Riegl VMX-250, and Trimble MX8. The exact accuracy of LiDAR data varies from system to system.

Recently, several studies have been conducted to evaluate the accuracy of various MTLS systems relative to state agencies' inventory program requirements. A study funded by Washington State Department of Transportation (WSDOT) evaluated whether mobile mapping technology can meet WSDOT geospatial data requirements (Yen et al. 2011b). Nine mobile mapping systems, including Eagle Mapping system, Earthmine Mars Collection system, Mandli Communications mobile LiDAR system, Optech Lynx, Riegl VMX-250, 3D Laser Mapping StreetMapper 360, Ambercore's Titan, Topcon IP-S2, Trimble MX8, are tested. All of these but the Earthmine Mars Collection system are MTLS systems. The data accuracy requirements of three existing WSDOT programs including RFIP (Roadside Feature Inventory Program), Bridge Clearance Program, and Americans with Disabilities Act (ADA) Feature Inventory are shown in Table 4; these requirements were compared against the data accuracy of MTLS systems. A survey-grade MTLS

system can generally meet the data accuracy requirements of these programs. In another LIDAR study for airport runways, Uddin (2011) reported the used MTLS system achieved a vertical accuracy within 10 mm of the digital levels from the independent NGS measurements of the Real Time Kinematic (RTK) GPS survey based on the difference in their mean values. However, another study by Caltrans investigated whether the survey-grade MTLS systems can be used to produce digital terrain models of pavement surfaces (Yen et al. 2011a). The freeway pavement surface survey, the most hazardous task for Caltrans surveyors, generally requires 10 mm horizontal and 7 mm vertical accuracy for hard surfaces. The results indicated the current MTLS systems fall slightly short of this requirement due to the positioning error from the positioning sensors (GPS, IMU, and DMI). The improvement of vehicle positioning accuracy is critical for improving the overall accuracy of a MTLS system given that commercially-available LiDAR sensors are quite capable of providing measurements as accurate as 7mm.

Table 4. Data Accuracy Requirement in Three Existing WSDOT Programs

Programs	**Data Accuracy Requirement**
RFIP Program	Mapping level accuracy (1 foot for absolute accuracy and 0.1 foot for relative accuracy)
Bridge Clearance Program	Absolute accuracy for bridge location: ~2' Bridge Column/Piers (horizontal clearance) - within 4 inches optimum Bridge Girders (vertical clearance) - within 1 in Overhead Restriction (including truss members) - within 1 in. vertical; within 3 in. horizontal Bridge Rails/Guard Rails (horizontal clearance) - 3 in. Edge of Pavement (horizontal clearance) - 1.5 in. to 6 in. Sign of Bridges (vertical clearance) - within 1 ft.
ADA Feature Program	0.01 ft of relative accuracy for horizontal and vertical measurements of ADA features

MTLS Data Collection Effort and Cost. MTLS systems are capable of collecting large volumes of detailed highway inventory data in a short amount of time. Collecting a 20-mile highway corridor with traditional survey methods usually requires a field survey crew to work 10 days in good weather conditions. A MTLS system can collect such data in 30 minutes, and all the data processing tasks can be completed in the home office. It is estimated that a MTLS system can collect field data up to 150 miles a day (Yen et al. 2011b). The downside with the MTLS system is that it requires expensive equipment and may still require a supplemental survey with foot-on-ground survey crews to collect specific items beyond the field of view of MTLS systems, such as measurements of ditch slopes. The data collected by LiDAR may also need significant amount of data reduction effort to extract required highway inventory data. One previous study actually showed manual highway inventory data collection techniques were more cost-effective than mobile mapping systems, as the latter incurs high equipment cost and significant data reduction effort (Khattak et al. 2000). A more recent study by the Washington State DOT investigated the cost of mobile LiDAR system-based highway inventory data collection. The mobile LiDAR systems evaluated in this study include both mobile photogrammetry and mobile terrestrial laser scanning systems (Yen et al. 2011b). They estimated the cost of seven operation options for a 6-year program with three cycles of data

collection and processing. These options include: 1) Contract for mapping-grade mobile LiDAR services; 2) Contract for bridge clearance measurement services; 3) Rent and operate a mapping-grade mobile LiDAR system; 4) Purchase and operate a mapping-grade mobile LiDAR system; 5) Rent and operate a survey-grade mobile LiDAR system; 6) Purchase and operate a survey-grade mobile LiDAR system; and 7) Purchase fractional ownership of a survey-grade mobile LiDAR system. The study found that the costs of these options are in the range of \$5,779,500 to \$10,730,588. A significant part of the cost is related to data extraction, more precisely the data post-processing part, as shown in Figure 2. This is clearly reflected in Figure 3, as it shows the proportion of cost associated with data extraction in the total cost ranges from 42%-59% with an average of 51%. The cost of option 2 (contract for bridge clearance measurement services) is not considered since it only concerns a specific DOT program.

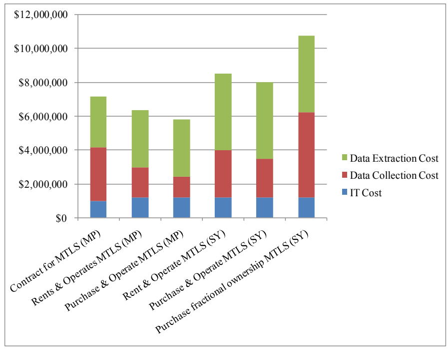

Figure 3. The Cost Scenarios of MTLS based Highway System Data Collection (Data source: Yen et al. 2011b)

CONCLUSIONS

The sensing capability of MTLS systems renders such a technology an attractive tool for meeting state DOTs' geospatial data needs, including inventory documentation of numerous types of roadside objects. The speed and improved safety of data collection and the richness of data collected are driving state DOTs to consider adoption of MTLS technology for highway inventory data collection. However, significant challenges exist for immediate and widespread implementation of MTLS systems. The initial investment with MTLS systems is high relative to other highway inventory methods that have been routinely used by state DOTs. As the MTLS technology evolves, it can be expected to meet most of the accuracy requirements outlined by various DOT programs. However, the cost of data extraction represents a major roadblock for increasing the overall MTLS data efficiency. Despite extensive research in the general field of point cloud processing, 3D scene understanding, integrated point cloud and image processing, most of MTLS data extraction, such as feature extraction, still has to be done manually. Extensive QA/QC is required to eliminate errors in the data processing process. There is a clear need for dedicated studies on automating MTLS data extraction tasks and the overall MTLS workflow. These studies will need collaborative efforts in the fields of computer vision, image processing, knowledge discovery and data mining, geometric modeling, and transportation engineering. The need for open access MTLS data sets and open source MTLS data processing software framework is particularly evident considering

that: 1) most researchers don't have access to MTLS data sets since collecting MTLS data sets is cost prohibitive; 2) most MTLS data processing programs are proprietary systems with limited development support; open source programs like Point Cloud Library (PCL) provide opportunities to crowd source the challenge of automated MTLS data extraction; and 3) open access MTLS data sets and open source programs facilitate benchmarking the performance of new data extraction algorithms. Despite these challenges, MTLS technology provides significant potential to save federal and state funds for maintaining the nation's transportation infrastructure and improve road safety during data collection and for the traveling public.

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Pothole Properties Measurement through Visual 2D Recognition and 3D Reconstruction

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ABSTRACT

Current pavement condition assessment methods are predominantly manual and time consuming. Existing pothole recognition and assessment methods rely on 3D surface reconstruction that requires high equipment and computational costs or relies on acceleration data which provides preliminary results. This paper presents an inexpensive solution that automatically detects and assesses the severity of potholes using vision-based data for both 2D recognition and for 3D reconstruction. The combination of these two techniques is used to improve recognition results by using visual and spatial characteristics of potholes and measure properties (width, number, and depth) that are used to assess severity of potholes. The number of potholes is deduced with 2D recognition whereas the width and depth of the potholes is obtained with 3D reconstruction. The proposed method is validated on several actual potholes. The results show that the proposed inexpensive and visual method holds promise to improve automated pothole detection and severity assessment.

INTRODUCTION

The roadway network of a developed or a developing country contains several thousand centerline kilometers of pavement, which consists of bituminous, concrete, or composite pavements. These pavements vary in age, condition, and performance. Since the majority of the pavement costs in the U.S. are related to road maintenance, programs such as the Long-Term Pavement Performance program (LTPP) are established. LTPP is concerned with data collection, storage, and analysis and product development of the road network (FHWA 2009). Such programs recognize surface condition assessment as a component that requires reliable, good-quality measurements for distresses such as cracks, potholes, and rutting (FHWA 2009).

Currently, roadways are usually maintained dedicated vehicles that collect pavement surface video and profile data. These data are then evaluated manually by technicians on computers. Manual analysis of data is a time-consuming task.

Moreover, though well-defined criteria for assessment exist, subjectivity and experience of raters influences final assessment (Bianchini et al. 2010). To address these limitations, several research studies are being conducted for automated detection and analysis of various types of distresses. One particular type of distress that has received more attention in the recent years is pothole. Potholes are elliptical, bowl shaped depressions in the pavement surface. Current methods for pothole detection include 3D surface reconstruction methods using 3D laser-based scanning (Li et al. 2010, Wang et al. 2009, Chang et al. 2005), and stereovision (e.g Wang 2004) systems, vibration based systems that use accelerometers (Yu and Yu 2006), and image based 2D appearance detection approach (Koch and Brilakis 2011a and b). Despite the benefits, none of these techniques can simultaneously use appearance and depth information from images to detect and measure distress. To address the limitation of current state-of-the-art techniques, this paper presents a new approach for detection and measurement of potholes. Our approach is based on integration of image-based 2D recognition with 3D reconstruction algorithms to first verify the existence of potholes and then find geometric properties used for severity levels.

BACKGROUND

Current State of the Pavement Assessment Practice: Process of pavement assessment can be divided into three parts: 1) data collection, 2) distress identification and classification, and 3) distress assessment. Nowadays, inspection vehicles are quickly replacing traditional methods of data collection. These inspection vehicles equipped with several sensors such as cameras for surface imaging, optical sensors for distance measurement, laser scanners for profiling, ultrasonic sensors for rutting detection, and accelerometers for roughness measurements can collect data at speeds up to 60*m/h* (96 *Km/h*) (Fugro Roadware 2011, MNDOT 2009). Despite the automation of data collection process, the second two steps of distress classification and assessment are still predominantly manual.

The collected data is currently analyzed manually by technicians who identify the existence of distresses and assess their severity from the computer screen. Such a manual procedure is labor-intensive and due to the large size of the collected data can make the process non-systematic, ultimately affecting the quality of the assessment. For example, the Georgia Department of Transportation employees 60 full time engineers to assess the condition of its 18,000-mile (29,000*km*) centerline highways (GDOT 2011). Although there are well-defined guidelines for asphalt distress assessment, manual identification and assessment, the experience of the technicians has an impact on the final assessment (Bianchini et al. 2010).

An automated solution for pavement distress classification and assessment is based on 3D surface profiles from time-of-flight laser scanners (Fugro Roadware 2011) or using hybrid imaging devices that integrate digital cameras with infrared lasers to capture consecutive images of lines projected by infrared lasers (Li et al. 2010). Nonetheless, these commercial software applications do not identify and compute the total number of detected potholes. Pavemetrics (2011) claims to use 3D data from laser scanners to automatically detect and analyze potholes but its performance is not documented or validated. Moreover, the cost of laser scanning

equipment is significant at vehicle-level and suffers from mixed pixel phenomena that can affect the quality of the results.

Current State of the Research in Pothole Detection: Research related to pothole detection can be classified into 1) 3D reconstruction based, 2) vibration based, and 3) 2D vision-based approaches. 3D reconstruction based methods can further be divided into 3D point clouds obtained from laser scanners or stereovision methods. 3D point clouds obtained from laser scanning are based either on time-of-flight based 3D point coordinates (Chang et al. 2005) or from hybrid systems that use digital cameras to capture lines projected by infrared lasers (Li et al. 2010). However, the cost of laser scanning equipment is still significant at vehicle-level, and suffers from mixed pixel phenomena that can affect the quality of the results. In addition, these works only focus on the accuracy of the 3D measurements, and no particular method for classification of distress is presented.

Another line of research for comprehensive pavement assessment proposes stereovision based surface modeling (e.g. Wang 2004). Using a 3D point cloud, Chang et al. (2005) used a clustering approach is used to compute severity and extent of potholes on the pavement and Wang et al. (2009) proposed a method to identify, locate, classify, and measure depressions such as potholes. Stereovision based methods require both cameras to be very accurately aligned. Given the vibration of the vehicle motion, the cameras may misalign and affect the quality of the outcome.

Vibration based methods use acceleration sensors to "*feel*" the ground conditions as opposed to "*seeing*" them with cameras. Yu and Yu (2006) present an initial evaluation of pavement condition based on a vibration based method. These systems require small storage, are cost-effective, and can be used for real-time processing. However, response of the sensors is modulated by the vehicle response and results are not comparable unless the vehicle service condition is calibrated. In addition, the ratio of false positives in current algorithms is still significantly high (Eriksson et al. 2008). For example, in several cases bridge joints have been detected as potholes. Furthermore, potholes that appear in the middle of a lane (which usually fall between the wheels of a vehicle) are also not identified by this method.

2D vision-based approaches include detection of computer-generated (simulated) potholes that are larger than 2*ft* (60*cm*) and appear white in color (Karuppuswamy et al. 2000) but these assumptions are simplistic and do not reflect real pavement conditions. Recently, a method for automated 2D detection of potholes in images has been presented which includes image segmentation, shape and texture extraction, and finally comparison of the textures from a potential pothole area and healthy pavement area (Koch and Brilakis 2011a). Texture obtained for the healthy pavement area is a small, scattered area due to the presence of a pothole and related fatigue cracking. Hence, healthy pavement texture is not appropriately represented. Moreover, though this method identifies potholes, scattered images do not enable systematic counting of the number of potholes that is a metric used to assess severity.

To address the limitations of the above method, an automated video-based pothole detection method was presented by Koch and Brilakis (2011b). In this method, a pothole is recognized over a sequence of frames that facilitate calculating the total number of potholes. Additionally, representative healthy pavement texture is progressively generated over the sequence of video frames. The experimental results

from this method indicate 75% precision and 84% recall in recognition, wherein the precision is the ratio of correctly detected potholes to the number of detected potholes and recall is the ratio of correctly detected potholes to the actual number of potholes. To further improve the automated video-based pothole detection performance and provide the required measurements (width, depth, and number) for severity assessment, the results of the 2D vision-based pothole detection are combined with 3D reconstruction based on the videos from a single camera.

METHODOLOGY

Figure 1 shows the process and data of the proposed method. Videos recorded by a High Definition camera are used initially to detect potholes in videos. Simultaneously, the same video is used for an initial sparse 3D reconstruction. Based on the results of 2D detection and 3D sparse reconstruction the existence of potholes is verified to reduce the number of areas wrongly identified as potholes. Next, the outcome of the sparse 3D reconstruction is improved using a dense reconstruction algorithm. The dense 3D point cloud model and the results generated from the 2D appearance-based recognition are fused to measure the geometrical properties of the potholes and assess their severity.

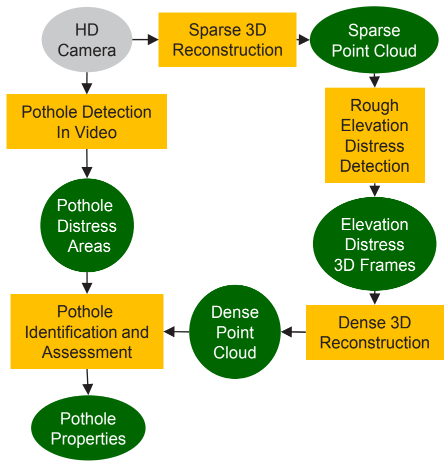


Figure 1. Proposed Methodology

2D Recognition of Potholes from the Video Streams: This step in our methodology builds upon the previous work of Koch and Brilakis (2011a and b). First, the potholes are recognized as bowl-shaped depressions that have a darker surrounding border (low intensity). The inner texture of a pothole is coarser and grainier as compared to the surrounding healthy pavement. Using these properties of a pothole and intensity histogram, shape-based thresholding, based on triangle algorithm (Zack et al. 1977), the image is segmented into distress and non-distress areas. Using the low intensity (darker shadow) regions of a pothole, the skeleton of the shadow is calculated. Then an ellipse shape is approximated using geometrical properties of the skeleton. To differentiate between stains/shadows on the road and potholes, the texture inside the pothole is compared with our training dataset that includes healthy pavement texture obtained from several frames in the video. Once a pothole is identified, it is tracked using a kernel based tracking method proposed by Ross et al. (2008) until it leaves the view. Pothole detection is suspended while a pothole is tracked. Once a pothole leaves the view, pothole detection is reinitiated.

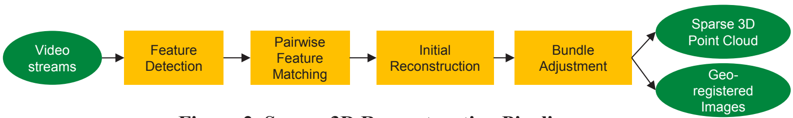


Figure 2. Sparse 3D Reconstruction Pipeline

3D Sparse Reconstruction of the Potholes: This step in our methodology builds upon the previous work of Golparvar-Fard et al. (2009) (Figure 2). First, a video stream is broken down into a number of consecutive frames. Next, these frames are analyzed independently to find a series of distinct and scale-invariant feature points. In our work, we modified the existing SIFT algorithm in Golparvar-Fard et al. (2009) with SIFTGPU algorithm (Wu 2007) for rapid feature detection. Once the features are detected, there are matched in a pairwise fashion. Among all matches, a pair, which has a minimum of 200 matches and for which the ratio of percentage of inliers with respect to Homography to the percentage of inliers with respect to Fundamental Matrix is minimal, is selected and this pair is used for initial reconstruction. Finally more frames are added to the bundle adjustment stage and the position of the points, and the cameras configurations are optimized accordingly. The outcome of this 3D sparse reconstruction pipeline is a sparse 3D point cloud along with location and orientation of the images in the scene.

3D Dense Reconstruction and Mesh Modeling of the Potholes: The outputs of the sparse reconstruction are fed into the dense 3D point cloud reconstruction of Golparvar-Fard et al. (2012) to generate dense 3D point cloud models (Figure 3). Next, using the Poisson surface reconstruction approach (Kazhdan et al. 2006), colored mesh models are created. The resulting mesh models can enable automated detection and measurement of the depth within the reconstruction surface.

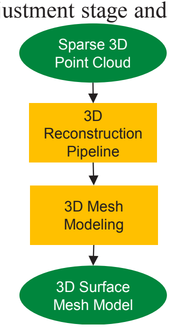


Figure 3. 3D Mesh Modeling Pipeline

EXPERIMENTAL RESULTS

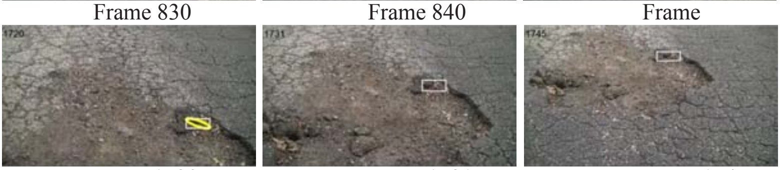
In our work, the main idea is to use monocular cameras for the purpose of surface data collection. In the U.S., the Cameron Gulbransen Kids Transportation Safety Act of 2007 has required all new cars to have rearview cameras by 2014 (NHTSA 2010). We benefit from the availability of these cameras on all vehicles and will use them as a sensing device for pavement monitoring and assessment. In our experiments, a Canon Vixia HD camera was used for data collection at approximately 20*fps* at approximately 20*mph*. Figure 4 shows how the camera was mounted on a car at an approximate location and orientation of a backup camera. Using this camera, a few series of video streams were collected from a road, which had multiple potholes on its surface. Prior to the experiments, the camera was internally calibrated to initiate an approximate estimation for the focal length of the camera. This calibration only needs to be done once for each camera. An approximate value for the focal length helps with a better initialization of the 3D sparse reconstruction pipelines and

minimizes the chances of the bundle adjustment optimization step to converge to local minima.

Pothole 2D Recognition and 3D Reconstruction – Several experiments were conducted using the video streams collected from the mounted camera were placed into our 2D recognition and reconstruction systems. Figure 5 shows detection results from video based pothole recognition.

Figure 4. Camera mounted on vehicle

Frame 830 Frame 840 Frame



Frame 1720 Frame 1731 Frame 1745

Figure 5. 2D pothole recognition. Left-most column shows detection and the other two columns show subsequent tracking

Figure 6a shows the outcome of the sparse 3D reconstruction for the pothole detected in frames 1720 to 1745 of figure 5. In this figure, 6b shows the outcome of the dense 3D point cloud reconstruction, while 6c and 6d are the Poisson mesh model and the textured Poisson mesh model. In this case, 77 1440×810px frames were used to generate these point clouds model. The sparse and the dense point cloud have a total of 166,134 and 726,538 points and the mesh model contains 86,791 vertices. The generated mesh model was used to measure the geometry of the pothole. As observed in Figure 6e, the depth of the pothole was 0.12*m*, and the width (Figure 6f) was 1.06*m*. Figure 7 shows another pothole detected using 77 1440×810px frames. Table 1 shows the results of the 2D pothole detection that are verified using the outcome of the 3D mesh modeling approach. This table also presents the geometrical properties of the potholes.

CONCLUSIONS

This paper presents a new approach based on 2D recognition and 3D reconstruction for detection and measurement of potholes using a monocular camera. The preliminary experimental results show the promise of applicability of the proposed method. Future work includes real-time detection of the pothole and

assessment of the total number of frames that need to be used for 3D reconstruction. This will significantly expedite the 3D reconstruction, as only a part of the surface will need to be meshed. More experiments also need to be conducted for validation. These are part of ongoing research and the results will be presented soon.

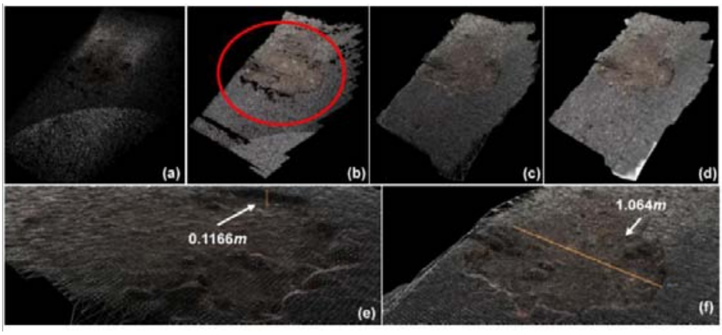


Figure 6. 3D pothole surface

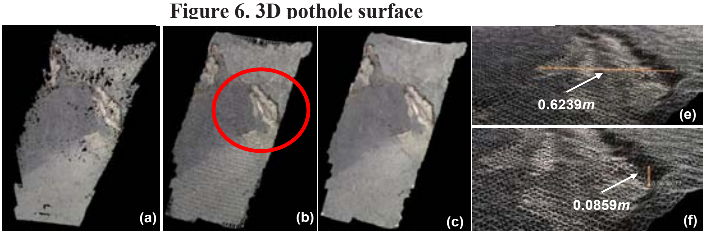


Figure 7. 3D pothole surface

Table 1. 2D recognition verified/corrected by 3D reconstruction and pothole measurement (TP- True Positive, FP- False Positive, TN- True Negative)

Pothole #	Frame #	TP or FP	Verification/ Correction by 3D reconstruction	Width (*m*)	Depth (*m*)
1	840	TP	TP	0.630	0.086
2	1720	TP	TP	1.064	0.117
3	2070	FP	TN	--	--
4	2441	FP	TN	--	--

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Assessment of a Smart Phone-Based Indoor Localization Solution for Improving Context Awareness in the Construction Industry

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ABSTRACT

Context awareness has the potential to improve various work processes in the construction industry, by automating the delivery of location specific information for a wide range of onsite information-intensive tasks, and supporting crucial management and decision making processes. Implementation of context awareness relies on an accurate and cost-efficient localization solution. Current indoor localization solutions require significant investments on hardware, and require users to carry additional beacons. This study addresses these limitations by proposing a solution that is built on the recent popularization of smart phones. The proposed solution collects the received signal strength indication (RSSI) data of all detectable WiFi access points (APs) in an indoor environment using the built-in WiFi sensors in smart phones. The RSSI data is compared to that of a set of known reference locations namely fingerprints, which is measured beforehand and recorded in a database. In this way, the nearness of a user with respect to each fingerprint in terms of the Euclidean distance is determined. A field test that covered three rooms and a corridor was carried out. The results showed that the solution achieved an average coordinate-level accuracy of 2.55 m and a room-level accuracy of 100%. The tests were repeated one and half months later and the results revealed the time invariance of the fingerprints, and the reliability of the solution over time.

BACKGROUND

The construction industry is highly information-intensive, which requires the generation, storage, and exchange of tremendous amount of data and involves a range of parties in the construction projects. Efficient information retrieval and delivery is therefore essential to ensure the productivity of construction workers and the quality of the construction work. Context-aware information delivery is a novel concept that has been studied in the civil engineering area in the recent decade. It is believed to have the capability of improving the construction work by providing a mechanism to determine the information relevant to a particular context (Behzadan et al. 2008). Although context-aware computing is an established area of research within computer science, its application in the construction industry is still in its infancy. Most current information delivery applications designed to support mobile construction workers

are static and are not able to take into account workers' changing context and the dynamic project conditions (Aziz et al. 2009), resulting in either overwhelming amount of or lack of information required by mobile workers. To address such need for context-awareness and enhance the search, filtering, and delivery of required information, researchers in the civil engineering area have proposed and tested several context-aware information delivery solutions. Anumba and Aziz (2006) proposed an architecture that comprised of context capture, context brokerage, and context integration, and presented three case studies. Wei and Yang (2010) brought the context-awareness to construction quality management, and argued that the efficiency of quality management could be improved by using a distributed, hierarchical, and ontology language-based context-aware service model. Cheng and Das (2011) applied context-awareness to building information exchange and update by using ontology-based standardized web services. The web services allowed the efficient delivery of partial building models to users for review and modification based on users' context.

The success of context-aware information delivery requires an effective localization solution, as context-aware applications need to know the location of the user/object to determine and provide relevant information and services. While outdoor localization need has been well satisfied by the GPS technology, indoor localization remains to be addressed, and various technologies have been assessed for this purpose, including inertial sensors, ultra wide band (UWB), radio frequency identification (RFID), and wireless sensor network (WSN). Recent development of smart phones has provided another promising avenue, with its ever-improving performances, pertaining affordability, ubiquity, portability, and power consumption (Kothari et al. 2011). The improvement in the sensory and computational capabilities is especially remarkable, as demonstrated by the integration of diverse sensors and the revolution of high performance processors. Such rapid technological development has made smart phones a valuable platform that bears significant potential to support context aware applications. This paper proposes a smart phone-based indoor localization solution that utilizes the embedded WiFi sensors in smart phones, and employs a fingerprinting algorithm for location estimation. The rest of the paper is organized as follows: the next two sections summarize related work, and present the research methodology and objectives. Test setup is described next, followed by findings and the discussion of the findings. The last section concludes the paper.

LITERATURE REVIEW

The improving sensory and computational capabilities of smart phones and their potential for supporting indoor localization have begun to attract attention. Miluzzo et al. (2008) tested the embedded localization function of iPhones without developing any new hardware or algorithm, and reported an accuracy of between 5 - 22 m in different indoor environments. Link et al. (2011) developed a system that used accelerometers and compasses in smart phones to locate users and provide them with turn-by-turn navigation services. Step detection and heading estimation were carried out and calibrated by a sequence alignment algorithm. Reported accuracy was around 10 m, and errors caused by faulty direction recognition were noticed. Zhou et

al. (2008) integrated GSM and WiFi technologies, by merging the two signal strength sources and creating a new data space. The location estimation was then done by finding the fingerprint that had the smallest Euclidean or Mahalanobis distance to the user's current location, or that maximized the Maximum Likelihood Estimator. A centimeter- level accuracy was reported. The fingerprints and user locations were limited to certain fixed points aligned along the corridor of the test bed, and both training and validation data were collected at the same time, providing no evaluation of the time invariance of the system. Martin et al. (2010) proposed to use WiFi sensors in smart phones. By collecting the signal strength of WiFi radios, they were able to generate signal fingerprints in an offline training phase, and to locate the users in an online application phase. They achieved an accuracy of up to 1.5 m. The tests were done using 25 WiFi radios on average, which was beyond what is available in most real-life scenarios. Users were also required to face the same orientation during the application phase as the way the fingerprints were collected during the training phase. Kothari et al. (2011) built a smart phone-based indoor localization system using embedded accelerometer, magnetometer, gyroscope, and WiFi sensors. Dead reckoning and fingerprinting algorithms were used. A robot was used to collect the WiFi fingerprint data. The tests done in two indoor environments both reported an accuracy of around 10 m, which had the potential for further improvement. It was also found that in the location estimation, dead reckoning using the inertial sensors played a more important role than fingerprinting using the WiFi sensor. Pei et al. (2009) proposed to locate a smart phone user by using six sensors, including GPS, Bluetooth GPS, assisted GPS, cellular network, motion and WiFi sensors. These sensors were integrated by five-layer software, and implemented in a Nokia S60 platform. Results showed that the best accuracy was around 1 m using the assisted GPS, while the cellular network yielded the worst accuracy, which could be up to hundreds of meters. This research required additional sensors that are expensive and unavailable in existing smart phones.

METHODOLOGY AND OBJECTIVES

Indoor localization methods using received signal strength indication (RSSI) can be generally categorized as 1) triangulation-based, which is done by mapping of the RSSI values to the distances and triangulating the target; 2) proximity-based, which is done by determining the nearness of the target to reference points in its vicinity; and 3) scene matching-based, which is done by comparing the RSSI values of the target and those of predetermined fingerprints, and finding the fingerprint that best matches the target’s location (Pradhan et al. 2009, Li and Becerik-Gerber 2011). The study, described in this paper, adapts the scene matching-based method. This method, when used in a smart phone-based localization solution, is not subject to the errors associated with the triangulation method that result from inaccurate modeling of the RSSI-distance relationship in complex in-building environments. Moreover, the scene matching method only need a few access points (APs) rather than an extensive amount of reference points as the proximity-based method does, therefore requires less infrastructure and causes less intrusion to buildings.

Using the scene matching method, the authors aim to perform an assessment of the smart phone as a mobile sensory and computational platform for the indoor localization purposes. Although WiFi-based indoor localization method has been assessed in previous research, users are required to carry WiFi beacons, and the location estimation is done in a separate platform, which requires additional data transmission, and makes self-localization difficult. A major potential drawback of the method is that fingerprints may be susceptible to changes in the environment, which may require significant maintenance efforts. In order to assess the reliability of the fingerprints and of the proposed solution, the authors partially repeated the test after one and half months.

TEST SETUP

Field tests were carried out in a campus building. The authors did a survey of the availability of existing WiFi APs in corridors of all four floors of the building. The results showed that in all surveyed locations at least 5 APs could be detected. However, about 40% of the detectable APs had RSSI values lower than -85, and were considered unstable and thus unusable for localization. The test bed was located at a corner of the building's second floor. It had an area of about 300 m^2, covering two large conference rooms, one small pantry room, and a corridor. A total of 7 WiFi APs could be detected, including 5 existing WiFi APs that had RSSI values above -85, and 2 APs that were set up specifically for the tests. A total of 13 fingerprints were collected during the training phase, and 7 target locations were randomly selected in the application phase, as illustrated in Figure 1. An iPhone 4 was used in both the training and the application phases, through an application that could report the RSSI values of all detectable WiFi APs in the environment.

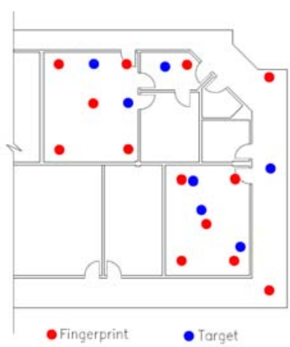

Figure 1: Test bed layout

A second test, which partially repeated the initial test, was carried out one and half months later. One of the existing APs that were used in the previous test was missing for some unknown reason, so a total of 6 APs were used. The layout in both conference rooms experienced noticeable rearrangement of furniture and equipment. The second test consisted of two parts: 3 fingerprints were re-measured, and compared with the previous measurements to investigate whether the fingerprints

remained reliable over a certain period of time; 3 target locations were re-measured, and their locations were estimated based on the new RSSI measurements and the fingerprints collected in the previous test. The purpose was to investigate whether the solution remained reliable over time without the need for updating the fingerprints, given the APs' locations kept static but one AP was missing and the environment underwent certain changes.

FINDINGS

Localization performance. KNN recognition rate is an indirect indicator of the accuracy achievable by the solution. For a certain *k* value, a higher recognition rate suggests that more nearest neighbors of targets' locations can be recognized, which is expected to result in a higher accuracy. Figure 2 shows the KNN recognition rate. It can be seen that the KNN recognition rate varies between 70% and 80%, and it gradually increases when the *k* value increases. The fact that the majority of the KNN were recognized in the test indicates that increasing the density of the fingerprints positively impact the localization accuracy, as the KNN of a target location will form a smaller polygon that encompasses the target location, resulting in a smaller maximum possible error.

It's also important to evaluate the accuracy at the room-level. The room a target's nearest fingerprint is located is considered as the room in which the target is located. The solution yielded an accuracy of 100% at the room-level.

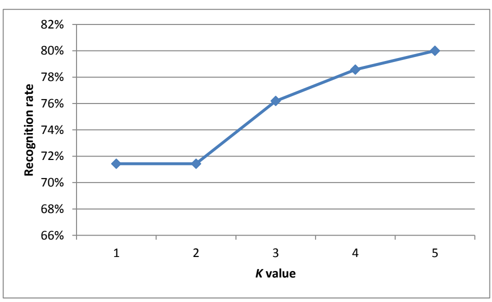

Figure 2: KNN recognition rate

Table 1 presents the accuracy of each target's location for different *k* values. The results show that for all k values, an accuracy of higher than 3 m could be achieved. The average accuracy for all target locations and all *k* values was 2.55 m. *K*=2 or *k*=3 yielded the highest accuracy in the test. Using small or large *k* values (*k*=1 or *k*=5) yielded lower accuracy than using median *k* values (k=2-4), which is consistent with the results reported in (Li et al. 2011).

Reliability of the fingerprints and time invariance of the solution. Three fingerprints were re-measured in the second test and compared with the corresponding fingerprints collected in the initial test. As there were 6 readings per

Table 1: Accuracy of each target for different *k* values

Target #	*k*=1 (m)	*k*=2 (m)	*k*=3 (m)	*k*=4 (m)	*k*=5 (m)	Average (m)
1	1.24	0.83	4.35	4.84	4.93	3.24
2	2.89	4.21	1.59	1.84	2.59	2.62
3	2.20	1.43	2.21	2.18	2.90	2.19
4	8.05	4.38	0.73	2.07	2.22	3.49
5	1.00	0.72	2.33	2.95	3.94	2.19
6	1.94	2.75	3.39	2.17	1.01	2.25
7	3.24	1.57	1.31	1.21	2.10	1.89
Average	2.94	2.27	2.27	2.47	2.81	2.55

location corresponding to 6 WiFi APs, there were a total of 18 readings. A paired t-test result shows that the probability of the null hypothesis, i.e. the fingerprints remained statistically reliable over the one and a half month, being true is 74.78%. Based on the assessment of the re-measurements of the sample fingerprints, it can be concluded that the fingerprints generally remained reliable over time, even though the environment had changes.

The RSSI values at target locations 2, 4, and 7 were re-measured, and their locations were estimated using the fingerprints collected in the previous test. The results are shown in Table 2. As the second test used fewer WiFi APs, in order to perform an apple-to-apple comparison, the estimation of these re-measured target locations in the previous test was repeated after removing the RSSI values associated with the missing AP, as shown in Table 3.

Comparing the results in Tables 1 and 3, it can be concluded that the average accuracy of target location 2 under all *k* values remained the same, while that of target locations 4 and 7 decreased by 24.5% and 7.0%, respectively. The overall accuracy of the three target locations decreased from 2.55 m to 3.00 m.

On the other hand, comparing the results in Tables 2 and 3 shows the average accuracy of target location 2 under all *k* values decreased by 27.5% in the second test, while that of target location 7 increased by 44.2%. Target location 4 had almost the same accuracy. In general, the accuracy of the three target locations was consistent between the first and second tests, with a slight increase from 3.00 m to 2.97 m.

One indication that can be inferred from the results is that using more WiFi APs will improve the accuracy. This is due to the fact that more WiFi APs will increase the number of dimensions of the RSSI value vector, and enrich the data that is used to identify the nearest neighbors of the target location. The proposed solution demonstrated some reliability over time and yielded consistent accuracies in two tests. Unless the locations of APs change, a set of fingerprints can be continuously used to support the proposed indoor localization solution.

DISCUSSIONS AND CONCLUSIOINS

The proposed solution could locate indoor smart phone users at an accuracy of within 5 m in 97.1% of the time with an average accuracy of 2.55 m. Room-level accuracy was 100%. This indicates that the proposed solution has the potential to

Table 2: Accuracy of 3 target locations under different *k* values in the second test

Target #	*k*=1	*k*=2	*k*=3	*k*=4	*k*=5	Average (m)
2	3.00	4.09	3.32	2.98	3.34	3.35
4	4.56	3.00	3.50	5.83	5.25	4.43
7	0.00	1.68	1.43	1.14	1.39	1.13
Average	2.52	2.92	2.75	3.32	3.32	2.97

Table 3: Accuracy of 3 target locations under different *k* values in the first test

Target #	*k*=1	*k*=2	*k*=3	*k*=4	*k*=5	Average (m)
2	2.89	4.21	1.59	1.84	2.59	2.62
4	8.05	4.38	5.00	2.07	2.22	4.34
7	3.24	2.24	1.31	1.21	2.10	2.02
Average	4.73	3.61	2.63	1.71	2.30	3.00

provide user locations with sufficient accuracy to support a variety of context-aware applications, such as indoor navigation. Moreover, the density of fingerprints in the tests was as low as $0.058/m^2$; increasing the density is expected to further increase the accuracy, although this requires an increase in the investment. Using more APs will also contribute to an increased accuracy, as proven in the tests. In addition, the iPhone used in the tests has an embedded compass, which can provide accurate orientation information. The integration of the orientation information and the location information can enable the proposed solution to capture richer context of the users, and open up more possibilities for context-aware applications in the construction industry. Lastly, it needs to be noted that better accuracy with the scene matching methods has been reported by previous research (e.g. Zhou et al. (2008) reported an accuracy of less than 3 m). The difference between the accuracies is an indication of the nuances in built environment, such as existence of metal objects and movements of building occupants, that were not all reflected in testes done in more ideal or controlled environments.

The increasing adoption of smart phones among all populations and the increasing availability of WiFi APs in commercial and residential buildings suggest a high applicability of the proposed indoor localization solution. The solution takes advantage of smart phones' sensory and computational power, and requires only minimum investment on setting up APs and generating initial fingerprints. The applicability of the proposed solution is further improved by the finding that the fingerprints can be reliable over a certain period of time, and that the solution can remain reliable over time, as long as the locations of the APs don't change. Changes in the environment don't have considerable impact on the performance of the solution.

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Understanding the Influence of Occupant Behavior on Energy Consumption Patterns in Commercial Buildings

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ABSTRACT

Years of research have investigated factors that contribute to high-energy consumption in buildings. These efforts have primarily focused on consumption by building systems such as HVAC systems, lighting systems and appliances. Moreover, research efforts using simulation tools have been directed at influence of occupant behavior and how occupants interact with building systems and other energy consuming devices. Simulation tools can be rigid in depicting occupant behavior and therefore continued research to understand diversity and complexity of occupant behavior and appliance interaction is required. This research, examines occupant behavior in an office environment by sensing their daily activities and their interactions with energy consuming devices. Visual observation is used to detect occupant activities while non-intrusive appliance load monitoring is used for energy monitoring. Results from a five-week long period tracking daily activities of occupants of an office building and their energy consumption patterns are presented. This research has identified and tracked five commonly used office appliances and how they contribute to energy consumption. The objective of this study is to leverage the correlation between consumption and occupant usage data to create occupant awareness of how much energy they waste. The results of this study show that even though occupants seemed oblivious, turning off appliances when not in use can realize 38% energy savings. In addition, findings of this study indicate that there is a need for energy awareness and literacy campaigns to positively modify occupant behavior as a way to reduce energy consumption.

INTRODUCTION

Buildings account for approximately 40% of the total energy used in the United States (EIA 2009), and about 2 to 20% of it is wasted through inefficient appliances consuming energy without performing their principal function, a concept known as "electricity leakage (Chakraborty and Pfaelzer 2011). Although heating, ventilation and air conditioning (HVAC), and lighting systems account for 29% and 27% of commercial building's energy consumption (EIA 2009) respectively, ubiquity of office equipment and other appliances like PCs, network equipment, servers, to name a few, are increasingly becoming a major player in energy consumption (Agarwal et al. 2009).Computers by themselves consume 3% of the total energy used in commercial buildings (EIA 2009). Research efforts have also been dedicated to

understanding the influence of occupant behavior and their interaction with appliances using simulation tools (Hoes et al. 2009). However, continued research can be pivotal in minimizing the rigidity of simulation tools in modeling diversity and complexity of occupant behavior. To reduce energy consumption of appliances, a study (Kim 2009) proposed using operating systems that support power management such as stand by modes. In addition, power meters are used to provide a basic audit of appliance consumption. These power meters accumulate or average power readings, which can be displayed as volts, current, apparent instantaneous power, actual power, and power factor over a period of time. Unfortunately, most conventional power meters cannot establish usage patterns since they are not designed to disaggregate energy consumption by end use (McLauchlan and Bessis 2011). Though newer versions of power meters can disaggregate energy consumption, however, they are relatively expensive (Darby 2006).

On the other hand, there is a growing interest to make occupants aware of their energy consumption, for example buildings - fitted with smart meters to provide real-time access to power readings (McLauchlan and Bessis 2011) . Previous research (Hart 1989; Jin et al. 2011) have explored non-intrusive load monitoring (NILM) to achieve a building's power decomposition down to equipment level. Power decomposition at appliance level is used to extract appliance signatures. As shown in these studies (Hart 1989; Jin et al. 2011), signatures can provide measurable parameters of the total load, which can provide useful information about the operating state of individual appliances. With its potential, correlating occupant activities with consumption patterns can enrich the current NILM approaches.

In this research, appliance electricity loads are monitored and then linked with occupant activities extracted from visual observations. The objective of this study is to leverage the correlation between consumption and occupant usage data to create occupant awareness of how much energy they waste. The end goal is to inspire occupants to be more energy efficient, by providing access to their energy usage data. In the reviewed literature, occupant activities are deduced based on a database of signatures collected over the load-monitoring period. If deduction of occupant activities is not translated correctly, the generated results can be misleading and also might result in high computational costs (Berges et al. 2008). To minimize the challenges of deduction, and questionnaire discrepancies, this research used visual observations to track and link occupant activities to monitored electricity loads. This research examined occupant behaviors in an office environment by observing their daily activities and their interactions with their energy consuming devices. By tracking occupants' daily activities in an office building and their energy consumption patterns, the most significant contributors to variability in energy consumption trends were identified. Appliance profiling was achieved by automating electricity capture to produce unique power signatures and occurrence patterns of power loads and is presented in the following section.

RELATED WORK

Hart et al.(Hart 1989) explored NILM to monitor electricity consumption in buildings by experimenting with appliances, which switch on and off independently.

The essential steps for an automated capture and naming of appliance signatures was introduced by Hart et al. (Hart 1989) and since then other pattern recognition techniques that provide the best match with the measured signal, have emerged. A recent study (Berges et al. 2008) sought to improve NILM further through development and simplification of techniques and algorithms, which comprise of feature extraction, event detection, and pattern recognition. Appliance signature acquisition has enabled the emergence of calibration free systems. For example, Lisovich et al. (Lisovich et al. 2010) show how to extrapolate activity information from power-consumption data. Tzeng et al. (Tzeng et al. 1995) utilizes statistical methods to derive appliances' usage patterns from electricity readings. These studies (Lisovich et al. 2010; Tzeng et al. 1995) point out challenges of developing a NILM that can disaggregate power intelligently without a priori determined appliance signatures and matching these signatures to occupant activities. Another challenge that may be more dominant in residential than commercial buildings is access to power flow. In commercial buildings research teams can partner with facilities management to gain access whereas in residential buildings research teams need to get a buy in from individual residential occupants. Hart et.al have (Hart 1989) demonstrated that the nature or operating state of individual appliances can be learned from signatures, which are quantifiable indicators of energy loads. Though learning from these signatures can provide clues of appliance usage, this paper adds the occupant dimension by invoking daily activities in commercial buildings. Visual observation can accurately detect occupant activities without the computational costs and steep learning curves associated with inference approaches.

TEST BED DESCRIPTION

Load monitoring becomes more meaningful if it is paired with real time occupant activities that contribute to the consumption footprint. Different kinds of activities occur in office buildings on a daily basis. Some examples of daily office activities that involve interactions with electrical equipment and therefore may impact electricity consumption are printing, faxing, charging cell phones, use of reading desk lamps, and using computers. With visual observations, recorded occupant activities and monitored electricity expenditure can be used to extract patterns of appliance use. These patterns are useful in correlating occupant activities to their impact on the total building electricity consumption. This paper used visual observations, to track and record activities of office occupants, while energy consumption by desktop computers, laptops and printers was monitored continuously.

Setup. The experiments were carried out in an office space (shown in Figure 1) with 5 occupants for 5 days a week and 9 hours a day. Desktop computers usage was tracked in five workstations marked with letters A to E. The experiment was designed as a five-stepped-process, namely hardware configuration, sketch upload, calibration, data capture and visual observation.

Hardware Configuration. Load monitoring was carried out using a load monitoring apparatus consisting of a breadboard, an Arduino microcontroller, voltage and current sensors as shown in figure 2. The load monitoring setup was assembled to measure

voltage by an AC-AC power adapter and to measure current by a clip attached on the current transformer (CT) sensor.

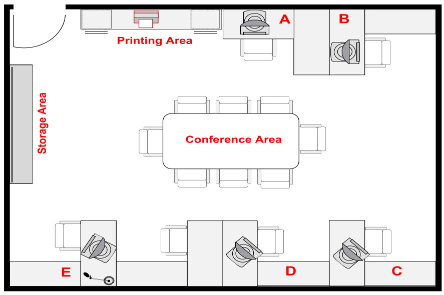

Figure 1: Office Layout

Arduino Sketch Upload. An Arduino sketch, an open source piece of code compatible with Arduino microcontrollers, was uploaded to the load monitoring apparatus. The Arduino sketch converts the raw data from its analog input into values and then outputs them to a serial monitor. The energy monitoring system was configured to calculate real power, apparent power, power factor, root mean square voltage (Vrms) and root mean square current (Irms). All calculations were done in the digital interface of Arduino sketch, connected to a computer and data logger to make use of the data. The output signal from the CT sensor was conditioned to an analog input signal between 0-5v, which is the base voltage for an Arduino microcontroller.

Calibration. In order to get accurate measurements, the load monitoring apparatus was calibrated using an off the shelf wattmeter. Calibration was done through a two-step process; power factor calibration and voltage and current calibration. Power factor calibration normalizes phase displacements from the CT sensor, power adapter and multiplexed ADC readings. The voltage and current calibration was done to reflect domestic plug meters. Arduino software takes advantage of phase calibration and digital high pass filter to eliminate potential offsets that may negatively impact the results.

Load Monitoring and Data Capture. The load monitoring required extracting signatures of appliances used by office occupants. All appliances were pretested using an off the shelf wattmeter to establish their typical energy signatures. Once these signatures were derived, the next step was to monitor usage patterns and extract signatures of different types appliances in use. For data collection, occupant workstations were instrumented with a prototype system assembled from various off the shelf components, which together logged appliance power consumption every second. Figure 2 graphically depicts a simple energy load monitoring apparatus that was used to measure electrical energy usage.

For analysis purposes, data was downloaded and saved into a repository every one hour of monitoring. Each entry in the serial monitor data log from left to right shows real power, apparent power, power factor, Vrms and Irms as shown in figure 2.

This data was logged every second, which helped to detect finer patterns that may not possible with conventional hardware and software methods.

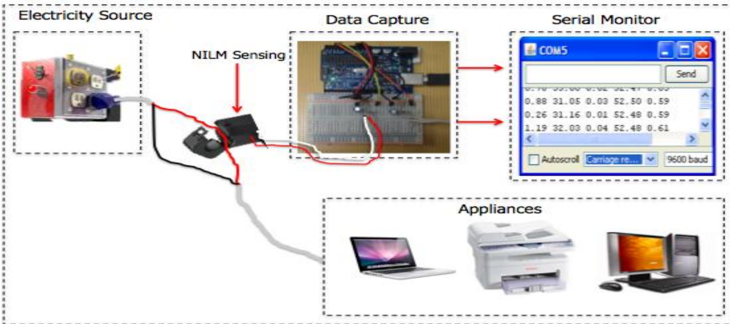

Figure 2:Load Monitoring Apparatus

Visual Observations. Visual observations were employed since it can produce detailed physical activities of occupants at workstations A, B, C, D & E which can then be used to identify, compare and contrast with data obtained by the load monitoring apparatus. Occupants were covertly observed for 1 week to establish their general schedules. Afterwards their use of office appliances was monitored for 2 weeks. The typical occupant appliance usage activities observed were use of desktop computers, computer monitors, laptops, and printers.

Table 1: Occupants' Observation

Appliance	State	Usage	Energy load (Kwhr)	Cost (US $) @ $0.25/Kwhr	Workstation A	B	C	D	E
Desktop computer	Active	24%	51.8	12.95	√	√	√	√	√
	Stand by	76%	(82.8)	(20.60)					
	Off	0%	0.00	0.00					
Computer monitor	Active	24%	8.42	2.11	√	√	√	√	√
	Stand by	76%	(15.4)	(3.85)					
	Off	0%	0.00	0.00					
Laptop	Active	32%	4.67	1.17	√	X	X	√	√
	Stand by	67%	(6.51)	(1.63)					
	Off	1%	0.10	(0.03)					
Printer	Active	13%	24.6	6.15	Shared by all 5 occupants				
	Stand by	87%	(164.7)	(41.17)					
	Off	0%	0.00	0.00					
Legend: √-Available at workstation X- Unavailable at workstation									

Single user appliances accessible to all occupants, specifically desktop computers, were used for associating occupant activities with energy consumption. Desktop computers were used for comparison purposes; because they were available at each workstation and are known to have low event generation rate and predictable states of energy loads i.e. active, stand by and off. The main variable was the influence of occupant activity on operating schedule of energy loads. Table 1 represents average usage of desktop computers, computer monitors, printer and laptops. The numerals shown in parenthesis represent potential savings that could

have been realized over the monitoring period if the occupants shut off appliances when not in use.

RESULTS AND DISCUSSION

The data was processed to extract features of energy loads. These features indicate physical states of appliances, for example, active, stand by or off. From the data, transient behavior (change from one state to another) and steady-state durations (equilibrium) were observed as shown in figure 3. As shown in table 1, with exception of laptops, which were turned off 1% of the overall monitoring period, all other monitored appliances remained on even when not in use.

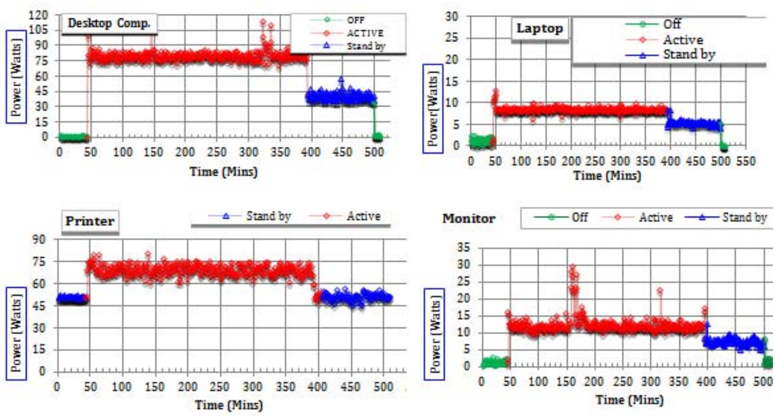

Figure 3: Appliance signatures

Due to the space limitations, this paper only focuses on the use of desktop computers. Transient events enable identification of occupant interaction with desktop computer and therefore allow matching of occupant activity and energy loads with appliance state. The processed data was tagged to represent both the appliance type and power events as indicators of occupant activities. After tagging, these patterns are then mapped to the occupant activities detected using visual observations. To determine the operating schedules of individual appliances, instances of change in power measurements from one steady state to another where compared with visual observations. All occupants kept their computers running when using laptops or even when not at the workstation. As shown in table 1, desktop computers at all workstations averaged 76% and 24% stand by and active, respectively. As shown in figure 4, workstation C had the highest stand by time, 30% followed by workstation E. Workstation D had the lowest stand by time while workstation, A and B had 8% each of standby time. As observed in figure 4, a desktop computer in stand by state consumes almost 50% of energy consumed when in active mode. From the results, about 38% of energy could have been saved if occupants turned off their computers

when not in use. In addition to energy wasted from computer use, other appliances such as printer and laptops contribute to energy saving when not in use.

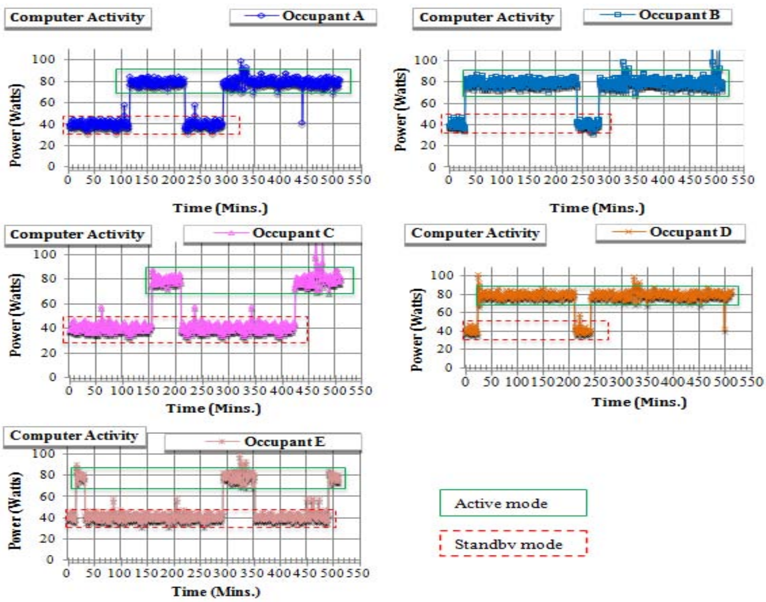

Figure 4: Comparison of occupants' desktop computer use.

CONCLUSION AND FUTURE WORK

This paper used a combination of NILM and visual observations to extract extra features, which were then correlated with occupant activities to identify energy consumption and potential waste. Using an Arduino prototype board, appliance signatures were extracted such as real power, power factor Vrms and Irms. Both active and stand by modes of appliances were computed for energy consumption calculations. Based on the findings, it is evident occupants were not usually aware of how much energy can be saved they turned off or completely unplug appliances from power sources. Secondly, providing occupants with info on their energy consumption patterns at fine granular levels has a potential of reducing energy through behavior modification. The next step is to develop a sensor base actuator agent to send requests to occupants for behavior modification as a way to reduce energy consumption.

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Using Wearable Physiological Status Monitors for Analyzing the Physical Strain – Productivity Relationship for Construction Tasks

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ABSTRACT

Anecdotal evidence suggests that physical strain may negatively affect workforce productivity and safety performance. Thus, an effective management of construction workforce physical strain could be very beneficial in improving construction productivity and safety. However, clear relationships between physical strain, safety, and productivity have yet to be established because of limitations in data collection procedures and technologies. This research has utilized recent innovations in sensing and communication technology to investigate the physical strain vs. productivity relationship. Data collected by physiological status monitors were analyzed through regression analysis that adopted heart rate as predictor of physical strain. Productivity and heart rate data of seven subjects performing a four-hour, simulated construction task were collected. The analysis showed that heart rate is a significant predictor with a strong parabolic relationship with productivity. Therefore, this research provided evidence of the physical strain vs. productivity relationship and, for the first time, proposed a mathematical formulation of such a relationship.

INTRODUCTION

The importance of effective productivity and safety management on the construction site has been widely recognized as one of the key parameters for construction project success. In fact, workforce productivity is a major aspect in determining whether a construction project can be accomplished on time and within budget (Ghanem & AbdelRazig, 2006; Jenkins & Orth, 2004). Moreover, accidents and fatalities greatly affect the construction workforce and industry at large (e.g., workers can be killed or be severely injured; activities are disrupted; workers' morale can be seriously affected; extra costs are generated; insurance premiums may increase; and, adverse publicity can damage companies' reputation) (Coble, Haupt, & Hinze, 2000). Nevertheless, construction productivity and safety are still compelling

challenges for today's construction industry. As cited by Brilakis et al. (2011), estimates suggest that industry-level construction productivity is declining (Allen, 1985; Allmon, Borcherding, & Goodrum, 2000; Dyer & Goodrum, 2009; Gu & Ho, 2000; Harrison, 2007; A. L. Huang, Chapman, & Butry, 2009; Jorgenson, Ho, & Stiroh, 2005; Stoke, 1981). Moreover, although the construction industry's safety performance has been improving in the last decades, the construction industry is still lagging behind other private industries Huang & Hinze (2006).

According to the literature (Abdelhamid & Everett, 1999, 2002; P. Astrand, Rodahl, Dahl, & Stromme, 2003; Bouchard & Trudeau, 2008; Brouha, 1967; Edwards, 1972; Garet et al., 2005; Nechaev, 2001; Oglesby, Parker, & Howell, 1989), there is anecdotal evidence suggesting that work performance and Physical Strain (PS) are related. It is generally assumed that excessive PS may negatively affect productivity and safety performance due to a decrease in motivation and capacity to perform muscular work, and to an increase in unsafe behavior occurrence.

Construction operations comprise numerous ergonomic hazards and physically taxing activities, such as heavy lifting and carrying, forceful exertions, pushing and pulling, sudden loadings, repetitive motions, vibrations, and awkward work postures (Damlunda, Gøtha, Haslea, & Munka, 1986; Hartmann & Fleischer, 2005; Koningsveld & van der Molen, 1997; Schneider & Susi, 1994). Further, construction activities are generally outdoors activities often performed in severe environments. Thus, an effective management of construction workforce PS could be very beneficial in enhancing construction productivity and safety. However, no clear relations have been determined between PS, safety, and productivity (Abdelhamid & Everett, 1999). In fact, the classifications of work severity generally adopted (Andersen, Masironi, Rutenfranz, & Seliger, 1978; P. Astrand et al., 2003; Brouha, 1967) determine the level of work severity (e.g., light work, moderate work, and heavy work) in relation to physiological parameters (e.g., heart rate and/or oxygen consumption) without giving further details on worker performance.

Continuous monitoring of construction workforce has been limited to observations. However, continuous advances in information, communication, and computational technologies can be used for improving safety and productivity performance of the construction industry. While these technologies have entered in almost every aspect of people's life, they lack a similar level of penetration in certain industry sectors. Above all, the construction industry is one that is characterized as conservative. This industry has been historically plagued by a below average productivity, a lack of skilled workforce, and an improving – but still disturbing – safety record. Demonstrating that cyber-technologies are able to study and, eventually, increase productivity and improve safety performance will suggest paths to recovery for this industry that has been hit especially hard by the recession.

Hence, the aim of this paper is to utilize commercially-available physiological status monitors to investigate the PS – productivity relationship by analyzing the physiological and productivity data of seven subjects performing a simulated construction task. Initially, the experimental design is presented with the collected data. Then, the data are used to generate several regression models to investigate the nature of the relationship between the independent variable PS and the dependent variable productivity. Finally, conclusions are drawn.

MATERIALS AND METHODS

Participants. The participants of the study were seven apparently healthy volunteers (three males and four females; age 20.3±1.25 yr.; height 1.70±0.09 m; mass 65.8±7.70 kg) with limited or no experience in material handling and/or construction activities. All participants provided a written informed consent and were informed about the potential risks of the study. Further, the subjects completed a physical activity questionnaire (adapted from the PAR-Q) and a health history questionnaire to verify that it was safe for them to perform moderate physical activity. Thus, subjects with a history of cardiovascular disease (e.g., cardiac surgery, angina during exertion, hypertension induced by exercise) were excluded from this study. The University of Washington Institutional Review Board granted permission to perform the study.
Experimental Design

Construction task and working conditions. The simulated construction task selected for the experiments was assembling a modular raised deck consisting of concrete panels (20×41×5 cm; 7 kg) and plastic supports. A two-step assembling procedure (i.e., 1-place the supports and 2-place the panels) was designed to have an extremely short learning curve and to be easily performed by subjects with little or no experience in construction activities. Participants worked for four hours having working periods of 52 min with a central pause of 16 min. Participants were allowed to drink as much water as they needed. However, they could eat only during the central pause (i.e., 16 min).

Productivity assessment. A video camera was implemented to record the experiments and assess productivity. In particular, productivity was defined as unit of completed work over labor period. The unit of completed work was a row of three panels and four supports. The labor period was the time (in minutes) necessary to accomplish the unit of completed work. The time spent by subjects in activities not related to the simulated task (e.g., fasten toe-guards) was not counted as labor period.

PS Assessment. Heart Rate (HR) has been successfully used and validated as parameter to assess PS (Ainslie, Reilly, & Westerterp, 2003; Kirk & Sullman, 2001; Muller, 1950) in numerous laboratory and fields studies dealing with different occupations, such as construction workers (Abdelhamid & Everett, 1999, 2002; I. Astrand, 1967; Turpin-Legendre & Meyer, 2003) and manufacturing workers (Kang, Woo, & Shin, 2007; Myrtek, Fichtler, Strittmatter, & Brügner, 1999). Nevertheless, various factors can either affect HR without influencing PS or influence HR and PS regardless of the level of workload, such as environmental conditions, health conditions (e.g., illnesses); emotional/mental activity or stress; hydration; digestion; stimulant substances (e.g., coffee); and, depressive substances. Thus, the following procedures were implemented to control and minimize the influence of these factors:

- Environmental Conditions. The environmental conditions were kept stable during the experiments.
- Health Conditions. The health history questionnaire filled out by participants allowed for selecting subjects that did not present pathologies capable of affecting

the heart activity. Further, participants were instructed to not take any over-the-counter medicines within two hours prior the experiment;

- Emotional Activity. The working conditions and subject preparation procedures were designed to reduce any mental stress;
- Hydration. Water was provided and participants were allowed to drink as much water as they needed; and,
- Digestion, Stimulant, and Depressive Substances. Participants were instructed to not assume any stimulant or depressive substances, or food within two hours prior the experiment. Further, the food available at the laboratory was easy to digest.

Given that previous factors' influence on HR was controlled and minimized, HR was implemented as unique index of PS. Thus, the physical status monitor BioHarness BT (BH-BT; Zephyr Technology Corporation, Annapolis, MD) was implemented to monitor HR and, therefore, assess PS.

Subject Preparation. Experimental guidelines (e.g., do not drink energy drinks within two hours prior the experiment) were sent to each subject the day before the experiment. Upon arriving at the laboratory, participants were asked to wear BH-BT for HR monitoring. According to the manufacturer's instructions, BH-BT chest belt was placed just below the chest muscles after moistening the skin electrodes. Participants were then instructed on how to operate BH-BT; wear and use the implemented PPE (i.e., gloves, toe guards, kneepads, hard hat, and safety glasses); and, handle material to avoid back injuries. Finally, the raised deck assembling procedure was described and working schedule and conditions explained. Moreover, a trained lab assistant assisted the subjects at the beginning of the experiments to correct any major error in performing the assembling procedure and, therefore, to minimize the learning curve.

COLLECTED DATA

All participants accomplished the testing procedure with no adverse events. The HR data of subject 7 could not be saved due to a system crash. Hence, the subject was excluded from any analysis. Table 1 presents the actual durations of working periods and pauses for each subject. Productivity and HR summary statistics are shown in Table 2 and
Table 3.

Table 1: Actual duration of Working Periods (WP) and pauses.

Subject	WP1	Pause	WP2	Pause	WP3	Pause	WP4
1	53' 54"[1]	6' 19"	50' 27"	18' 21"	42' 35"	18' 43"	45' 24"
2	31' 20"[2]	6' 43"	47' 23"	19' 23"	47' 20"	8' 56"	50' 57"
3	51' 14"	30' 13"[3]	27' 53"[3]	20' 36"	47' 26"	9' 12"	51' 5"
4	50' 1"	12' 6"	43' 34"	16' 17"	29' 11"[4]	29' 36"	21' 14"[4]
5	49' 1"	8' 33"	52' 33"	17' 22"	36' 43"[5]	9' 51"	61''38"
6	52' 28"	7' 48"	51' 52"	18' 35"	51' 37"	7' 34"	44' 11"

[1] BH-BT malfunctioned not allowing the collection of meaningful physiological data for WP1; [2] BH-BT malfunctioned in the initial part of WP1; [3] the video recording covers only the last 28 min of WP 2; [4] the subject reached critical PS and could not

keep on working even after taking long pauses; and, [5] the subject needed to go the restroom before the end of WP3.

REGRESSION MODELS

Several regression models were generated to investigate the nature of the relationship between the independent variable PS and the dependent variable Productivity (P). The procedure followed to generate and analyze the model is presented in the following sections.

Signal processing. HR and P were measured with different reporting intervals. In particular, the reporting interval for P was not constant since it was equal to the time spent to complete a unit of completed work, while HR reporting interval was 1 sec. Thus, P was re-sampled on 1 sec epochs. Nevertheless, it was impractical to perform the regression analysis on the data sampled on 1 sec intervals. In fact, HR is generally meaningless as index of PS when considered on such short intervals. Therefore, the data were averaged on Time Intervals (TIs) in order of magnitude of minutes to be significant. To the best of the authors' knowledge, there are not similar studies that can be referenced to establish a suitable time interval. Thus, the variables were averaged on eight TIs (i.e., 5, 10, 15, 20, 25, 30, 35, and 40 min).

Table 2: Productivity (panels/min) Summary Statistics.

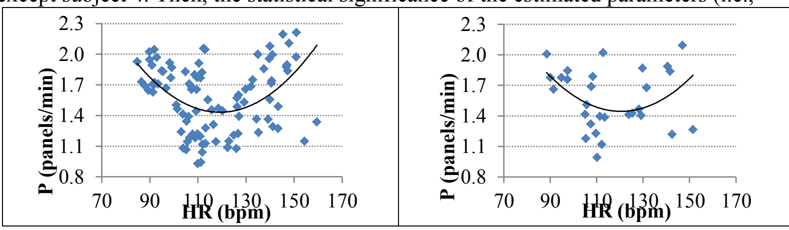
Subject	*1*	*2*	*3*	*4*	*5*	*6*
Average	1.76	1.34	1.98	1.24	1.73	1.36
Minimum	1.42	0.78	1.24	0.59	1.13	0.86
1st Quartile	1.62	1.09	1.80	0.88	1.51	1.16
Median	1.73	1.35	1.94	1.35	1.70	1.38
3rd Quartile	1.89	1.55	2.25	1.49	1.91	1.58
Maximum	2.77	2.43	2.77	1.88	3.00	2.17

Table 3: HR (beats per minute) Summary Statistics.

Subject	*1*	*2*	*3*	*4*	*5*	*6*
Average	93.0	125.4	141.2	144.8	137.8	107.0
Minimum	71	82	86	87	88	68
1st Quartile	89	121	137	136	132	101
Median	93	126	142	147	139	107
3rd Quartile	97	130	149	155	146	113
Maximum	108	146	163	173	165	139

Visual analysis. A visual analysis of the scatter plots P vs. HR for every TI was performed to determine the nature of the relationship (e.g., linear, parabolic, logarithmic) between the variables. As shown in Figure 1, it could be assumed that the relationship between P and HR is parabolic. Moreover, the collected data were analyzed to determine if the data of one or more subjects significantly deviated from the other data. According to the visual analysis, subject 4 data points significantly diverged from the parabolic relationships regression line. Subject 4 was the only subject that reached critical PS level and could not continue to perform the simulated task even after taking long pauses. Hence, it can be assumed that subject 4 data points were outliers due to the extreme fatigue she experienced during the experiment.

Analysis of the regression models. Eight regression models (i.e., one for each TI) were generated considering a parabolic P – HR relationship and all the subjects except subject 4. Then, the statistical significance of the estimated parameters (i.e.,



The black line is the proposed regression line.

Figure 1: P vs. HR for TI 15 min (left) and 40 min (right).

HR and HR^2) and the goodness of fit of the model were verified by performing an F-test for the overall fit and t-tests for the individual parameters; checking that the scatter plots of the residuals vs. each predictor and the predicted value (i.e., residual plots) resembled null plots; and, calculating the coefficient of determination (R^2) and Standard Error of Estimate (SEE). The models proved to be statistically significant and the obtained R^2 and SEE are shown in Table 4.

Table 4: R2 and SEE for each TI.

TI (min)	5	10	15	20	25	30	35	40
R^2	0.467	0.554	0.585	0.611	0.791	0.750	0.783	0.719
SEE	0.248	0.208	0.202	0.177	0.131	0.142	0.126	0.139

CONCLUSIONS

In this study, an attempt was made to determine the nature of the relationship between PS and P implementing regression analysis. In particular, HR was investigated as predictors of PS, and therefore, of P. An experimental phase involving a simulated construction task performed by human subjects was designed and the data of seven subjects were collected. Further, eight regression models were generated using the collected data. The analysis of the models confirmed that HR is a significant predictor in assessing subjects' PS and P when variables are averaged on time epochs between 25 and 40 minutes. In particular, the regression analysis showed that a parabolic relationship between HR and P could be established. The results also suggested that subjects departing from such parabolic relationship might undergo critical PS.

This initial study of the relationship between physiological parameters and construction significant success factors (i.e., productivity) suggests that the construction industry is now provided new opportunities for controlling projects and monitoring workforce safety, productivity, and wellbeing. New fabric sensing technology and wearable devices are now available for development of a Physical Demand Monitoring System (PDMS). This system could minimize physiological strain throughout the workday: HR at a given level of activity will reflect the overall strain of the work + environment and there will be a direct relationship between increased HR and reduced productivity and unsafe behaviors in the workplace. In

addition, extending beyond the results of this study, we can envision that skin temperature over the chest could be directly related to HR and also used to assess the physiological strain of the worker. This information could facilitate the development of predictive models to ensure body hydration status before and during work (from body weight changes or bioimpedance values). As a result, these systems would reduce physiological strain and improve productivity and safety. Similarly, during work in a hot environment, rehydration with fluids with low concentrations of sugar and electrolytes will result in greater fluid replacement, less physiological strain, and greater productivity and safety.

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Providing guidance for evacuation during emergency based on a real-time damage and vulnerability assessment of facilities

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ABSTRACT

Following a disaster or an emergency situation (e.g., earthquake,) in a facility, it is crucial for emergency response teams to rapidly access navigation information of the facility, its contents and the final status of the facility (e.g., damages and vulnerable locations). However, in the current practice, accessing these information items is time-consuming and the accessed information is incomplete, since there are multiple sources of information that are mostly disorganized. This study proposes a Building Information Model (BIM) based approach integrated with sensors to provide the damage and vulnerability information of the facility for efficient response and for safe evacuation of the facility. The proposed framework integrates navigation algorithms, a vulnerability assessment approach and the status information obtained from various sensors that are strategically deployed inside the facility. This framework will be used for guiding the occupants and rescue teams through safe locations in a facility during evacuation.

INTRODUCTION

When an emergency situation occurs in a facility or when a disaster (e.g., earthquake) strikes a facility, multiple parties including first responders, emergency response teams, and occupants require information about the building, such as its structure, damage condition, contents and vulnerable locations. Moreover, in many cases, disasters such as earthquakes trigger other hazardous situations in buildings (e.g., post-earthquake fires), and thus, responders and occupants need to deal with multi-hazard emergencies. Such conditions require first responders to perform rapid vulnerability assessment and evacuation in facilities. In the current practice, information about the damaged building, building content and occupancy condition is not completely available to response teams (Jones and Bukowski 2001, Evans et al. 2005, Son and Pena Mora 2006). The lack of such necessary information affect the efficiency of response

operations, and this leads to increases in the number of casualties during emergency situations (Kwan and Lee 2005, Ergen and Seyis, 2008). Therefore, there is a need for an approach that enables rapid damage and vulnerability assessment in facilities, guides occupants during evacuation and directs emergency response teams to vulnerable locations.

This study proposes a framework that utilizes Building Information Model (BIM) integrated with sensors to provide the damage and vulnerability information of a facility that is under the threat of multi-hazard emergency situations. The main goal is to efficiently guide the occupants during the evacuation of the facility and assist emergency response teams in rescue operations. In the study, the native BIM file is transformed into Industry Foundation Classes (IFC) format, from which a graph network model (GNM) is obtained by defining graph network elements in IFC. The obtained model is then integrated with the results of the vulnerability assessment along with the status information obtained from different sensors that are deployed inside the facility. The navigation algorithms run on the resulting model, calculating the safest evacuation path based on the damage and vulnerability conditions. In this paper, the proposed system framework is provided and the research challenges are discussed.

BACKGROUND RESEARCH

Effective evacuation of damaged buildings following a disaster or an emergency situation is crucial for saving more lives. However, it is difficult to effectively evacuate buildings on time since buildings might have complex indoor environments. Moreover, a primary disaster (e.g., earthquake) might trigger secondary disasters (e.g., fires) which requires first responders to contend with multi-hazard situations, and makes it even harder to evacuate buildings efficiently. To address these issues, previous studies about emergency response focused on navigation. Some of these studies developed navigation systems that are integrated with BIM and/or two or three dimensional (i.e., 2D, 3D) Geographic Information System (GIS) since indoor navigation heavily relies on the accurate representation and storage of building information (Lee 2005; Kwan and Lee 2005; Qing et al. 2006; Lee 2007; Lee and Zlatanova 2008; Ivin et al. 2008; Park and Lee 2008). Recent studies revolves around indoor navigation, rather than outdoor navigation (Meijers et al. 2005; Pu and Zlatanova 2005; Kwan and Lee 2005; Qing et al. 2006; Yuan and Zizhang 2008). By using indoor navigation approaches, alternative evacuation paths are created following emergency (Lee 2007; Lee and Zlatanova 2008; Yuan and Zizhang 2008; Park and Lee 2008; Rueppel and Stuebbe 2008).

In addition to accurate and up-to-date geometry and semantics of buildings; Yuan and Zizhang (2008) highlighted the need for information about threats and building accessibility for a successful indoor navigation. In their study, information provided by BIM is integrated with 3D GIS for determining the evacuation paths during emergency response. Another study utilized 3D GIS to obtain information related to a building for generating graph networks to be used for navigation during emergency response (Lee 2007). Other similar studies used data in IFC format for computing accessible distances for handicapped people in wheelchairs based on a length-weighted graph structure and the objects needed for creating a graph network for indoor navigation (e.g., IfcSpace, IfcDoor) are determined (Lee et al. 2008; 2010).

The previous studies do not include the information about the overall status and condition of the building following a disaster or emergency in the navigation approaches. However, it is important to consider the damaged locations and parts of the building during evacuation for the safety of occupants and the responders. Therefore, the framework proposed in this study utilizes sensors to obtain the status information of the building and integrates this information with navigation algorithms to guide the occupants and the responders during evacuation.

Another important aspect during emergency response is to perform vulnerability assessment in the damaged building and to identify vulnerable locations and contents. There are a few studies that focus on building-scale vulnerability assessments (Leite et al. 2008; 2009; Leite and Akinci 2012). Leite and Akinci (2012) presented a formalized vulnerability representation schema that is aimed to support vulnerability assessment during building emergencies with a facility management point of view. For example, it identifies which critical contents in the facility (i.e., server computers) might be affected by an emergency that is triggered by a failure in a building system (i.e., power outage). It mainly focuses on building systems failures that might directly impact a facility and its critical contents Leite and Akinci (2012). However, the study explained in this paper focuses on building emergencies that are caused by disasters (e.g., earthquakes) with an emergency management viewpoint and building system failures are not in the scope of this study. In this study, hazardous contents in buildings, their potential effects on human lives and the way that they can interfere with the evacuation process are considered.

OVERVIEW OF THE PROPOSED FRAMEWORK

In this study, vulnerability assessment is defined as the process of identifying the location of hazardous materials and determining the potential threats that are susceptible to these materials. Threats are the building contents that can have harmful effects in case of a disaster and/or can develop secondary disasters, such as explosion or fire. Vulnerable locations that contain hazardous materials and threat bearing contents have the possibility to cause injuries and mortality. The vulnerable locations that are in close proximity of occupants should be avoided during emergencies.

To describe how the proposed system works, and to explain its functions and scope in detail; a system framework is developed (Fig. 1). The proposed framework mainly composes of three steps: (1) placing nodes and edges into the IFC-based building model, (2) creating a deformed GNM of the building which includes up-to-date damage condition and vulnerability assessment results, and (3) providing shortest paths to the users. The graph network elements (i.e., nodes and edges) are created in an IFC-based building information model as a first step towards identifying evacuation paths. The different types of sensors that are deployed inside the building will provide information about the status of the building (e.g., blockage and damage status). The status information obtained from sensors and the vulnerability analysis results will be transferred to the graph network that is driven from the IFC-based building model. The resulting GNM that includes the vulnerable and damaged locations inside the building is the deformed GNM of the building. The last step is to compute the shortest evacuation paths based on the up-to-date building information and the results of

the vulnerability assessment. Following paragraphs provide the details for each step.

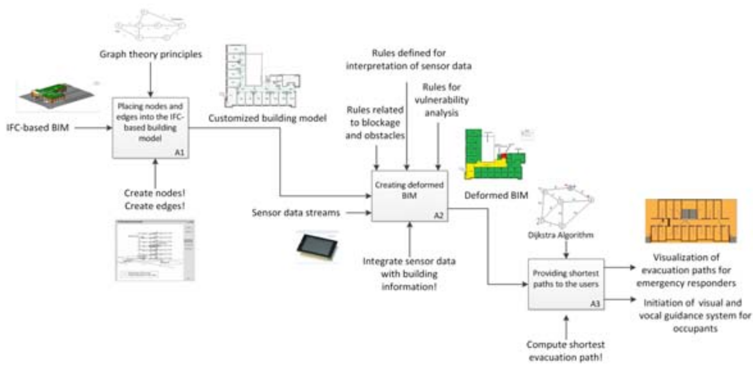

Figure 1. Proposed system framework

Step 1: Placing nodes and edges into the IFC-based building information model. In this step, the graph network will be developed using the information related to each storey in a building and other required information contained in BIM. This will be the basis for the shortest path algorithms (SPAs) which will compute the shortest paths according to the accessibility of routes inside the building.

IFC-based BIM: The proposed framework integrates the graph network driven from BIM, along with the SPA and the results of vulnerability analysis. All the information that is required to generate graph networks and to compute shortest paths (i.e., building geometry, plans and elements, storeys and spaces inside the building and their relations) will be obtained from the building information model. The building model will be created using a BIM tool (e.g., Autodesk Revit) and it will be exported to IFC format instead of working with the native format to enable interoperability. Also, IFC provides the opportunity to extend the standard to include the classes needed for creating graph networks (i.e., nodes and edges) which are not currently defined in IFC, by using programming languages (e.g., Java).

Graph theory principles: In mathematical definition, a graphic (G) is a set consisting of two finite sets called node (N) and edge (E), (i.e., G = (N, E)). While IFC standard provides information about buildings; graph network elements, nodes and edges, are not currently defined in IFC. Thus, the IFC standard needs to be extended to define the required objects, along with the attributes, methods and the relationship in between them, in accordance with the graph theory principles.

Creating nodes and edges: Graph theory elements are created by extending IFC based on the graph theory rules and principles, and the customized GNM is developed.

Customized graph network model: Customized GNM is obtained as the nodes and edges are placed into the IFC-based building model; and ready to be used as an input for the next step.

Step 2: Creating deformed graph network model. The information related to the status of the building and the accessibility of nodes and edges as well as the vulnerability information is used to determine: (1) the damage that is caused by the disaster, (2) the secondary hazards that are triggered by the disaster, and (3) the related risks. The data obtained from sensors (i.e., damage/blockage information) and the vulnerability assessment results are stored in the deformed GNM, which will be used as an input for the third and last step for computing the shortest paths.

Customized graph network model and sensor data streams: The customized GNM will be used to examine the accessibility of nodes and edges, while the sensor data will provide the status information regarding the condition of the building (i.e., damaged/blocked locations) following a disaster. The Cameras and different types of sensors (e.g., gyroscope, ultrasonic distance sensor) will be deployed on strategic locations to provide critical information on whether some building elements (e.g., columns, walls) are damaged (e.g., collapsed) or not.

Rules related to damage and blockage and rules for vulnerability analysis: The information retrieved from the sensors will be used to determine the accessibility of nodes and edges, and to understand the level of damage inside a building. There is a need for establishing some rules for combining and interpreting the information received from different types of sensors. The reason is that more than one type of sensor might be monitoring the same building element. In such case, these rules will be used to interpret the condition by considering the threshold values of each sensor, and the decision will be made based on whether the node or the building element related to the sensor is blocked/damaged or not.

Vulnerability assessment will be performed to evaluate the risks that are associated with the vulnerable building contents and the threats (e.g., fire) that a disaster (e.g., earthquake) can induce. The types of vulnerable contents that are present in the building and their locations are entered in BIM during the design phase. By using this predefined information, a vulnerability algorithm (i.e., vulnerability risk ranking) will prioritize all possible threats in accordance with the related risks, which may occur due to the vulnerabilities in the building. According to the results of the vulnerability assessment, vulnerable locations will be avoided in the shortest evacuation path calculation as much as possible. When an evacuation path must pass through one or more vulnerable location/s, this ranking approach will be used to choose in between the two vulnerabilities to create alternative evacuation paths.

Integration of sensor data with building information: The sensor data is integrated with the customized GNM that constitutes of nodes and edges. By the interpretation of the data obtained from sensors according to the predefined damage/blockage rules; the system decides whether a node is accessible or not (i.e., should be included in the shortest path computation or not).

Deformed graph network model: The damaged/blocked nodes of the customized GNM are determined by interpreting the data obtained from the sensors and the nodes to be added to the shortest path calculation are identified. Similarly, the risks associated with the vulnerabilities inside the building are determined with the vulnerability risk ranking approach. The resulting model reflects the condition of the building after the disaster, according to the vulnerability assessment and the damage occurred in the building. This is the deformed GNM that will be the input for the next step that calculates the shortest evacuation paths.

Step 3: Computing and providing shortest paths to the user. Shortest path computation will be performed by running SPAs in deformed GNM. For every node inside the building, shortest safe evacuation paths will be calculated and provided to the users as a means of vocal and/or visual guidance. Also, the paths that are computed for the occupants will be presented to the emergency response teams (e.g., via hand-held computers) to help them in performing effective search and rescue.

Deformed graph network model: The aim is to use the information stored in the deformed GNM as a basis for setting up the SPA and to compute the shortest evacuation paths that will help evacuate the occupants to safe places.

Dijkstra Algorithm: Dijkstra, which is a commonly used algorithm in computing the shortest path between two nodes (Ivin et al. 2008), will be used for shortest evacuation path calculations.

Computation of the shortest evacuation paths: In the final step, the shortest evacuation paths are calculated based on the vulnerability assessment results, and the damage/blockage condition of the building obtained from the deformed GNM.

Initiation of visual and vocal guidance system for occupants and the visualization of evacuation paths for emergency responders: After the shortest and safest evacuation paths are computed, the occupants will be guided in accordance with the computation results. Also, the emergency responders will be informed about the status of the building, the vulnerabilities and possible threats, and the evacuation paths that are provided to the occupants.

DISCUSSION

It is envisioned to use different types of sensors that are deployed in the building to obtain status information after a disaster. This limits the utilization of the proposed framework to the buildings with light to moderate damage only, since in heavily damaged buildings the sensors will become inoperative. Also, it is a challenging task (1) to work with different types of sensors and combine data retrieved in different formats and (2) to integrate the results with the IFC-based building model. For instance, the cameras will interpret visual information, as if a space is damaged/blocked or not. Similarly, the cable sensor will only give Boolean results such as a wall is damaged (i.e., 0) or not (i.e., 1); but it will not provide any specific information (e.g., to which side it has collapsed and how). On the other hand, the gyroscope gives the results in terms of angular velocity. Thus, to interpret the raw data obtained from sensors in different formats, some experiments should be performed with the sensors to determine their threshold values. Consequently, when a value exceeds the threshold, it will mean that the building element is damaged, otherwise not damaged. Also, further experiments should be carried out for the cases where some of the sensors are damaged while others are functioning properly. This will help understanding if the system still performs well when less number of sensors are available.

Moreover, there is a need to establish some rules regarding the situations when a building element is being monitored by more than one sensor, since different sensors might give contradictive results for the same element. To determine the reliability of each type of sensor, a number of experiments should be carried out to evaluate the success rate of each sensor in assessing a condition correctly.

Another challenge is to efficiently guide the occupants in accordance with the

shortest path computation results. This can be performed visually and/or vocally. Feasibility of different approaches should be evaluated. Also, a robust approach is needed to inform the responders of the paths to which occupants are directed and the conditions of the building.

CONCLUSIONS

This paper gives an overview of a framework that composes of IFC-based BIM integrated with sensors and vulnerability information for assisting responders and occupants following a disaster. The main objective of this study is to perform indoor navigation based on the final conditions of facilities determined through the assessment of the facility in terms of damage and vulnerability aspects after a disaster. Further research on the performance of sensors is planned as future work, such as conducting experiments for examining individual performance of sensors in determining building element conditions and for combining the data collected by multiple sensors,.

ACKNOWLEDGEMENTS

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Automated Hybrid Ventilation Control in Complex Buildings

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ABSTRACT

Complex buildings such as hospitals and laboratories require intensive ventilation in order to meet operational demands. This research focuses on reducing cooling and ventilation loads in these types of buildings by incorporating hybrid ventilation in public spaces that do not require intensive air conditioning. Our research departs from previous works by justifying an optimal control strategy through experimentation rather than simulation. Ideally, designers would incorporate modeling to optimize building design and control, but these models are often not economical if created post-construction, and rarely result in accurate implementation of hybrid ventilation strategies. The method establishes a number of generic hybrid ventilation strategies to be tested in the public space of a complex building. The paper describes a multiple regression analysis of data to determine which controls and set-points are best for maintaining comfort while optimizing energy use. These controls and set-points are inputs for a building automation program developed to automatically determine whether a space should be naturally or mechanically cooled and actuate the analogous commands. It also calculates the expected energy savings associated with each strategy. This automated hybrid ventilation control is illustrated through a case study example, which has shown public space ventilation energy reduction of up to 56 percent.

INTRODUCTION

Buildings consume over 40 percent of the total energy produced in the United States each year and commercial buildings in particular account for 19 percent of the total energy consumption of the US (EIA 2010). Heating, ventilation and cooling (HVAC) most significantly impact building energy use, accounting for 51 percent of total building energy usage (EIA 2010). Due to high HVAC energy demands, this system is often the target for energy savings initiatives, especially in complex commercial buildings such as laboratories and hospitals that require high energy loads to meet code standards (Federspiel et al. 2000). A study of commercial buildings with high process loads shows that these buildings use up to five times more energy than typical commercial buildings due to high HVAC loads (Federspiel et al. 2000). One way to reduce the high HVAC energy demand in these buildings is to incorporate hybrid ventilation (HV) in their public spaces (Short and Lomas 2007).

Hybrid ventilation integrates natural ventilation (NV) and mechanical cooling when a building's ventilation needs cannot be met naturally. Natural ventilation (NV) is often harnessed through two natural phenomena, cross-flow and buoyancy driven

ventilation (Roth et al. 2006). Cross-flow ventilation refers to air-flow from one side of the building to the other caused by wind, and buoyancy, or stack effect ventilation, is bulk movement of air due to temperature stratification in spaces with high ceilings (e.g. atria). These two NV phenomena have the potential to significantly reduce HVAC energy consumption (Roth et al. 2006).

NV is often overlooked as a viable option for ventilating complex buildings as building codes do not facilitate its acceptance and a majority of climates do not allow these buildings to operate solely through NV (ASHRAE 2010). Complex buildings in these types of climates do, however, have the potential for HVAC energy savings through the incorporation of mixed mode cooling, or HV. These systems provide flexibility for energy savings and comfort, but typically require robust automated control to operate effectively in spaces that have transient occupants.

Due to the complexity and size of mechanical systems in high load buildings, utilizing HV in non-critical areas (e.g. public spaces) may provide a means of low-cost energy savings. This research focuses on reducing HVAC loads in complex buildings by incorporating HV in spaces that do not require intensive air-conditioning. The research departs from previous works by justifying an optimal control strategy through experimentation rather than simulation. The method establishes a number of generic HV strategies to be tested in the public space of a complex building to track performance criteria with the aim of selecting the most effective strategy. The research describes a multiple regression analysis of energy data to determine which controls and set-points are best for maintaining comfort while optimizing energy use. These controls, set-points, and the building automation system (BAS) data are inputs for an automation program developed to determine whether a space should be allowed to run HV and actuate the analogous commands. This experimental approach to optimizing HV and developing an automated control is illustrated through a case study example of the Wisconsin Institutes for Discovery on the University of Wisconsin-Madison Campus.

OBJECTIVES AND METHODOLOGY

The proposed framework is a means of measuring, analyzing and optimizing HV in public spaces of complex buildings in order to create an automated control for the strategy. The framework guides the testing of different HV strategies in existing buildings by tracking performance criteria: energy savings, thermal comfort, and IAQ. The objective is to test and monitor the building to rate the performance of the installed HV system under different control strategies. The best strategy was selected and an automated control was developed to operate it. Figure 1 outlines the framework by establishing Testing Setup (I), Data Collection (II), Data Analysis (III), and Automated Control Development (IV) where the primary focus of this paper is Phase IV as the first three phases are discussed at length in a previous study (Taylor and Menassa 2012). This figure describes what was done to develop the automation control and model.

The focus of Phase I is to determine what HV components and strategies to test, how those tests will be implemented through a testing matrix, and how each control will be developed. To track tests developed in the experimental matrix, Phase II (completed in parallel to Phase I) describes a means for collecting data through

building sensors, data acquisition software or other sources (i.e., weather stations or occupancy comfort surveys) by organizing them in a database. After completing tests, Phase III utilizes energy and regression analysis to determine the singular best HV strategy for the building. The best strategy was determined in the previous study and the automated control developed (Phase IV) for this study actuates it. This control will collect weather and other data as inputs and output an actuation for the HV strategy as well as provide energy savings information. The control is then modeled and validated through a case study.

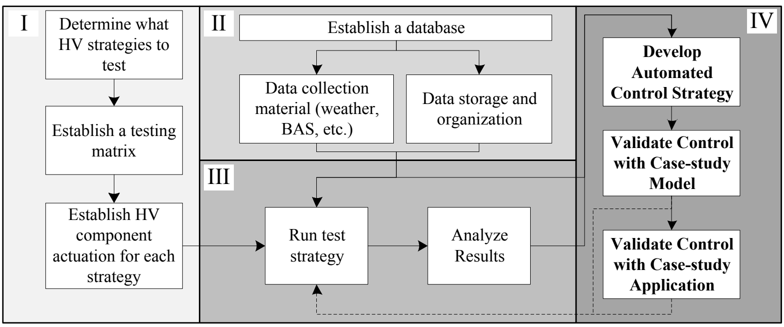

Figure 1. Experimental Methodology

TEST SETUP (I) AND DATA COLLECTION (II)

The first parts of the framework establish tests and data which substantiate which HV strategy performs the best. Phase I of the framework establishes what dynamic building components are related to HV. Table 1 shows how these components were organized into a testing matrix allowing the operator to test various strategies in order to determine which one works best in the space. This matrix describes how components and strategies interact. Components denoted with alpha characters (e.g. A. Normal Mechanical Cooling) and their subsequent actions (marked by an X) are defined in columns. For example, Open Zone Supply off refers to air terminals (AT) serving the areas located near windows, whereas Closed Zone Supply refers to areas that have no direct access to windows or louvers and an X describes when those ATs are closed.

By identifying the HV components and how these components can work together, one can establish different actuation strategies by varying what components are used (marked with X). These strategies are denoted by the rows of Table 1. HV Tests (Test 1.1-1.x) are run as variations of the Base Case HV Test (Test 1.0). Figure 2 illustrates the actuation strategies defined from the HV Test Strategy 1.2 described in Table 1. The actuation occurs when conditions are favorable for HV as defined by the operator or automated control. Using the testing matrix and HV strategy diagram, HV strategies were tested over a variety of days capturing varying internal and external conditions for each case. This data was then used to determine the best strategy and develop the automated control.

Once the testing strategies are established, a data collection framework is developed to track the three performance criteria (Energy Use, Occupant Comfort and IAQ) for each strategy established in the testing matrix. Taylor and Menassa (2012) detail data to collect, the data's source, what performance criteria it tracks, its placement and purpose. Data pertaining to Air-Handling Unit (AHU) energy use is to be collected for both the HV testing period when window testing is being conducted and throughout the cooling season for comparison.

The primary information of interest is outdoor-air (OA) temperature (T_{OA}), humidity, and pressure as well as AHU data: mixed-air enthalpy (h_{MA} [BTU/lb dry air]), supply-air enthalpy (h_{SA} [BTU/lb dry air]), supply-air fan power (P_{SAFan} [kW]), return-air fan power (P_{RAFan} [kW]), and volumetric flow rate ($\dot{V}_{SA}$ [CFM]). The data collected when traditional HVAC is operated will be used to generate a regression fit of AHU energy use as a function of OA temperature and time of day. The HV testing data will be compared to this regression model to justify the best strategy.

Table 1. General testing matrix for hybrid ventilation strategies

Test Strategy	A. Normal Mech. Cooling	B. Windows	C. Open Zone Supply	D. Closed Zone Supply	E. Atria Louvers	F. Mechanical Assist Vent
x.x	**(setback)**	**(open)**	**(off)**	**(off)**	**(open)**	**(off)**
1.0 – HV Test 0	X	X	X			
1.1 – HV Test 1	X	X	X	X		
1.2 – HV Test 2	X	X	X		X	
1.3 – HV Test 3	X	X	X	X	X	
1.4 – HV Test 4	X	X	X		X	X
1.5 – HV Test 5	X	X	X	X	X	X

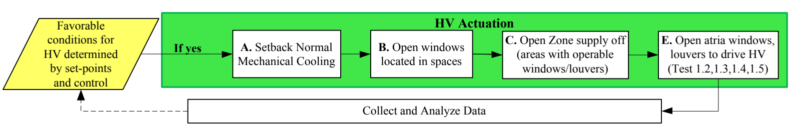

Figure 2. Varying HV strategies based on Test Matrix

DATA ANALYSIS (III)

Data collected from AHUs was analyzed to obtain energy consumption of the HVAC system by considering a control volume about each AHU. This can be done by considering that most AHUs consume power to move air and require cooling input to air at a specific flow-rate and air density. Thus, AHU energy consumption for all times (full use or HV) is determined by the following relation: $E_{AHU}=\left[(P_{SAFan}+P_{RAFan})+\dot{V}_{SA}\times\rho_{Air}\times(h_{SA}-h_{MA})\right]\times\Delta time$. A regression model of AHU energy use for days when normal ventilation was used provided a benchmark. Each tests' performance was compared to the benchmark to select the most effective strategy. Actual energy use can be compared with the regression model to determine savings through utilizing HV.

Data was collected by applying HV strategies discussed in Table 1 and tested

over the course of two weeks from 09/28/11–10/10/11. Data collected from the entire cooling season (06/01/11–10/15/11) was used to develop a regression model of AHU energy consumption. These variables were used to produce the simple multiple regression: $E_{Regression} = 188.7 - 34.86T_{OA} + 2.37{T_{OA}}^2 - 0.04{T_{OA}}^3 + 1.45hour + 0.11hour^2 - 0.01hour^3$. This regression model fit the data well with an adjusted R^2 value of 0.72, and residual standard error 24.33 on 2563 degrees of freedom. A sensitivity analysis found a 10.20 percent variation between measured conventional mechanical cooling energy use and the regression model. Of the eight strategies specified in Table 1, six were carried out in this study with initial results proving that the other two strategies need not be tested. The test results show that Strategy 1.2 provided the most savings from the baseline at 56.58 percent savings with a standard deviation of 7.88 percent.

AUTOMATED CONTROL DEVELOPMENT (IV)

HV testing and analysis determines the most effective actuation strategy among those listed in Table 1. Since individuals cannot be relied upon to control their own environment in a public space, an automated process for determining when to actuate HV must be incorporated in the BAS. The automated control has been developed using a traditional programming language that takes BAS information and reads in three primary inputs which is shown in Figure 3. These inputs are analyzed in sub-codes which are brought together to determine whether conditions are optimal for actuating a given HV strategy. The program then outputs an actuation signal to the HV strategy chosen from Phase III and also prints energy savings calculated from the set-back AHU and the regression model.

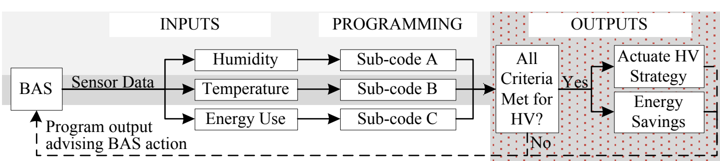

Figure 3. Automated Control Outline

The details from the outlined program are provided in Figure 4 which identifies the logic in the three sub-codes and inputs. To begin, the program is controlled with a feedback loop from the BAS. These inputs include IA humidity (H_{IA}) and OA humidity (H_{OA}) readings taken from sensors generally located in the intake of an AHU and throughout the occupied space respectively. The second input is temperature data provided from the intake of an AHU (T_{OA}), zone temperature readings taken from air terminals located in the occupied space (T_{IA}) and forecasted high daily temperature (T_{high}). The final input is energy data specified in Phase II gathered from AHUs servicing the area utilizing HV. Each sub-code determines if set-points are adequately met for HV actuation.

Humidity. The first sub-code determines whether internal and external conditions allow for HV based on relative humidity readings. This logic ensures that both IA and

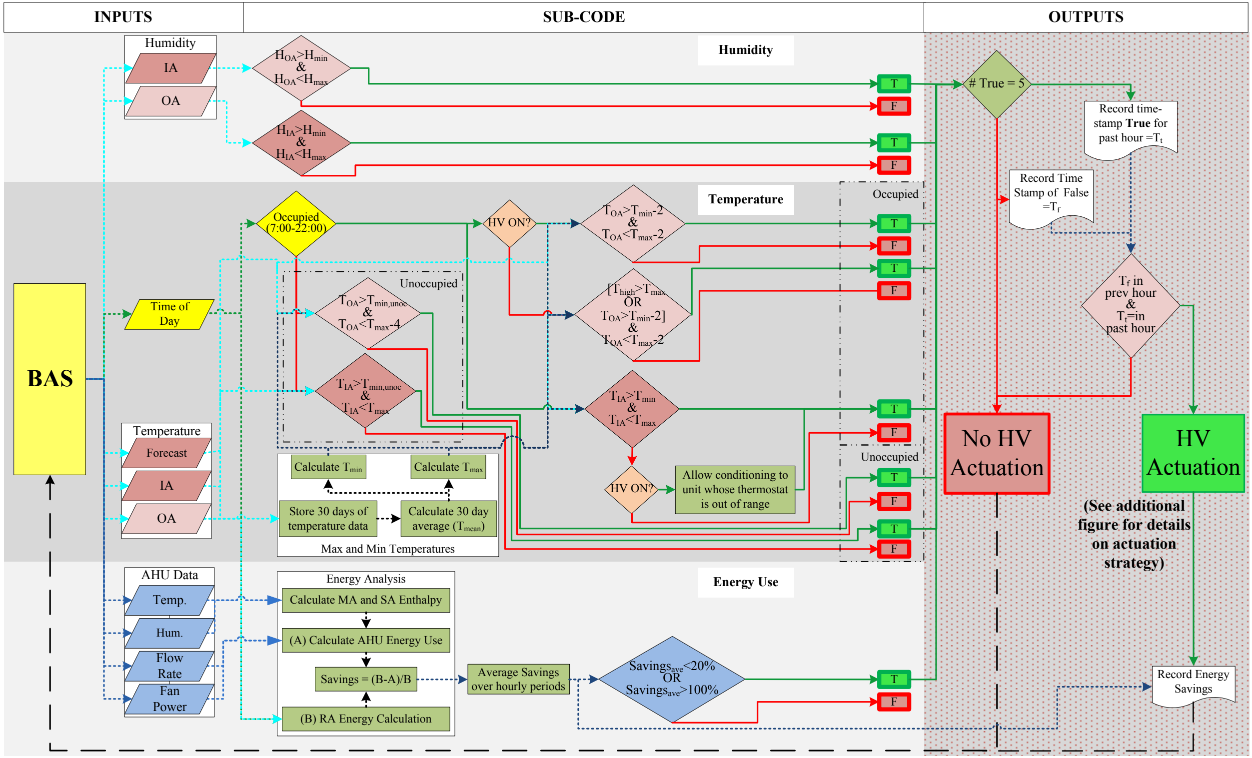

Figure 4. Automated Control Actuation Program for Hybrid Ventilation

OA relative humidity are within H_{min} to H_{max} (20-70 percent) (ASHRAE 2010).

Temperature. The second sub-code determines whether internal and external conditions allow for HV based on temperature readings. This program sorts information based on time of day as temperature ranges are dependent on occupied and unoccupied hours. The American Society for Heating Ventilation and Air-Conditioning (ASHRAE) Standards suggest minimum T_{IA} ($T_{min,unoc}$) of 12.75°C for unoccupied hours and occupied minimum T_{IA} is determined by the function $T_{min} = 0.205T_{mean} + 15.35$ where T_{mean} is the mean T_{OA} over the past 30 days. ASHRAE standards also suggest maximum T_{IA} (T_{max}) be determined by the function: $T_{max} = 0.205T_{mean} + 22.87$ (ASHRAE 2010). T_{OA} set-points have been determined by Taylor and Menassa (2012) based on T_{IA} requirements and measured interior energy generation.

Thus, T_{IA} ranges for unoccupied and occupied periods are provided by the following relations respectively: $T_{min,unoc} \leq T_{IA,} \leq T_{max}$ and $T_{min} \leq T_{IA} \leq T_{max}$. The following relations provide T_{OA} ranges for unoccupied and occupied periods respectively: $T_{min} - 2°C \leq T_{OA,unoc} \leq T_{max} - 2°C$ and $T_{min} - 2°C \leq T_{OA,ocup} \leq T_{max} - 2°C$. The BAS supplies T_{OA} forecasts which are utilized by this program. If the forecasted high T_{OA} for the day exceeds T_{max} then HV may be initialized once the building enters occupied mode. Since the AHUs are still servicing some spaces additional space cooling provided to overheated areas will require little energy use. If a zone temperature sensor (T_{IA}) records a value exceeding T_{max}, the AHU is to service that air-terminal to cool the overheated space.

Energy Use. The final sub-code determines energy savings from utilizing HV against the regression model found in Phase III. AHU energy inputs to this sub-code are detailed in Phase II. These savings are averaged over hourly periods to buffer inconsistencies. The HV tests detailed below have shown that energy savings are expected to be substantial and therefore, if energy savings are no greater than 30 percent, the BAS will return to normal HVAC operation. This will also limit additional energy supplied to air-terminals that are turned on to cool space that has overheated.

Output. All of these sub-codes must find conditions favorable for HV actuation at which point the output sub-code will ensure that the control is not cycling. Once the HV actuation has been cancelled, it cannot be reenacted for one hour. If all of these conditions are met at any time step (determined by the BAS data polling service), the program will signal the BAS to actuate the optimal HV strategy selected in Phase III and record energy savings.

RESULTS AND CONCLUSIONS

This automated control is verified using data from the Wisconsin Institutes. The control actuation program developed for this particular system was described in Phase IV and is generalizable to many HV systems that rely on automated actuation. The program has not yet been used through the BAS, but it was tested using a basic programming software. Data collected for the entire cooling season was input to the

program to track its outputs and ensure that HV actuation was being appropriately controlled. Figure 5 provides an excerpt of these outputs documenting when the program actuates HV strategy 1.2 and prints actual energy use when operating HV strategy 1.2 in comparison to the regression model. Figure 5 shows substantial energy savings in comparison to the regression model especially throughout periods of the day when energy consumption is typically highest.

While the exact HV strategy used in each case will be different, the automated control program developed in this research is generalizable and can be used in most public spaces where automated HV actuation is a possibility. HV can provide substantial energy savings to public spaces in complex buildings, but it is important to automate this system so that mechanical and HV components work in concert. Especially for large spaces with small operations staff, an automated control is an effective way to operate HV while monitoring energy savings, comfort and IAQ. This research has established a generalizable automated control that takes into account multiple facets of facility management and comfort. Future research will integrate the program into a simulator to track performance of the automated HV control.

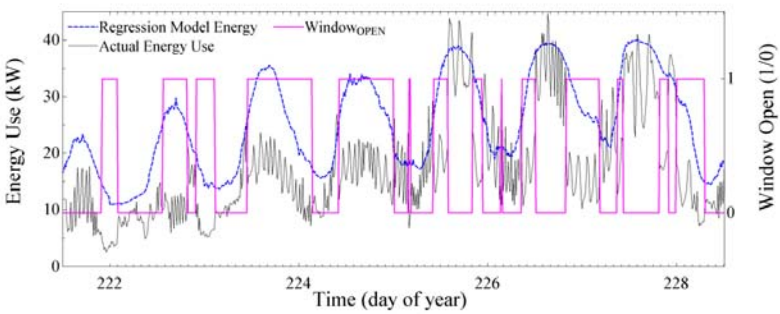

Figure 5. Plot of AHU energy use when HV is utilized for a sample week

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Web-Based Eco-Feedback Visualization Of Building Occupant Energy Consumption in Support of Quantifying Social Network Effects on Conservation

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ABSTRACT

Exposing building occupants to information about their energy use and the energy use of others in their social network through eco-feedback systems has been shown to significantly impact occupant energy consumption. In this paper, we describe the design and development of a web-based visualization system that exposes building occupants to real-time information about their individual energy utilization, the utilization of their peers in the building, and the average energy utilization of all monitored individuals in the building. The system also monitors and records user interaction with the system and other users of the system providing relevant usage data for conducting analysis to quantify network effects on user energy consumption. A description of the system's physical and virtual architecture and how its design enables meaningful analysis, visualization and effective user monitoring is provided. We conclude by presenting the methods and challenges related to how our visualization system was developed to facilitate and monitor social interaction around energy conservation, and how it enables research into the underlying mechanisms that drive these actions.

INTRODUCTION

Residential and commercial buildings currently account for 75% of the total electricity consumption in the United States, and this percentage is expected to rise with increased domestic demand in the future (DOE 2011). Demand side energy efficiency initiatives represent a relatively simple, scalable means of consumption reduction. Many such initiatives build on experimental evidence that access to increased information about energy consumption positively encourages consumers to conserve electricity (Fischer 2008).

BACKGROUND

Numerous studies have been conducted on the effect of increased information about energy consumption on energy conservation behavior in a variety of settings, including: dormitories (Peschiera et al. 2010, Petersen et al. 2007), residential households (Fischer 2008, Seligman et al. 1978), and commercial/institutional domains (Lucid Design Group, Jiang et al. 2009). These studies and some established theoretical models such as the Theory of Planned Behavior and Value Belief Norm

Theory, have demonstrated that high granularity and real-time energy consumption feedback motivate behavioral change by enabling an individual to establish a connection between action and consequence on a personal level. Our method and developed system build upon recent technological advancements to advance research on normative influences on network dynamics. Our system combines near real-time energy data visualization at the individual user level with network energy consumption information, while tracking relevant user and network statistics such as personal network size, network energy performance, and user clickstream data for the purpose of effectively analyzing social network effects on individual and network energy consumption.

Fig. 1 presents a set of academic and commercial energy efficiency initiatives organized by level of granularity and update frequency of consumption data. The concentration of commercial initiatives located in Zone II reflects a common acceptance of the experimentally and theoretically supported benefits of highly granular real-time data. The major differentiators of our system, which follows this migration to highly granular real-time data, is the method by which energy data is analyzed and visualized and the built-in capability of our system to record relevant user engagement data that enables us to effectively isolate normative influences on individual behavior. Of all the initiatives in Zone II, only two are academic studies that focus on normative effects on energy consumption. Other academic studies concerned with normative network analysis have historically been limited in their approach by the technology available at the time of deployment (Brandon and Iver et al. 2006, Lewis 1999, Siero et al. 1996), and therefore are not in Zone II. Consequently, these studies only examined normative influences on the building and entire network scale.

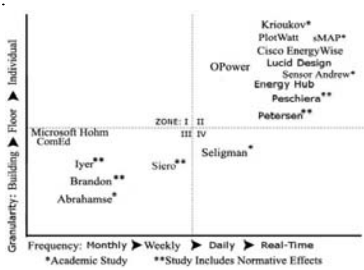

Figure 1. Demand-Side Initiatives

Certain commercial initiatives (Lucid Design Group 2011, Microsoft Hohm 2011, ComEd 2011) also utilize normative comparisons to encourage conservation. Such initiatives are not focused on investigating the fundamental aspects of network behavior. Our system is uniquely capable of investigating the effects that social networks have on energy consumption and is being used in studies to quantify these effects. In this way, we can begin to identify the relative effectiveness of social networking strategies.

With the advancement of sensor network technologies and their web-based integration, all-encompassing sensor network systems have begun to be deployed in industry and academia (Cisco EnergyWise 2011, Sensor Andrew 2011, sMAP 2011).

Numerous academic studies have utilized these technologies and attempted to evaluate the effects of various data analysis and visualization strategies on energy consumption. Such strategies range from automated resource controls (Krioukov et al. 2011), historical data comparisons (Abrahamse et al. 2007, Petersen et al. 2007, Seligman et al. 1978) and point-reward systems (Brandon and Lewis 1999) to normative comparisons (Brandon and Iver et al. 2006, Lewis 1999, Siero et al. 1996) and goal setting (Siero et al. 1996, Seligman et al. 1978). There remains a degree of uncertainty about which strategies are the most effective in facilitating energy conservation. The remainder of this paper explains the principles behind the sensing, analytical, and visualization architecture that make our system uniquely capable of examining the network effects on energy consumption behavior.

ECO-FEEDBACK SYSTEM FOR BUILDING OCCUPANT NETWORKS

The system was developed to provide users with the most useful representation of energy consumption data while minimizing any physical interference related to its installation and maintenance. The three main components of the system include its sensing architecture, data analysis, and data visualization.

Sensing. The physical system consists of a network of 0-20 Amp Continental Control Systems current transducers attached to individual electrical sub panels. The system was originally installed in a dormitory. Each transducer monitors current flow to an individual room and RMS amperage is recorded by Onset Computing HOBO U30 data loggers. Through a wireless router located near the electrical sub panels, the data loggers push minute-interval amperage data to a server hosted by Onset every 10 minutes. Apparent power (volt-amperes) is then derived and stored within the file by multiplying the RMS current value by 110 volts; the voltage value was independently validated to within 10% of 110 V by sample testing individual outlets in the dormitory. The power data for each room is stored in this database and is queried when a user interacts with the system. It can be divided by the number of room occupants to represent per capita consumption.

While the physical sensor network is constantly monitoring a user's energy consumption, the virtual system is monitoring several aspects of the user's interaction with the system. Modern web tracking technology in the form of clickstream data has been shown to be an effective means of measuring user behavior quantitatively and assessing the performance impact that design components have on a web based application (Benevenuto et al. 2009, Das and Turkoglu 2009, Srivastava et al. 2005). Clickstream data related to user logins, views of incentive pages, changes in power/energy consumption graph displays, energy audit submissions, and queries into other users' energy consumption information is recorded by our system. All of the data is separated by individual user and stored in an independent SQL database, kept apart from the consumption data to facilitate analysis.

Analysis. In order for energy consumption data to be effectively communicated to the users, user power data must first be processed. Apparent power is converted to energy consumption upon user request by calculating the Riemann sum of minute by minute power values. The sum of these minute-interval energy values is then computed for a

24-hour period (1440 minutes) and displayed to the user as kilowatt-hours per day. Minute by minute granularity is utilized in order to mitigate error that may be attributed to sudden power load fluctuations over the course of a day.

In order to motivate users to engage with the system on a deeper level and provide a means by which to improve self-efficacy, an energy audit tool that allows users to disaggregate energy consumption data to the appliance level was developed. Development of this tool was motivated by Fischer's review (Fischer 2008) of eco-feedback studies that affirmed the importance of interface tools that draw a direct link between specific actions or appliances and consumption. Providing such granularity allows users to increase self-efficacy associated with consumption behavior modifications (Wilson and Dowlatabadi 2007). The audit tool works by calculating the difference in aggregate power draw between user designated times that the appliance is operating and turned off.

We developed a new analytical feature (Eqs. 1 and 2) to encourage user engagement. Users are provided an opportunity to accrue virtual points, proportionate to the amount of energy they conserve relative to a pre-determined baseline value, which they can exchange for prizes.

$$(1)\quad Daily\ Points = Daily\ Consumption\ (Watthours)x\ [\delta_{daily} - \delta_{baseline}]$$

$$(2)\quad \delta_{daily,baseline} = \frac{P_{d,b} - C_{d,b}}{C_{d,b}}$$

wherein *P* is the average participant daily power draw, and *C* is average per capita daily power draw of the control group. The baseline value is derived by comparing an individual user's energy consumption over a period of time before the incentive program is announced to the consumption of a pre-determined control group. The percent difference, whether positive or negative, becomes the baseline value. When the incentive program is initialized, the user's daily consumption levels are again compared to the control group, and the daily percent difference is compared to the baseline value. The difference between values is then scaled to the amount of energy the user consumed that day. The user is rewarded or penalized 500 points for each kilowatt-hour that is conserved or wasted relative to the baseline. To encourage system interaction, users are additionally rewarded 1,000 points for performing an online energy audit and completing a study-related survey. The point reward system is flexible and fully automated, and can be applied to different components of the system in order to encourage interaction. Users can subsequently trade in accrued points for various rewards (e.g. energy saving power strips, gift cards, etc.).

Visualization. The components of our web interface were designed with the intention of maximizing usability. Detailed images of the system can be viewed at http://www.cend.cee.vt.edu/research/WCCE2012.shtml. Fig. 2 displays the different viewgraphs that a user can activate through the web interface. These viewgraphs represent the core functionality of the system and therefore occupy a centrally dominating position within the interface. Users can use a tab located above the viewgraph to toggle between multiple perspectives.

The *24 hour view* (Fig. 2(a)) displays a line graph that plots a user's average power draw, in watts, over 10-minute intervals for the previous 24 hours. The *Last Week view* (Fig. 2(b)) displays a bar graph that presents a user's daily energy consumption totals, in kilowatt-hours, for the previous week. The color of the bars in the *Last Week view* is indicative of the user's daily consumption relative to the building average, and is used to visually encourage conservative and discourage wasteful consumption behavior. Green indicates that the user consumed at least 20% below the building average on the specified day, red indicates at least 20% above the building average, and yellow indicates that the user's consumption was within 20% of the building average. The *To Date view* (Fig. 2(c)) allows users to view their daily consumption, in kilowatt-hours, on a line graph for all days back to the date when energy monitoring began.

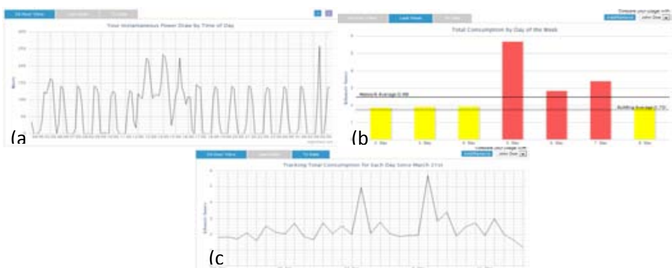

Figure 2: (a)10min-interval Average Power Draw for Preceding 24hr Period (b)Daily Energy Consumption for Previous Week (c)Daily Energy Consumption from Start of Study Period

Beyond simple historical data visualization, the *Last Week and To Date* views provide an additional social perspective by allowing users to view the consumption levels of their peer networks and individual friends. This additional data is overlaid on the user's historical data thereby allowing direct comparison. Additional peer network information is provided in the friend feed feature of the interface. The friend feed and energy audit tool are located together below the historical viewgraph and can be observed in Fig. 3. The friend feed automatically notifies a user's network once the user completes an energy audit, or redeems reward points for a prize. The friend feed reminds users of other interactive features of the system while simultaneously encouraging them to engage those features by way of social, normative stimuli. It further acts to reinforce the normative comparison feedback presented in the historical viewgraphs.

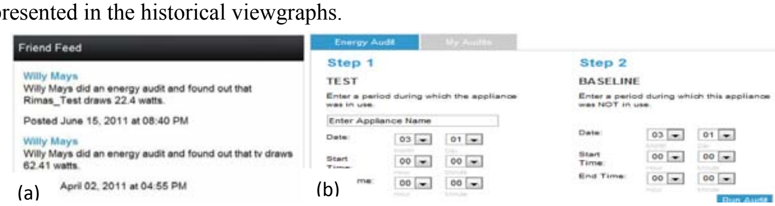

Figure 3: (a) Friend Feed (b) Energy Audit Tool

The energy audit tool provides users with the ability to further disaggregate data at the individual appliance level. Results from a user's energy audit are broadcast

to peers through the friend feed, encouraging network collaboration to further disaggregate energy data. Our system records user utilization of the energy audit tool, and can track the tool's use across networks. This provides us with one of many ways to identify the propagation of practices, in this case energy audits, across networks.

VALIDATION

Our system was successfully deployed at a Columbia University dormitory across multiple studies (Chen et al. 2011, Jain et al. 2011, Peschiera et al. 2010) that yielded statistically significant results linking reductions in energy use to both network effects and key components of the eco-feedback system. Peschiera et al. (2010) first validated the system in using it to demonstrate that networks have a statistically significant impact on energy consumption. Chen et al. (2011) used the data from the Peschiera et al. study as well as data from a subsequent year of experiments using the system to develop a statistically robust agent-based simulation model to predict energy consumption. Jain et al. (2011) validated the visualization component by quantifying a link between usage and energy consumption reductions.

LIMITATIONS

The system provided valuable data during its deployment that has led to insightful research on the effects of networks on energy consumption. One of our system's major functions is to collect, process, and communicate energy consumption data. However, the nature of our system requires that we additionally process and communicate network consumption data, record user interactions, and allow users to interact with their networks. These additional system responsibilities adversely impacted the load times of the historical and normative viewgraphs (Figs 2a, b, and c) due to the increased processing demands of such a large data set.

The configuration of the sensor data transmission system also leads to some inherent limitations, as minute-interval sensor data is transmitted to the database and made available for visualization after every fifteen minutes. With database optimization, more frequent sensor transmission will enable minute-level real time resolution. Additionally, true individual-level consumption data was limited by the fact that energy consumption was monitored on a room level. A user's performance, as reflected by the system, was therefore influenced by their roommate's consumption patterns.

FUTURE RESEARCH

Research into the role of social networks in the domain of energy efficiency is still very much in its beginning stages and stands to greatly influence future energy policy and efficiency initiatives. Recent technological progress has enabled research at a level of granularity not previously possible. By adapting our energy monitoring system to collect data relevant to other situational contexts beyond dormitories, it will be possible to understand the role of social networks across multiple domains. As technology advances, it will be possible to monitor shared resources (i.e. lighting, common appliances) and to relate actions of specific individuals and networks with their control. The introduction of the remote controllability of devices (turning

appliances on/off via IP protocol) will also expand research possibilities related to how network influences extend beyond a static physical location. With this increased understanding, it is possible to formulate effective strategies to positively influence these social networks to conserve energy. Regarding the existing system, the authors have identified methods to increase the efficiency of the data processing in order to expedite load times which will be shared with the research community in an upcoming publication.

CONCLUSION

Our system was developed in order to fill a gap in research related to social networks and how they relate to energy conservation. Prior to the development of our system, most social network research in the energy efficiency domain was constrained by technology. We were able to develop and successfully deploy a system that provides near real-time individual and network energy data to its users, while simultaneously tracking user interaction with the system and other users of the system. With our system, we are able to isolate and quantify many effects that social networks exhibit on individual energy efficiency behavior. These findings may significantly impact the design of future energy efficiency initiatives.

ACKNOWLEDGMENTS

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Evaluating Construction Methods for Low Carbon Emissions Using System Dynamics Modeling

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ABSTRACT

Construction projects are complex in nature, including multiple and conflicting project objectives and conditions. Although time and cost are traditional objectives that are considered in every project, environmental impact, such as greenhouse gas (GHG) emissions, has often been considered as another important objective recently. The complex construction environment makes it a challenge to determine construction methods that satisfy multiple objectives of a project. The complexity is further compounded by the need to consider the impact of changing project conditions on the time, cost and environmental impact (TCEI) to decide on the suitability of construction methods. In order to fulfill this need, this research discusses using system dynamics modeling to simulate and analyze various construction methods, as well as calculate their corresponding TCEI. The system dynamics model works with a decision-making system to select among construction methods and a project system to evaluate selected methods based on project objectives. The integration of the two systems has been applied to a case study of a highway construction project to determine a construction method that can best satisfy three potentially conflicting objectives as TCEI. The results have shown that the proposed model is effective in evaluating selected methods and suggesting resource utilization plans that can better fulfill the project objectives.

INTRODUCTION

The presence of multiple and conflicting objectives is one of the major complexities in building projects (Burns et al., 1996). Various objectives need to be optimized for the successful completion of a project. These objectives can include time, cost, safety, quality, and sustainability, where their significance among each other can differ from project to project (Kandil et al., 2010). For a long time researchers have focused on only traditional project objectives, such as time and cost. Recently, environmental impact has entered into the picture as a new criterion of project success. The influence of building industry on natural resources has shown direct and indirect relations between construction industry and sustainable development (Bourdeau, 1999). It has been a challenge to search a pool of available construction methods in order to fulfill the three project objectives as TCEI. The issue gets even more complicated, when external factors, such as changing project

conditions, are introduced to the complex construction environment. Although being an inevitable part of construction projects, dynamic project conditions have usually been discarded. The main reason for that is the complexity of foreseeing the effect of such conditions on project objectives. Analyzing the complexity of changing project conditions and their impact on TCEI objectives is needed to decide on the suitability of construction methods. The aim of this research is to simulate and analyze changing project conditions, as well as their influence on various construction methods and their TCEI. Systems dynamics (SD) modeling is used to perform decision-making to select among construction methods and evaluate selected methods based on TCEI objectives. The proposed SD model and the simulation process will be presented by the help of a case study.

SYSTEM DYNAMICS BACKGROUND

System dynamics is defined as a methodology for studying and managing complex systems (Sterman, 2000). The concept combines theories and methods to analyze the behavior of complex systems and understand the change of their behavior over time (Forrester, 1994). In some applications related to construction project management, the structures of an SD model are described as project features, a rework cycle, project control feedbacks, and ripple and knock-on effects. Project features represent the development tasks or work packages, rework cycle shows the iterative flow of work packages with respect to time, controlling feedbacks are used to control a project's performance and ripple and knock-on effects are defined as side effects of the gap between project performance and targets (Lyneis & Ford, 2007).

SD modeling is considered to perform strategically better than traditional operational project management tools, such as work breakdown structures (WBS) and critical path modeling (CPM) (Rodrigues & Bowers, 1996). The reason is that the traditional methods focus on different parts of the project management process, while the SD method considers whole project system. Previous studies have discussed how SD can improve traditional models, how traditional tools can be used to create SD models, and how both methods can be used to inform one another (Williams, 2002).

Several researchers have studied the impact of resource management on project performance using SD models. For example, Lee et al (2007) focused on developing project resource management to improve schedule performance. They emphasized the importance of resource management on timely completion of projects and reducing project durations. Additionally, the study had mentioned how managers' ability was constrained by challenges of managing uncertainties associated with project conditions and constraints imposed by cost, product architecture, and project participant relationships.

Constraints that are imposed by external factors, like project conditions or internal factors (e.g., project participant relationships) affect the decision-making structure of systems. Project features in SD models can also be used to model human decision-making, which is typically driven by perception gaps (differences between perceived progress and real progress), delays in human processes, and nonlinear relationships. The decision-making works as a mechanism to minimize the target-

performance gap in one or more performance dimensions such as time, cost, quality, and scope (Lyneis and Ford, 2007).

METHODOLOGY

In order to overcome the aforementioned shortcomings, the proposed SD model uses rework cycle and generates the decision-making mechanisms based on changes in project conditions, as well as the project goals (TCEI). The properties of project conditions are entered as input to the SD model. Based on defined decision-making rules, the most feasible CM is selected under the influence of project conditions. Then, TCEI is calculated for the selected CM. For each different set of inputs, CM selection and TCEI calculation are performed by the SD model. The flow chart for the proposed SD model is shown in Figure 1.

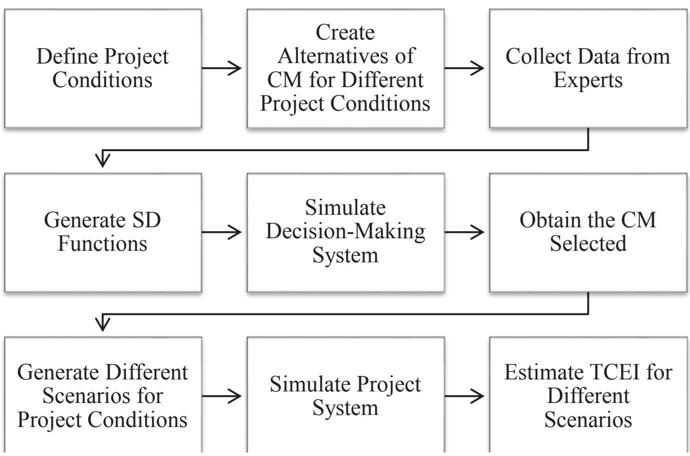

Figure 1. Flow Chart for the Proposed SD Model

The complex construction system can be modeled with two sub-systems such as decision-making and project systems. The decision-making system simulates a decision-making mechanism based on changes in project conditions, while the project system models resources and processes related to a project as well as calculation procedures for TCEI. This research is mainly focused on the integration of two systems as well as the details of the project system. The details of the decision-making system are outside the scope of this research. However, the decision-making process will be summarized to facilitate a full understanding of the SD model.

As a first step, seven conditions are defined based on previous studies about highway construction, change causes, and change effects. They are adverse financial issues of owner, adverse market conditions (affecting owner), change in design, unavailability of resources, delay in resource delivery, increase in unit cost of resources, unexpected conditions. As it can be observed from this list, the parameters

are selected to reflect the effect of external conditions on a construction method. Change in some conditions can directly affect owner's decisions, and cause an indirect impact on the decision-making process of contractors. The remaining of conditions, such as the ones related to resources, directly influence the contractor's decisions on what type of construction methods to use. These project conditions are coded as Ci in the system, where C stands for conditions, and i stands for the number of a condition from 1 to 7. The mathematical formulation for each project condition is created based on the language of the SD software. Being a user-friendly tool that is capable of presenting and analyzing flows and controls in a SD model (Bousquet and Le Page, 2004), Vensim PLE software is selected to perform the SD simulation in this study.

The decision-making mechanisms of agents are distributed among the CM indicators in Vensim. There are three CM indicators as material selection, equipment selection, and stabilizing additive selection. CM alternatives for different project conditions are created with the help of CM indicators. That is each alternative is composed of material, equipment, and stabilizing additive components, which can be coded in the Vensim model. The alternatives are discussed with experts from highway construction industry through structured interviews. The experts were asked to rate the relative importance of project conditions in affecting material, equipment, and stabilizing additive selection for different alternatives. This information was mainly used to create the skeleton of the decision-making sub-system. In addition to the qualitative information from the interviews, quantitative project data are collected. The data were used to create equations in the project sub-system.

The decision-making system includes decision paths of owner and contractor agents that are influenced by seven conditions. In order to show changes in project conditions, they were defined in terms of their probability of occurrence and impact values. The probabilities of seven conditions were obtained by interviews, while the impact values are entered by the user or decision-maker of a project. Describing a project condition with its probability and impact allows assigning quantitative values to changing conditions. As qualitative values cannot be used in equations, the numerical values were preferred to create various equations and functions to perform CM selections in Vensim. Then, the decision-making is performed by using IF-THEN rules, where IF part is the CM indicators and THEN part is the selected construction method. The CM Selection control unit selects the most feasible construction operation based on the combination of material selection, equipment selection, and stabilizing additive selection values. When a construction method is selected by a contractor under the influence of project conditions, it is entered into the project system. The CM selection is further decomposed into resources, which represents the outputs of the decision-making procedure of agents. Resources are used as connection points between the decision-making and project sub-systems. By using the CM indicators, the resource types for each activity are input to a simulation. Additionally, information, such as resource quantities, unit costs, activity durations, and fuel consumptions of equipment are available in an MS Excel database to calculate project time, cost and environmental impact in terms of greenhouse gas (GHG) emissions for each activity. After TCEI is calculated by using the MS Excel, the output is further input to the control units in the project SD model.

The TCEI calculated under the influence of project conditions are represented in project time, project cost and project GHG items in the project model. Then, this information is compared to the target time, cost and GHG entered by users. The gap between project TCEI and target TCEI are calculated to find the suitability of the CM selected. The suitability of the CM selected is further used with the rework cycle to maintain the flow of the SD system. The rework cycle decides if the current construction method need to be changed or it is the selected one to be used in the project. The flows progress rate and discover CMs needing changes get inputs from an extra project feature, and the stock cumulative real progress of CM change sends outputs to the decision-making system. By this way, the feedback loop is achieved in the model. The simulation stops if the selected CM is suitable for the user. If it is not, the simulation continues to reach the desired suitability of the CM selected value or the minimum possible value set by the user. The application of the system will be explained in the next part. The proposed SD model is shown in Figure 2.

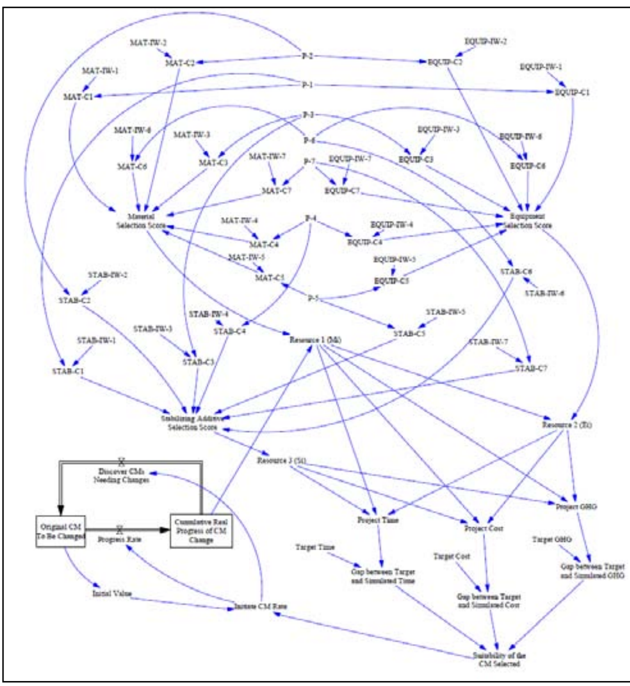

Figure 2. Proposed SD Model

CASE STUDY

The case study is a resurfacing project from FDOT. The project includes milling the existing asphalt, placing asphaltic concrete, and putting the concrete

friction course activities. In the original set of construction methods, Superpave asphalt is used in paving. Before the pavement of the new asphalt, the old asphalt is milled by using conventional equipment. The milled asphalt is hauled by dump trucks to be recycled. For the friction course layer, FC-5 is used as the basic material. The original construction method is referred to as existing method in this study. The existing method shows one way of delivering the project. The same project can be performed by using different resource utilization plans as well as different construction methods.

The SD model was applied in analysis to observe its effectiveness by simulating both decision-making and project systems. The proposed SD model was developed by using various inputs, such as different probabilities of project objectives. For each condition, a score was calculated by multiplying its relative importance weight and probability. This procedure was repeated for seven conditions to calculate the score of project conditions for material, equipment, and stabilizing additive selection. Then, the scores of project conditions were combined with each CM indicator. The differences between CM alternatives were reflected by different types of CM indicators. For each set of different probabilities, different construction method, i.e., resource results were obtained and used to test the model.

Sterman (2000) suggested three types of tests to evaluate the SD model. The first test is for determining structural similarity to the actual system. The proposed model is based on previously validated project models and literature, so the model's structural similarity is improved to match the actual system. For the second test, the model is checked for reasonable behavior over a wide range of input values. During simulation, the model behavior remains reasonable across changes in individual probability values, as well as with extreme input values as shown in Table 1.

Table 1. Case Study Input and Output Values

	Input Values							Output Values					
Trial #	**P-2**	**P-1**	**P-3**	**P-6**	**P-7**	**P-4**	**P-5**	**Mi**	**Ei**	**Si**	**C**	**T**	**GHG**
1	61	63	35	10	27	51	99	4	1	1	$1,945,751.89	36	3,857,983.11
2	44	63	98	88	17	62	67	4	1	1	$1,945,751.89	36	3,857,983.11
3	0	17	49	80	80	38	63	1	2	2	$1,998,046.87	36	4,130,521.55
4	27	74	14	49	48	15	95	2	2	1	$1,830,894.80	36	2,704,097.84
5	44	70	0	16	27	64	70	2	2	1	$1,830,894.80	36	2,704,097.84
6	10	63	71	43	97	98	12	2	2	2	$1,832,741.60	36	2,704,097.84
7	9	15	55	42	37	42	31	1	1	2	$1,961,275.87	36	4,556,064.96
8	21	83	95	35	75	31	18	2	2	2	$1,832,741.60	36	2,704,097.84
9	46	45	99	55	80	5	74	2	2	2	$1,832,741.60	36	2,704,097.84
10	83	1	85	72	64	89	80	4	1	1	$1,945,751.89	36	3,857,983.11
11	53	76	56	91	78	98	100	5	4	1	$1,363,662.60	22	3,313,032.61
12	80	86	98	96	80	70	83	5	4	1	$1,363,662.60	22	3,313,032.61
13	2	67	28	35	8	9	44	1	1	2	$1,961,275.87	36	4,556,064.96
14	10	15	40	15	40	5	10	3	1	2	$2,026,281.78	36	4,466,841.63
15	5	10	35	20	50	2	2	3	1	2	$2,026,281.78	36	4,466,841.63
16	76	1	29	12	80	41	75	2	2	2	$1,832,741.60	36	2,704,097.84
17	51	67	22	33	79	27	97	4	1	1	$1,945,751.89	36	3,857,983.11
18	23	27	2	63	7	63	1	1	1	2	$1,961,275.87	36	4,556,064.96
19	0	0	0	0	0	0	0	3	1	2	$2,026,281.78	36	4,466,841.63
20	100	100	100	100	100	100	100	5	4	1	$1,363,662.60	22	3,313,032.61

Table 1 includes probability values (P-1–P-7) as inputs to the system. Each probability matches with a project condition and defines its probability of occurrence as a percentage. As an example, P-1 represents the probability of occurrence of C1,

Adverse financial issues of owner. Similarly, P-2 stands for the probability of occurrence of C2, Adverse market conditions (affecting owner). The logic is the same for all seven conditions and their probabilities. Probabilities are then multiplied with the relative importance of their related conditions, and the score for material, equipment, and stabilizing additive selection is calculated by using all project conditions. The scores are further used to select the most feasible construction method.

In Table 1, simulations using extreme parameter values include simulating with no (zero) and maximum probabilities for all project conditions. In the case where all probabilities are 0% (Trial 19), there is no negative change regarding project conditions. This case can be referred to as the best-case scenario. In the case where all probabilities are 100% (Trial 20), all negative changes regarding the project conditions take place. This case can be referred to as the worst-case scenario. The model's behavior for typical conditions is also evaluated for the third test. The proposed SD model shows consistency in selecting the most feasible construction method. For example, when the same probabilities are input to different case studies (e.g., Trial 14), they output the same resource combinations as optimal, which implies the behavioral similarity of the proposed system to actual system behaviors. As a result, the changes in probabilities and relative importance weights of project conditions were successfully reflected to the CM selection and TCEI calculation in the model. The findings of these tests show the success of the decision-making model to characterize agent decisions by using multi-agents and IF-THEN rules.

CONCLUSIONS

The complex nature of construction projects makes it harder to satisfy multiple project objectives. A construction project can have several objectives, although the generally accepted ones are time and cost. Environmental impact has recently been considered together with time and cost objectives, as it is also affected by the impact of changing conditions in the construction system. This study proposed the need to understand such impact by using a system dynamics approach. The system dynamics model of a complex construction system has been developed to analyze construction method selections under the influence of changing project conditions. The model has utilized different types of resources to achieve time, cost and environmental impact objectives.

The results of the model have shown that the behavior of the SD model for typical and extreme conditions is consistent in selecting the most feasible construction method. Basing the model on previously validated project models and literature improves the model's structural similarity to an actual system. The changes in probabilities and relative importance weights of project conditions are successfully reflected in the CM selection in the model. Under the influence of project conditions, the model results in better resource utilization plans to achieve environmentally conscious construction. This emphasizes that multiple agents make decisions and take actions according to project conditions that have an impact on the flow of construction processes. Considering the findings, the proposed SD model is assessed to be effective in simulating multi-agent decisions and project processes.

As the data for the proposed model are collected from highway construction professionals and projects, the SD model is limited to this area. The model can be more generic when data from other types of projects are included. In the future, the project system can also be expanded to include objectives in addition to time, cost and environmental impact. Additional objectives would enhance the feedback mechanism to the decision-making system, so that much more factors can be taken into consideration for CM selections.

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Identify Information Exchanges by Mapping and Analyzing the Integrated Heating, Ventilating, and Air Conditioning (HVAC) Design Process

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ABSTRACT

Buildings consume 39% of the total energy in the United States. To address the urgent challenge to improve the building energy efficiency, numerous digital analysis tools have been developed. However, there is a general lack of interoperability among these tools which limits the collaborative potential or creates added work when using BIM on projects. In order for the industry to solve this interoperability issue in a concerted fashion, an overarching process model describing the building process and the information exchanges within is needed. As integrated design makes it easier for project team to deliver high performance buildings, and HVAC systems are critical to building energy performance, this research has begun to map out the HVAC design process in an integrated design environment, in which various digital tools will be used. With the process maps, the information exchanges among various digital analysis and simulation tools can be identified. The process maps developed by this research can serve as a foundation for the industry to overcome the interoperability challenges. For the design teams that are not familiar with integrated design process, this process model provides a generic guide for design planning.

INTRODUCTION

For the purpose of improving the energy efficiency of building design, many digital analysis and simulation tools have been developed. According to U.S. Department of Energy ((U.S. Deparment of Energy 2012), there are 131 energy simulation tools available in the market. Counting the load simulation, retrofit analysis, green building analysis, code analysis, and other analysis and simulation tools, the total number of building analysis tools exceeds three hundreds, and is still growing. However, those tools are generally not able to accommodate data sharing with all other software, hence do not communicate with each other well. This interoperability problem greatly impedes the integrated usage of the digital modeling and analysis tools in the design process. National BIM Standard (NBIMS) (buildingSMART alliance 2011) comes up with a method to bridge the interoperability gap using Industry Foundation Classes (IFC). One of the first steps of

this method is to develop process maps for various use cases. Currently, Information Delivery Manuals (IDMs) for different use cases are being developed by various organizations, mainly based on their expertise and interest. In the long run, this lack of coordination will cause problems as people cannot see clearly which missing IDMs need to be developed. In order for the industry to address this problem in a concerted fashion, a high level overarching process model with information exchanges identified is needed to demonstrate the big picture.

This research maps out the HVAC design process that can be supported with digital modeling solutions and implemented in an integrated design with the intent of identifying the needs for information exchanges. The reasons for this research to focus on integrated design process and the HVAC systems design are:

- Compared to traditional design, the integrated design approach more fully utilizes the professional knowledge of all related parties, which leads to a higher chance of energy efficient design solution. Integrated design also emphasizes higher utilization of BIM tools in the design process. Though isolated successful integrated design projects exist, many designers are still not clear about how to perform the integrated design process.
- HVAC systems are critical to the building energy efficiency. According to U.S. Environmental Protection Agency (EPA), HVAC systems consume 55% of the energy in a typical office building (National Action Plan for Energy Efficiency 2008). The Commercial Buildings Energy Consumption Survey (CBECS 2008) by U.S. Energy Information Administration shows that HVAC systems consume 33% of the electricity in a building. Previous design process models have done a good job in describing the general design process, but they rarely looked at the process from a system's perspective, including the HVAC systems design process.

Current understanding of the integrated design process. To better understand the integrated design process and the integrated building lifecycle, a workshop was hosted in Philadelphia, PA with 47 academics and industry professionals from various backgrounds. In the workshop the professionals were divided into three groups to map out the integrated design and building lifecycle process and identify the tools that enhance the process and information exchanges among the activities in the process. During process mapping task, it was found that there were strong disagreements among the professionals about when different activities occur, what can be called integrated rather than traditional, and what tools were best for integrated design and delivery processes. The debate around where and when each task needs to take place and what deliverables are essential to an integrated process shows a lack of process transparency, indicating that the whole design process is still unclear in people's mind. Hence developing process maps for integrated design process to show how activities are integrated throughout the design process will help people gain deeper understanding of the process and make the process more integrated and effective.

RESEARCH METHODOLOGY

The intent of this research is to map out the HVAC design process that can be supported with digital modeling solutions and implemented in the integrated design process. This will serve to identify the critical information exchanges in the process to help design team utilize digital tools as well as better understand the process.

The first step of the research was a literature review and content analysis of several well-known and well validated design process models. An initial set of integrated HVAC design process maps were developed building on the Integrated Building Process Model (IBPM) developed by (Sanvido et al. 1990), and also integrates process data from other resources like the Integrative Design Process (IDP) developed by (7group and Reed 2009). A series of interviews have also been conducted with experienced designers to help develop and review the initial process maps.

With the set of process maps developed from literature and interviews, a series of four HVAC process mapping workshops have also been conducted with experienced designers to validate and supplement the process maps by developing an independent typical HVAC design process. Process deliverables and information exchanges were discussed and identified. Two case study observations were also conducted on two small retrofit projects and their design processes are mapped out.

The data collected and the maps developed through literature, interviews, workshops, and case study observation were then analyzed using mapping techniques and content analysis. The process maps were refined and some information exchanges were identified.

PROCESS MODEL DEVELOPMENT

Redefine integrated design phases. In an integrated design, the process flow differs from traditional design. A key attribute of integrated design is to push design decisions upstream as far as possible as changes are more effective and less costly in the early phase of design. In addition, integrated design involves contractors early in the process and should leverage digital tools more intensely (American Institute of Architects 2007). Hence there is a need to redefine design phases to accommodate these attributes of integrated design and force people to rethink their assumptions about the process. To address this need, the process maps adopt and expand the Integrated Project Delivery (IPD) phasing definitions from American Institute of Architects (2007). The design phases are redefined to those shown in Table 1. The "Discovery Phase" as the first stage of the integrative design process is different from the IPD terminology because of the focus on retrofit project and because the predesign planning phase is an important part of the integrative design (7group and Reed 2009).

Table 1 Comparison of Phasing of Redefined Integrated Design Process and Traditional Process

Redefined Integrated Design Process Phases	Comparable Phase in Traditional Process
Discovery	Project Planning and Feasibility Study
Conceptualization	Expanded Programming & Conceptual Design
Criteria Design	Expanded Schematic Design
Detailed Design	Expanded Design Development and Construction Documents
Implementation Documents	Expanded Construction Documents and Shop Drawing Development

- The discovery phase is similar to the traditional planning and feasibility study phase. In this phase, the owner's needs and requirements are studied and defined, the Owner's Project Requirements (OPR) is established, and the constraints and the boundary of the project are studied.
- The conceptualization phase is the process of developing a program and an interdisciplinary design where alternatives of the main principles and system solutions are proposed. The alternatives are presented with pros and cons. After coordinative analysis, the design team recommends most feasible systems for further design.
- The criteria design phase is the process of refining and expanding the feasible concepts selected in the previous phase. At this stage, all the relevant principles and solutions are qualitatively analyzed and coordinated with other disciplines. System design is further with initial equipment sketches. A system schematic defining the logic of the HVAC system is selected for detailed design.
- The detailed design phase is a process of developing detailed design with the system components and distribution route layout finalized. Simulations of the systems and overall design are conducted to review the design. Development of preliminary specifications, drawings, and schedules begins in this phase. At the end of this phase, the design should be fully and unambiguously defined, coordinated and validated.
- The implementation documents phase should be a process of documenting how the design will be implemented, such as means and methods, based on the detailed design documentation (American Institute of Architects 2007). Contractors create shop drawings. BIM models are finalized.

HVAC Process design. The Integrated Building Process Model (IBPM) developed by Sanvido et al. (1990) is a generic integrated process model of essential activities and functions required to develop a facility and maintain the facility over its lifecycle. The IBPM consists of four models for four different phases of the building process, two of which are studied in detail in this research. They are the Integrated Facility Planning Process Model (IFPPM), and the Integrated Facility Design Process Model (IFDPM), which are developed through extensive interviews, site visits, expert

reviews, and validated through eight projects (Norton 1989). Because of the rigor and level of detail of the IBPM process, this research takes the high level of IFDPM and IFPPM as a framework and expands them to further level of detail with HVAC system specific process data. The IFDPM and IFPPM are checked against during the process development to make sure the rigor of the HVAC design process. Figure 3 shows the conceptualization phase activities from the IBPM represented by Business Process Management Notation (BPMN).

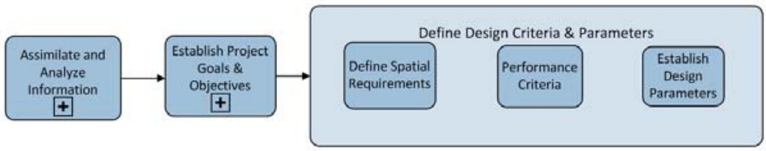

Figure 1 Discovery Phase Activities

With the IBPM serving as a high level process framework, additional literature was reviewed to extract HVAC design process data, including the HVAC design guides, ASHRAE design guide for energy efficient buildings(ASHARE 2011), and integrative design guide(7group and Reed 2009). The review also incorporated previously developed HVAC design process maps developed by Wix (2006), which show detailed information requirements among activities. Some information exchanges have also been identified through the interviews. An integrated design process workshop with 47 industry and academia participants was hosted in Philadelphia to initially map the integrated design processes. Those maps serve as a reference for the development of initial design process.

Several other process maps are developed through series of in-depth workshops and two case study observations. Content analysis was performed by cross comparing the process maps generated from workshops and case studies with the initial integrated HVAC process. There are several types of differences across process maps, appropriate measurements were taken for each situation:

- Activities sequential relationships are different. In this scenario, if no clear reasons are identified, such as the problem of different delivery method, more literature will be compared or it is noted to be resolved in the interviews,
- Activities describe tasks at different levels of detail. In this scenario, activities are merged, and the more detailed activities serve as part of the sub-process of the higher level activities,
- Activities are different because the process maps they are part of were generated from different perspectives and with different goals. In this scenario, decisions are made according to specific situation, and noted to be confirmed in interviews,
- Activities are supplementing each other. In this scenario, activities are either merged or both included in the new process map.

After comparing and merging all the process maps created through data collection process, process maps for the HVAC systems design were developed. One of the maps is shown in Figure 2, which is the detailed design phase of the HVAC detailed design process.

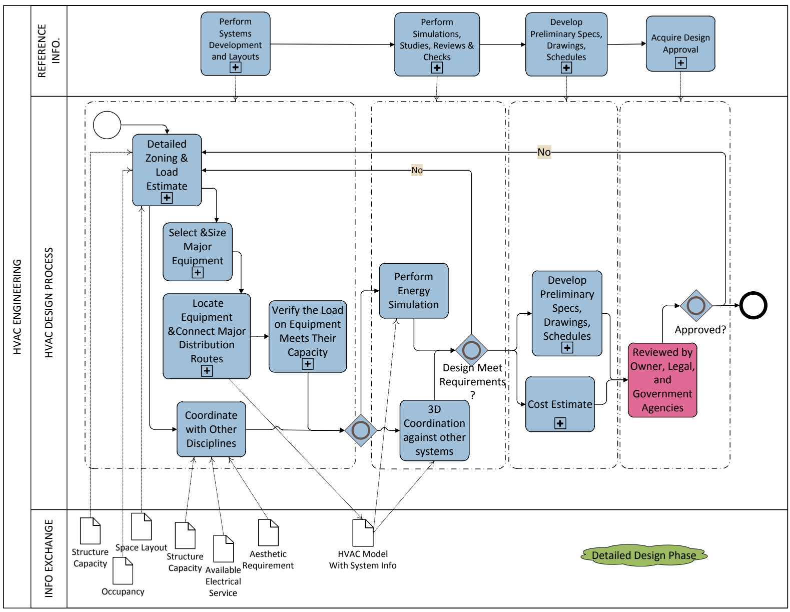

Figure 2. Detailed Design Phase of the HVAC Design Process

The above process map is also developed using BPMN. The top swim lane is the process of detailed design in IBPM. As mentioned previously, the IBPM process maps were used as a framework and high level reference that define the general sequence of HVAC design process. In the second swim lane, the four dashed boxes each contains a group of activities that correspond to the general activities in the first swim lane. This further expands the generic activities in IBPM from a HVAC system perspective. For example, from the perspective of HVAC systems design, the general activity "Perform System Development & Layout" in the IBPM can be further developed into five activities, 1) Detailed Zoning & Load Estimate, 2) Select & Size Major Equipment, 3) Locate Equipment and Connect Major Distribution Routes, 4) Verify the Load on Equipment Meets their Capacity, and 5) Coordination with other disciplines. After the development of the processes, the necessary steps are shown to identify the information exchanges among the tasks in the process. In the detailed design phase, information of building load data is exchanged between the load calculation activity and the HVAC equipment design activities, which indicates the need of information exchange between the load simulation software and the HVAC authoring software. Also, "HVAC systems model with System Info" feeds into the activity of "Coordination between Trades" and "Perform Energy Simulation." This indicates there are needs to exchange information between the HVAC authoring software and the 3D coordination software, and between the HVAC authoring software and the energy simulation software.

FUTURE RESEARCH

With the validated HVAC design process developed, and some information exchanges identified, the next steps are further developing the information exchanges both among the different disciplines in the integrated design process and among the various digital tools used in the processes. Interviews will be conducted with HVAC designers as well as designers in other disciplines who have integrated design experience. The interviews will help to identify the integration points in the HVAC process so that the process model can tie to other systems design models which are under development. With the process model, it is easy to find out when and how digital tools can facilitate the tasks in the process. It will be possible to identify when those program need to exchange information and what types of information through interviews with designers who are experienced with BIM tools and software vendors who know different programs well.

CONCLUSION

A process model for the HVAC system design that can be implemented in an integrated environment and supported with digital tools is beneficial to the process planning of the design team was developed. The information exchanges identified in the process lay the foundation for industry to develop methods of solving the interoperability issues. This research identified and built upon well-known and well-validated process literature. The research implemented IPD phasing definition and terminology for integrated design process. Combining literature review, interviews and workshop discussion, the research showed the current status of lacking transparency for integrated design and developed a set of process maps for the integrated HVAC design process, from which some information exchanges have been identified.

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A Dynamic and Context-Driven Benchmarking Framework for Zero-Net-Energy Buildings

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ABSTRACT

The building sector has consumed a significant portion of energy produced in the United States. In order to achieve Zero-Net-Energy (ZNE) for Buildings in the near future, designers need to consider energy consumption and CO_2 emissions during planning and design stages. Benchmarking is the systematic process of measuring performance against best performers to determine best practices leading superior performance. Today, benchmarking, such as the Energy Star designation, is already being applied to measure building energy performance. However, questions still remain as to how effective the benchmarks are. Due to the uniqueness of each building and the dynamic nature of building operations, the value of dynamic and context-driven benchmarking is not fully understood. This paper presents a framework for using automatic data collection techniques, such as sensors, to contextualize and compare the energy consumption and CO_2 emissions of a building. The authors also discuss how these benchmark data can be used in planning and design phases.

INTRODUCTION

A significant portion of energy is consumed by the building sector. Globally, buildings account for 40% of the world's energy-use (WBCSD 2009). In the United States, the building sector consumes 49% of all energy produced in the US

(Architecture 2030 2011), whereas building in the European Union accounts for only 25% of the total annual energy consumption (Beusker et al. 2012).

In order to reduce the amount of energy consumed in the building sector, there have been various efforts to design and develop zero-net-energy (ZNE) buildings. A ZNE building is defined as ‘a building where, as a result of the very high level of energy efficiency of the building, the overall annual primary energy consumption is equal to or less than the energy production from renewable energy sources on site.’ (Hernandez and Kenny 2010; European Parliament 2009). Torcellin et al. (2006) describe a ZNE building as a building with greatly reduced energy needs through efficiency gains.

The energy performance measure is one important step towards reaching the ZNE goal (Torcellin et al. 2006). Since 1979, the Commercial Building Energy Consumption Survey (CBECS) performed by the US Department of Energy (DOE) has measured the energy performance of buildings. The survey data have been used by the ENERGY STAR rating system and Leadership in Energy and Environmental Design (LEED) for energy performance benchmarking. However, the efficacy of these benchmarks is questionable. This paper presents how the energy performance for building has been measured and used for benchmarking, problems in the current energy performance benchmarking system, a framework for the new benchmarking system, and solutions for the realization and application of the system.

BENCHMARKING FOR BUILDING ENERGY PERFORMANCE

Benchmarking is a continuous process to search and implement the best practices leading to superior performance by measuring performance and comparing it to the competitors in the market (Camp 1989). Some key concepts in benchmarking include performance measures, comparison with competitors or a peer group, development of best practices, and the ongoing management process. Benchmarking, if well implemented, generates various benefits, such as better decision-making (Beatham et al. 2004; Costa et al. 2006), more efficient work, and more proactive managers (Garvin 1993; Costa et al. 2006). These concepts enable best practices to be creatively incorporated into the internal processes of building in order to achieve competitive advantage (Camp 1989).

The benchmarking technique has been applied to energy performance as well. Currently, the Environmental Protection Agency’s (EPA) ENERGY STAR building label and LEED by the US DOE and US Green Building Council are the most popular programs for measuring and evaluating the energy performance of buildings. The ENERGY STAR program provides an energy star score on a scale of 1 to 100. The score is determined based on the comparison of a building’s source energy-use among a peer group of buildings. For example, if a building’s energy star score is 50, this means that the building’s energy performance is average. Buildings scoring 75 or higher earn energy star certification (ENERGY STAR 2011). Energy-use data collected by CBECS are employed for the scoring. The US DOE performs this survey every four years. Using the data, the peer group is determined by taking various factors into account. These factors include the building’s physical characteristics,

such as building type, size, and location, as well as the building's operational characteristics, including operation hours, number of workers, etc.

The LEED program determines a building's energy performance points by comparing its energy performance to a baseline building's performance which is generated by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers' (ASHRAE) standard 90.1-2007 for new buildings (USGBC 2011). For existing buildings, Energy Star Rating and benchmarking against the energy performance of similar types of buildings in the national average source-energy data (CBECS) are used (USGBC 2008).

As the LEED certification considers the energy performance, it is reasonable to assume that LEED-certified buildings show better energy performance than the national average obtained by the CBECS dataset. Indeed, reduction in building energy needs is the strongest motivation for green renovation work by building owners (McGraw-Hill Construction 2010). By comparing LEED-certified buildings and non-LEED buildings, Turner and Frankel (2008) found that LEED buildings show better energy performance. However, the report also found that 25% of the LEED buildings had energy star ratings below 50, indicating that the energy performance of those buildings is below average. Another finding from the report is considerable variance between the estimated energy-use of a baseline building and the actual energy-use of a building. This means the actual energy-use can be substantially higher than the estimated value in the planning or design phase. The findings highlight the need to revisit the factors influencing energy performance and the benchmarking system comparing the estimated and actual energy-use.

DYNAMIC AND CONTEXT-DRIVEN BENCHMARKING

As discussed in the previous section, the current energy performance measures show significant variance between the estimated energy-use and actual energy-use. There can be various reasons for the inconsistency, which include operational issues such as occupancy or operating hours, construction change, knowledge transfer gap between the design team and end-user, and type of activity (Turner and Frankel 2008; Newsham et al. 2009; Sabapathy et al. 2010).

Among the various presumable causes, this study focuses on operational issues and type of activity. First, the current system probably misses some factors influencing the level of energy-use by a substantial amount. For example, even among buildings in the same region with the same purpose, size, and operation hours, the level of energy consumption can vary depending on the types of activities that building users participate in. Second, how the buildings are operated can significantly affect the energy-use. For example, the maintenance of factors contributing to energy consumption during operation hours, such as temperature, humidity and light control, and others, should have an impact on energy performance. In addition, how these factors are maintained after operation hours is another aspect related to energy-use.

In order to consider the aforementioned causes, measurements of post-occupancy energy-use are instructive. The idea is that the types of activities in which people participate should be identified to measure energy consumption. In addition, the measurement should be real-time or dynamic to better understand how energy is

consumed both during and after operation hours. Linking the energy consumption information to the context-driven information will help to identify which factors influence energy performance. The information can then be used for benchmarking in the planning and designing phases of new building construction.

Figure 1 illustrates the idea. First, there should be multiple sensors measuring various factors, including weather condition, energy-use, indoor occupancy, and types of activities. The data generated from the sensors should be entered into a server integrating all data. In order to identify factors relevant to energy performance, some data processing skills, such as data mining and pattern recognition, should be applied. Then, the information should be entered into the benchmarking system comparing energy performance. The system can be used when estimating energy performance for the new buildings in the planning and design phases.

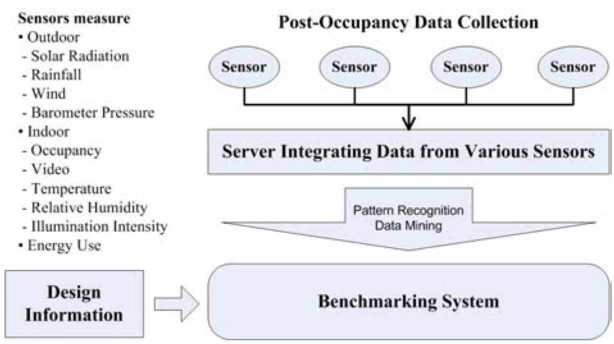


Figure 1. A Benchmarking Framework for ZNE Buildings

FRAMEWORK IMPLEMENTATION

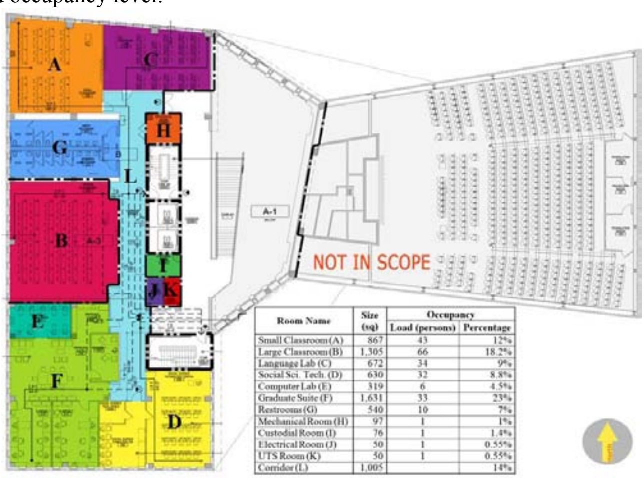
In order to test the framework in Figure 1, the authors started to analyze and deploy a smart-sensor computing infrastructure system, compatible with the Metasys® building management system from Johnson Controls. The purpose of the system is to collect real-time data and identify factors affecting the level of energy-use. For this test, Florida International University's (FIU) newly LEED Gold-certified School of International and Public Affairs was chosen. The building, shown in Figure 2, consists of five-floor levels with a footprint of 56,000 sf. The building's five-floor levels are oriented along the west side of the site, while a two-story auditorium flanks the east side of the building.

The SIPA-LEED engineers conducted an hourly baseline simulation using the TM2 weather file for Miami IAP, Climate Zone 1A, and the ASHRAE 90.-1-2004, Appendix G assessment. The baseline comparison was conducted with the Energy Star TARGET FINDER scoring 64 from the Energy Star Portfolio. The baseline claims that SIPA is 33.1% more energy efficient than the Energy Star baseline building through the use of increased insulation levels, highly efficient glass, a lighting design which is over 50% more efficient, occupancy sensors, and an efficient HVAC system. This also includes a small-scale Photovoltaic array composed of

UniSolarFlexlight panels which utilize amorphous silicon technology (thin film) to produce 38,700 KWH/year or only 4% of the building's estimated annual energy load.

Figure 2. Site Plan and Northeast View of the SIPA Building

Currently, there are some sensors installed in the building. In addition to them, more sensors measuring various factors will be installed on the second floor of the building. The second floor is comprised of small and large classrooms, a language lab, a social science technology center, a computer lab, graduate suites, and support areas. The facilities that are being surveyed on the second floor receive direct and indirect daylight from the north, west, and south elevations. However, much of the daylight that affects the second floor enters from the west elevation. Figure 3 shows the floor map and occupancy level.



Room Name	Size (sq)	Occupancy	
		Load (persons)	Percentage
Small Classroom (A)	867	43	12%
Large Classroom (B)	1,305	66	18.2%
Language Lab (C)	672	34	9%
Social Sci. Tech. (D)	630	32	8.8%
Computer Lab (E)	319	6	4.5%
Graduate Suite (F)	1,631	33	23%
Restrooms (G)	540	10	7%
Mechanical Room (H)	97	1	1%
Custodial Room (I)	76	1	1.4%
Electrical Room (J)	50	1	0.55%
UTS Room (K)	50	1	0.55%
Corridor (L)	1,005		14%

Figure 3. Second Floor Map and Occupancy

MEASUREMENT AND DATA COLLECTION

The measurement of energy consumption for all loads (HVAC, lighting, etc.) as it relates to indoor and outdoor environmental variables (temperature, relative humidity, illuminance, etc.) as well as usage patterns (number of occupants, etc.) over a period

of time are the two most important components of this study. To ensure the validity of the planned benchmarking effort, the followings have been identified as key criteria for the measurement process:

i. Accuracy
ii. High temporal and spatial resolution
iii. Adequate aggregation for trend and pattern identification
iv. Synchronization of measurements of different parameters for correlation studies

Based on these criteria two complementary systems have been selected to collect the data of interest. The first one is the preinstalled sensor and actuator system of Johnson Controls Inc. (JCI). JCI sensors continuously measure the temperature and relative humidity in every room at a single point, temperature of the blown air and return air in all individual HVAC air ducts, electrical power consumption of lighting systems on all floors, and electrical power consumption of the central HVAC unit. The measured data is uploaded to JCI's proprietary METASYS server for real-time monitoring and archiving through a dedicated network. Even with its extensive capabilities, the current JCI system has some deficiencies for this project. It measures temperature and relative humidity in only the rooms and at only a single point. Monitoring these environmental variables in high-traffic hallways, however, might be useful or even necessary for accurate benchmarking. The preinstalled JCI system neither monitors the outdoor environmental variables, nor the occupancy/presence of the space under study. Illumination level is also not measured at any point. It was therefore necessary to install a complementary sensor network with different components. A wireless sensor system from MONNIT™ has been chosen to measure the temperature, relative humidity, and intensity of light in lux (luminescence/unit area) at multiple points in each room. The points have been selected to allow for the extraction of the spatial gradient of the measured parameters. The measured data can be wirelessly transferred to a dedicated web server for storage. To monitor the occupancy level in the rooms and the traffic in the hallways, wireless network cameras have been adopted for installation. These cameras can be remotely controlled and the acquired video processed using in-house developed software to extract the number of people in the rooms or in the hallways. Outdoor environmental variables are monitored using the HOBO™ outdoor weather station which continuously measures temperature, relative humidity, light intensity, rain, wind speed, and wind direction. This system can also wirelessly upload the measured data to a dedicated webserver. The data collected from different sources are time-stamped to study the correlation between different parameters, specifically the effect of environmental variables and usage patterns on energy consumption.

USE OF THE BENCHMARKING DATA IN THE PLANNING AND DESIGN PHASES FOR ENERGY-EFFICIENT BUILDING CONSTRUCTION

During the planning and design phases, the proposed benchmarking system can be used to support component design and overall building design. Typically, a design process involves proper selection of building orientation, form and shape, materials, and building system. The selection decisions will be reflected in the choice

of building components. Figure 4 shows a partial conceptual framework that illustrates the integration of building components (only exterior enclosure and roofing), performance, and the proposed benchmarking system to support planning and design.

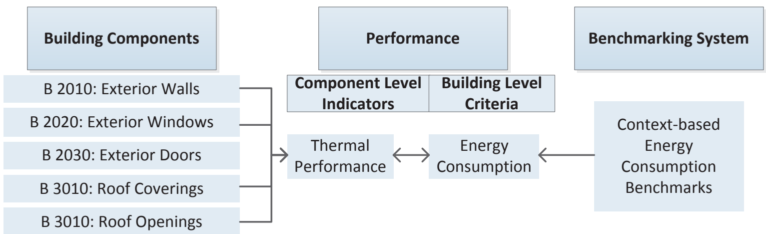


Figure 4. Integration of Building Components, Performance, and Benchmarking

For example, if energy consumption per square foot per person is a metric used for benchmark at the building level, the actual value used to evaluate a design varies according to the particular context of the building, such as location, use, and occupancy patterns. This value is then used in comparison with a simulation or estimation result based on the thermal performance of associated building components such as exterior walls, windows, and doors. It is expected that the use context-based benchmark will result in the better selection of building components.

CONCLUSION AND RECOMMENDATION

This paper presents a conceptual framework for a dynamic and context-driven benchmarking system. The current energy performance benchmarking system shows considerable variance between the actual energy-use and the estimated energy-use. This paper suggests a dynamic and context-driven benchmarking system that can take various operational issues and occupant activity types into account. It also presents the building that the authors have used to test the framework. Important criteria for measurement and data collection as well as use of the benchmarking data in the planning and design phases are discussed as well.

Once the framework is tested, there are many further issues to be investigated. For more meaningful apples-to-apples comparisons of energy performance, a hierarchy consisting of various criteria for sorting data should be developed. In addition to identifying the criteria, prioritization is also important as the benchmarking results could be affected by the priority of these criteria. In the current ENERGY STAR rating system, weather file, climate zone, and building type are the prioritized criteria for data sorting. With more criteria, the setting-up of the hierarchy should be studied. Metrics incorporating the new criteria should also be investigated. If the metrics are absolute (i.e., actual value per actual value), normalization is one issue to be investigated. The lack of consistent benchmarking and measurement being used to evaluate the benefits of ZNB buildings is one significant hindrance to deploying more ZNB buildings (McGraw Hill Construction 2010). Studies investigating how to quantify the benefits will contribute to resolving this hindrance.

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Radiance-based Model for Optimal Selection of Window Systems

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ABSTRACT

Daylighting performance is one of the primary metrics used for evaluation and selection of window systems. Radiance is one of the most accurate software tools for lighting simulations of buildings. However, it is difficult to use Radiance in the early stages of the daylighting design because of the complexity of the tool and uncertainty and variability of the design parameters. Repeated modifications of different design parameters are required in order to select appropriate design. As a result, simulation runtime is significantly increased. To solve the conflict between accuracy and length of simulation runtime, this research proposed a two-phase model for selection of window systems that can be used in the early design stages. The model uses Radiance for daylighting simulations and calculates the daylighting metrics by utilizing the optimization methods. A case study was conducted to illustrate the application of the model. This model not only provided relatively accurate daylighting simulation results but also reduced the overall simulation runtime.

INTRODUCTION

Windows influence the daylighting penetration and the transmitted solar gain. Illuminance levels at sensor points are usually used for evaluating the daylighting performance of window systems. The complexity of geometry of the space model and the uncertainty of design parameters of window systems make it difficult to manually calculate illuminance. Daylighting simulation tools mainly based on ray-tracing or radiosity algorithms were developed to offer flexibility that other methods (e.g., manual calculation, scale model) sometimes cannot provide (Heckbert 1990). According to the survey conducted by Reinhart and Fitz (2006), 50% of daylighting simulation tools used the Radiance simulation engine validated by Mardaljevic (1995; 2000). The Radiance-based annual simulation method "*Three-Phase Daylight Coefficient*" method (from now on this method would be mentioned herein as the three-phase method) developed by Ward et al. (2011) can simulate illuminances at sensor points for complex fenestration systems (see Eq. (1)) (Ward et al. 2011).

$$i = VTDs \qquad (1)$$

Where i = result vector (illuminances, or luminance); V = view matrix, relating outgoing directions on window to desired results at interior; T = transmission matrix, relating incident window directions to exiting directions (BSDF); D =

daylight matrix, relating sky patches to incident directions on window; s = sky vector, assigning luminance values to patches representing sky directions.

The three-phase method was based on the concept of daylight coefficient (DC) (Tregenza and Waters 1983) which is calculated by VTD in Eq. (1). The sky is divided into 145 patches and the sun is assigned to near patches. Once the building geometry and materials are defined, the contribution coefficient (i.e., DC) of a sky patch to a sensor point is kept the same no matter what absolute radiance value the sky patch may have.

The parametric design approach is normally used to select window system and a number of simulations have to be conducted in order to test different design parameters. The simulation time in the case of testing all possible parameters may become long and thus unacceptable if the window locations or types of windows systems are not well-defined. Therefore, the aim of this research was to develop a model that would optimize the process of the window system selection. The model was developed based on the three-phase method. The preliminary and detailed selection processes were conducted by the model.

METHODS OF THE MODEL DEVELOPMENT

The overview of the model structure is shown in Figure 1. The input information of the model included simulation parameters and building model. The simulation parameters specified the simulation periods and sky types needed for daylighting simulation. The simulation can be done annually or for a specified time period. The building model contains information related to the building geometry, reflectance of building surfaces and the material and structure of window systems.

In Phase I, the model was used for a preliminary evaluation of window systems to select a set of possible window types. A standard building model was created as a baseline for comparing the daylighting performance of different window systems. In Phase II, the ranking of the possible types and locations of window systems would be derived from the simulated illuminance levels. The two phases used three-phase method to calculate the illuminance values. Genetic algorithm (GA) was used in Phase II to determine the optimal window types and locations.

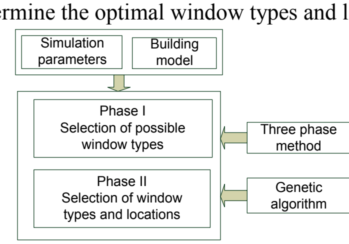

Figure 1. Overview of the model structure

PHASE I OF THE MODEL

A standard baseline building model was created to compare the performance of window systems without using the surface reflectance values. Two metrics were

calculated in this phase: (a) daylighting distribution along the surface and (b) the ratio of the transmitted daylighting to the total available daylighting.

Setup of baseline building surface. The baseline space model is shown in Figure 2. The area of the window system was calculated based on the window to wall ratio and the wall area. The window was located in the middle of the wall. The reflectance of interior surfaces was set to black (i.e., RGB values were zero). The width (W) of the space was equal to the height (H) of the space. The depth (D) of the space which was equal to the three heights H was used to analyze the daylighting distribution. Each surface (wall, floor and ceiling) was further separated into three evenly spaced subdivisions (P1, P2, and P3). The daylighting illuminance decreased exponentially with the increase of the distance from a window (Bansal and Saxena 1979). A single simulation evaluated one control state if movable shading system was used.

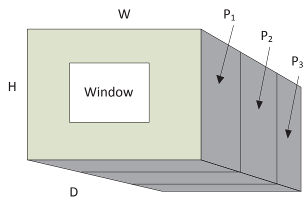

Figure 2. Prototype of the baseline building model

Metric calculation. The standard three-phase method developed by Ward et al. (2011) was used to calculate the illuminance at a sensor point. In Eq. (1), the s vector had a dimension of 146 x 1 for Tregenza sky subdivision with 146 patches (including ground). Vector s could be calculated by using Radiance genskyvec and gensky programs. The V matrix (numberOfSensorPoints x 145) and D matrix (145 x 146) were calculated by using Radiance rtcontrib program. T matrix (145 x 145) showed the transmittance values between interior and exterior surfaces of the window by using a full Klems BSDF basis. T matrix was included in the BSDF file which could be either measured or simulated using Window 6 (Huizenga 2011) or Radiance genBSDF program (Ward 2010). When a window system had an uneven surface (e.g., light shelf), subdivision should be used to divide the window surface into smaller areas and calculate BSDFs in different sections (Ward et al. 2011). Thus, multiple BSDFs were used for a single system.

The sensor points inside the baseline building were automatically added to the space surface by using a recursive algorithm similar to the binary search algorithm (see Figure 3).

```
Function Setup_Point(Point_1, Point_2)
  If (the difference of illuminances between Point_1 and Point_2 is larger than maxDiff)
      Add a sensor Point_3 point in the middle of Point_1 and point_2;
      Setup_Point(Point_1, Point_3);
      Setup_Point(Point_3, Point_2);
```

Figure 3. Pseudocode of sensor point setup

The illuminance distribution curve could be displayed by plotting the illuminance values against the distance of sensor points from window (see Figure 4).

From this curve, three metrics were calculated to compare the daylighting performance: (a) the ratios of the maximum illuminance value in each surface patch (i.e.,P_1:P_2:P_3 in Figure 3); (b) average illuminance ratio which was calculated by comparing the bounded areas S_1, S_2 and S_3 , where S_i ($i = 1, 2, 3$) is the area bounded by the two vertical lines, curve and the X axis as shown in Figure 4; (c) the transmittance ratio which was used to evaluate transmittance capability of the system and calculated by dividing summation of the transmitted rays that emit toward the floor by the total available outside rays. After the metric values were calculated, the metrics were ranked. Based on this ranking the user of the model selected the window types that were then prepared for the Phase II of the model.

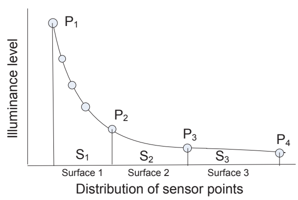

Figure 4. An example of the daylighting distribution curve

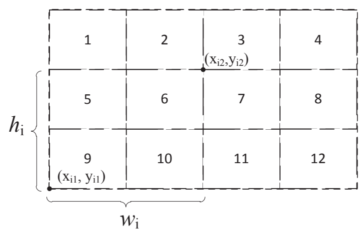

Figure 5. Patch division for possible locations of window

PHASE II OF THE MODEL

The main steps in Phase Ⅱ included (a) window subdivision and (b) daylighting simulation. The illuminance was calculated based on a revised three-phase method (see Eq. (2)). This method used a subdivision scheme to divide the possible window surface into smaller patches. The total illuminance level E at a sensor point was calculated by summation of illuminance transmitted from patches i that were occupied by windows. Genetic algorithm was used to select window types and locations.

$$E = \sum (V_i T_i) Ds \quad (2)$$

Window subdivision. The surface of a window system was divided into a number of patches. A daylighting system may occupy an integer number of patch areas. For example, in Figure 5, the whole possible area in which the window may be located has 2 x 2 patches. The actual window area might only cover or occupy two adjacent patch areas. By assigning different patch number, the window could have different locations and sizes.

The i^{th} window cannot be arbitrarily located in the wall surface and users should specify the constraints of the allowable locations. The constraint f_i specified the relationship among the lower left corner (x_{i1}, y_{i1}), the upper right corner (x_{i2},y_{i2}) and the window dimension (height h_i and width w_i) (see left part of Eq. (3) and Figure 5). Because the inequality (3) is linear, it could derive the right-hand side of the Eq. (3). The variable e_i denotes slack variables.

$$f_i(x_{i1}, y_{i1}, x_{i2}, y_{i2}, h_i, w_i) < 0 \Rightarrow g_i(x_{i1}, y_{i1}, x_{i2}, y_{i2}) = h_i(h_i, w_i, e_i) \quad (3)$$

By selecting different combinations of the values h_i, w_i and e_i, the coordinates (x_{i1}, y_{i1}) and (x_{i2}, y_{i2}) of the window area could be determined. The entire possible window coordinates (x_{i1}, y_{i1}) and (x_{i1}, y_{i1}) as well as BTDF would be stored in a data structure retrieved in the daylighting simulation phase (Phase 2) of the model.

Daylighting simulation. The possible position of the sensor points that would be used to evaluate the daylighting performance of window systems were set up by users. After that, the revised three-phase method was used to calculate the illuminances. The rtcontrib program was used to calculate the matrices V, D for each patch area as shown in Eq. (3). The genskyvec program could calculate the vector s. The matrices V and s were calculated once and then were stored. The times of calculating matrix D depended on the number of subdivisions of the window surface. Similar to Phase I, the matrix T was derived from BSDF files.

The selection of the location, dimension and material types of a window system is a combinatorial problem which may be solved by using genetic algorithms (GAs). The chromosome representation of GAs (see Figure 6) includes two sections. The first section represents the coordinate along the diagonal of the window system and the second section represents the index number of the BSDF files.

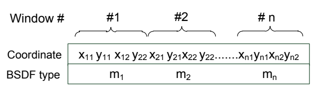

Figure 6. Chromosome representation

The objective function of GAs would be selected or defined by user of the model. Possible objective functions included maximizing useful daylight illuminance (UDI) (Nabil and Mardaljevic 2005), daylighting factor (DF), or horizontal workplane illuminance. Other functions might be used as long as the functions could be derived from the luminance or illuminance values. The objective function was used to calculate the fitness values that would be used to evaluate the solutions of the problem. The pseudocode of the fitness calculation is shown in Figure 7. A penalty value would be added to the fitness value in case the coordinate values do not satisfy inequality as shown in Eq. (3), for example, if the two window areas are overlapped or crossed.

The patch areas that were not covered or occupied by window surface were actually wall surfaces and thus they would reflect light. However, it was assumed in Eq. (3) that these patches are light sources and that no light is reflected from these patches to sensor points. Calculated illuminances would be smaller than actual illuminances as a result of lack of the reflection from these areas. Therefore, the function Correct_Error() shown in Figure 7 was used to compensate this reduction in the illuminance values. If a patch j was not covered by the window area, the illuminance values E_j at a sensor point due to light reflection from patch j was calculated by Eq. (4). It was assumed that the patch j had a Lambertian surface and had the same outgoing luminance value for each Klems angle.

```
Calculate the patch set G according to the chromosome information and each patch element g in the
set G is occupied by the window;
If (Coordinates represented by the chromosome violates the inequality of Eq. (3))
        Add a penalty value to the fitness value;
        Return the fitness value;
        For (each single patch element g in the patch set G)
            If (if illuminances at sensor points generated by a patch g are not calculated)
             // T (or BSDF) is selected based on the shading control state and
            // position of patch within the wall surface.
                Retrieve the matrices V, T, D, s from the database for each patch;
                Use Eq. (2) to calculate the illuminance values at the sensor points;
                Correct_Error(); // correct errors
                Store the calculated illuminance values for patches G to the database;
           Else //illuminance value was stored in the database, no need to calculate.
                Retrieve the illuminance value from the database;
                Add illuminance from each patch together to get the total illuminance
     Return the fitness value derived from total illuminance at sensor points;
```

Figure 7. Pseudocode of the fitness calculation

$$E_i = \sum_j \left[V_{ij} I_j \right] = \sum_j \left[V_{ij} \sum_k (V_{jk} I_k) \right] = \sum_j \left[V_{ij} \sum_k (V_{jk} T_k D_k s) \right] \tag{4}$$

Where V_{ij} (1 x 145) is the view matrix from patch j to a sensor point i; The luminance matrix I_j (145 x 1) defines the outgoing luminance of the patch j for each Klems angle. V_{jk} is the view matrix from patch k (occupied by windows) to patch j (not occupied by windows); the luminance matrix I_k (145 x 1) defines the outgoing luminance from the patch k covered by window for each Klems angle. T_k and D_k denote the transmittance and daylighting matrices for the patch k respectively; s (145 x 1) is the sky vector.

CASE STUDY

In Phase I, the model used the standard three-phase method which was simple to implement. The case study focused on the Phase II of the model. An office model created by the OpenStudio software (NREL 2011) had the dimensions 3.6m (width) x 3m (height) x 5m (depth) (see Figure 8). The window was located in the south wall. Twenty smaller patches defined the possible window locations. Three types of glass might be used: clear (#1), bronze (#2) and grey (#3). Automated blind system was used to keep illuminance at the sensor points below 2000 lx. The slat angles of the blinds could be set to -45°, 0°, 45°, and 90°.

The Ruby script "ModelToRad.rb" was used to convert the OpenStudio model to Radiance model (NREL 2011). CIE overcast sky type was chosen as the sky type. Two different windows that might be located in any of the possible 20 patch areas were simulated at the same time. The seven sensor points (SPs) were located at a specific distance from the window ranging from 0.5m to 3.5m with an increment of 0.5m (see Figure 8). The objective function of the GA was to maximize illuminance at sensor points and maintain it below 2000 lx.

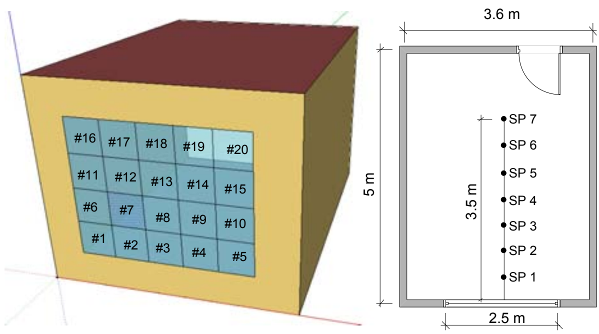

Figure 8. Perspective view and floor plan of the office model

In GA settings, uniform crossover was applied to the two sections of chromosome (see Figure 6). The probability of the gene mutation was set to 0.05. The simulation of GA was conducted by Matlab using a laptop with GPU 1.6 GHz. The simulation runtime was approximately 0.47 seconds. The values of illuminance levels obtained by simulation are shown in Table 1.

Table 1. Strategies for window selection (strategies correspond to sensor points)

Sensor Point/ Strategy	Illuminance (lx)	Window #1			Window #2		
		Position	Glass Type	Slat angle	Position	Glass Type	Slat angle
1	1304	#1-#10	#3	-45°	#11- #20	#1	-45°
2	1012	#1-#5	#2	-45°	#6-#20	#1	-45°
3	998	#1-#10	#1	-45°	#11-#20	#1	-45°
4	316	#1-#10	#3	0°	#11-#20	#1	-45°
5	195	#1-#10	#3	0°	#11-#20	#1	-45°
4	133	#1-#10	#1	0°	#11-#20	#1	45°
7	99	#1-#10	#1	45°	#11-#20	#1	0°

Seven possible strategies that correspond to the seven sensor points can be used for the selection of the window parameters to meet the objective function (see Table 1). The positions of the sensor points affected the selection of window types. When the objective function was applied to different sensor points, the types and locations of window systems calculated by GA were different. The illuminance was affected by the glass types and slat angles. Each row in Table 1 shows the optimal glass types and window locations for the specific sensor point. The optimal result in each row can give the maximum illuminance at that SP. The best strategy was to split the windows into upper (Window 1) and lower (Window 2) sections. The user should first determine which sensor point would be used to evaluate window systems, and then select the strategy according to Table 1. For example, if the objective is to maximize the illuminance at SP 2, the strategy/parameter values given in the second row should be used. Thus, the patches #1-#5 (in the lower section of the window) should use glass type 2 and patches #6-#20 (in the upper section of the window)

should use glass type #1. The slat tilt angle should be -45° in each window section. Similarly, if the objective is to maximize the illuminance at SP 5, the strategy/parameter values given in the fifth row should be used.

CONCLUSIONS

A two-phase model based on three-phase method was developed to help designers select appropriate window types and locations. The selection of windows was based on illuminance values at sensor points. In Phase I, the properties of the window systems were emphasized without considering the reflection of interior surface. In Phase II, daylighting simulation based on Radiance was conducted to calculate illuminances. Design parameters such as glass types and locations of window systems were selected based on objective functions of genetic algorithms. The model would be especially useful in the early stages of building design when many parameters were uncertain. A case study was conducted to illustrate the major process (i.e., Phase II) of the model. The validation of the model is an objective of the next phase of the research. The model may be validated by comparing this model with another model that utilizes the standard Radiance simulation.

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Identification of Potential Areas for Building Retrofit Using Thermal and Digital Imagery and CFD Models

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ABSTRACT

Monitoring actual energy performance of existing buildings and measuring performance deviations from benchmarked values can help identify the potential areas for building retrofit. However, current building auditing practices include application of energy simulation tools or sensor networks, which can be time-consuming and may only provide system or appliance-level retrofit suggestions. In this paper, a quick and cost-effective approach is presented to recognize potential areas for building upgrade using digital and thermal imagery in addition to Computational Fluid Dynamics (CFD) models. In the proposed method, a dense 3D point cloud model of an existing building is first generated using an image-based 3D reconstruction algorithm. Next, thermal images are fused by a novel thermal mapping algorithm. The expected thermal performance is then simulated by CFD analysis using the dimensions extracted from the reconstructed 3D building model. Finally, the actual and expected thermal performance models are automatically superimposed within a new Energy Performance Augmented Reality (EPAR) environment wherein performance deviations are visualized. The proposed method is validated on several rooms in an existing instructional facility. The experimental results reflect the promise that EPAR models can be used as a building retrofit decision-making tool to facilitate the retrofit process.

INTRODUCTION

Through the U.S. government's plan for "*Better Buildings*", efforts for more energy efficient buildings are continuing by reforming tax policies and providing new incentives for retrofit (DOE 2011). These initiatives are forming at the time when about 150 billion square feet of existing buildings (roughly half of entire building stocks in the U.S.) will need to be renovated over the next 30 years to meet the requirement of rigorous energy efficiency programs such as LEED and ENERGY STAR (Gould and Hosey 2009). In the meantime, recent statistics from the U.S. Department of Energy (DOE 2010) show that 87 percent of overall residential buildings and 74 percent of total commercial buildings were built before 2000. As a result, 86 percent of building construction expenditures is now being committed to renovation of existing buildings rather than new construction (Holness 2008). Under

this unprecedented market opportunity, the building industry is continuously facing with several technical challenges in identifying potential areas for retrofit:

1) Current building retrofit practices using existing energy performance simulation tools (e.g., EnergyPlus, Ecotect, and eQuest) are time-consuming and labor-intensive. Currently building geometry is mainly formed from as-planned CAD models or by using traditional field surveying techniques (e.g., tape measurement). Using the resulting geometry plus various simulation inputs (e.g., weather data and operation schedules), modelers manually develop 3D energy simulation models which can be later used for validating each retrofit alternative. As a result, significant modeling time and effort are required for building auditing activities.

2) Current methods using existing energy performance simulation tools focus on comprehensive measurement of energy usage in buildings (i.e., calculating the energy required to heat, cool, and light). These methods can only support decision-making related to building retrofit at the level of "building systems" (e.g., potential energy saving with retrofit of the heating system or windows). In the meantime, retrofit suggestions based on building energy audit tools (e.g., Microsoft Hohm and ENERGY STAR Home Advisor) particularly focus on 'what' consumes energy in buildings and provide more practical retrofit suggestions (e.g., change specified appliances). Nonetheless, these methods require many assumptions to model the as-is energy consumption status of a building. For example, all areas in a building are assumed to have similar insulation condition during each simulation process. As a result of these assumptions, these approaches may not provide accurate results.

3) Recent advanced sensing technologies (e.g., wireless sensor network (Wang et al. 2010) and voltage and current measurements without sensors (Berges et al. 2011)) help eliminate such questionable assumptions by using the measured data within an actual energy consumption modeling process. Monitoring appliance-level energy load data in buildings using sensors may involve time-consuming and costly installation processes. More importantly, these methods cannot determine high energy consumption resulted from construction defects or degradations. For example, due to poor thermal comfort caused by heated air loss through insulation void, occupants of a building may operate their heating systems more frequently. In such conditions, the heating system might be detected as the most suitable alternative for retrofit, while the actual reason for high energy consumption is the improper insulation of the building components. As a result, appliance-level electricity load monitoring cannot detect the building areas in need for retrofit.

To address these challenges, this paper presents new image-based 3D reconstruction and thermal mapping algorithms as well as a Computational Fluid Dynamics (CFD) modeling approach. Using digital and thermal imagery plus a CFD modeling approach, the proposed method focuses on identifying the deviations between actual and simulated thermal performances. Analyzing the deviations can help recognize potential areas for retrofit. In the following, we first give an overview of the related works in actual and simulated energy performance modeling. Next, the underlying approach in identifying potential areas for retrofit is presented. Finally, the results are presented on an actual case study and the potential benefits and limitations of our proposed method are addressed.

BACKGROUND AND RELATED WORKS

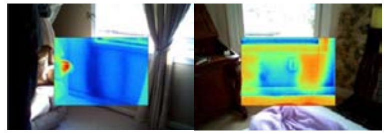

Figure 1. Traditional 2D thermography of existing buildings (HomeInspex 2011)

Actual energy performance modeling of existing buildings - A detailed perception of the performance of the built environment in which we live can be obtained by merging data acquired from different sensors (e.g., digital cameras, laser scanners, and infrared sensors). Among multi-sensor data fusion approaches, *thermal mapping* is a robust technique in recording, analyzing, and reporting actual energy performance of existing buildings. This process involves detecting and measuring variations in heat emitted by objects through thermal imagery and transferring them to visual images. Thermal images from buildings are directly influenced by the building energy performance such as energy transfer through building components (e.g., thermal bridges) or space heating and cooling energy related to HVAC (heating, ventilation, and air conditioning) systems. Currently, most research on thermal mapping for building retrofit is based on 2D images (HomeInspex 2011, GeoInformation 2007). Figure 1 shows examples of 2D thermal mapping for existing buildings. Despite the benefits, these approaches require manual texture-mapping of all pairs of thermal and digital images in an ordered manner. Furthermore, these methods may cause non-systematic and subjective decision-makings due to the absence of an expected thermal baseline to identify performance deviations. To geo-register the visual thermal performance data in 3D and provide a detailed interpretation and visualization of the object under investigation, a 3D thermal modeling approach is needed. In this context, Stockton (2010) presented a 3D infrared thermal monitoring system to sense, analyze and manage power and cooling operations in a data center. This work shows the effectiveness of 3D thermal mapping for building retrofit, yet due to the manual process involved in creating image mosaics and performing texture-mappings, this approach may also be time-consuming and labor-intensive.

Expected energy performance simulation of existing buildings - Current building energy simulation software (e.g., EnergyPlus, Ecotect, and eQuest) are valuable tools for evaluating overall energy and thermal performance of buildings, yet they can only provide general indication of thermal performance within a given space. These methods do not provide detailed information of 3D spatial distribution of thermal performance. In the meantime, Computational Fluid Dynamics (CFD) analysis can provide detailed information on thermal distribution and user thermal comfort analysis (Butler et al 2010). This analysis can assist in solving the conservation equations for thermal energy. Malkawi and Srinivasan (2005) introduced integrated augmented reality architecture for immersive visualization of indoor thermal data using CFD simulation and environmental sensors. DesignBuilder (2011) also presents a new approach combining CFD analysis with EnergyPlus. These works show the benefit of CFD analysis for evaluating building environment, yet require manual 3D spatial data collection for model setup. To generate environment maps, Lakaemper and Malkawi (2009) suggested utilizing a mobile robot mapping module which enables the spatial geometry modeling using laser feedback acquired by range sensors

to incrementally scan each room. Due to confined indoor environments, using a robot for interior modeling of residential buildings may be challenging and expensive.

OVERVIEW OF THE PROPOSED METHOD

Figure 2 shows an overview of data and process in our proposed method which includes three steps: 1) automatically generating an actual 3D spatio-thermal model; 2) analyzing expected building thermal performance using CFD analysis; and 3) creating an Energy Performance Augmented Reality (EPAR) environment, comparing actual and simulated models, and finally examining the deviation to find potential areas for retrofit. The following sections describe each step:

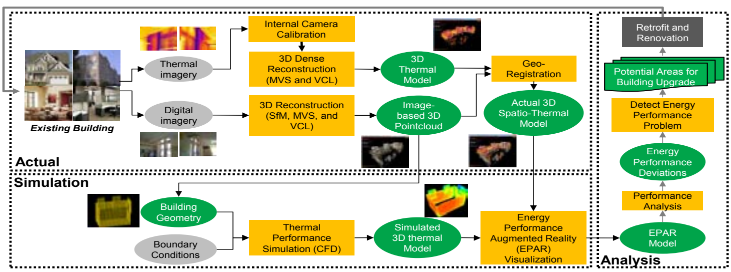

Figure 2. Overview of the proposed method

Actual 3D spatio-thermal model - Our method is based on a streamlined 3D image-based reconstruction algorithm which consists of Structure-from-Motion (SfM) (Snavely et al. 2008), Multi-View Stereo (MVS) (Furukawa and Ponce 2009), and Voxel Coloring/Labeling (VCL) (Golparvar-Fard et al. 2012), which can generate dense 3D image-based point cloud models from unordered collections of digital images. To generate 3D spatio-thermal model, thermal and digital images need to be co-registered to re-project thermal values captured in 2D thermal images back into the reconstructed 3D scene. To that end, our initial approach was to form Epipolar geometry (Hartley and Zisserman 2004) between every pair of digital and thermal images and compute the Fundamental matrix between each pair. In order to automate this process for all pairs, extensive experiments were conducted on the state-of-the-art invariant feature detection algorithms including SIFT, ASIFT, SURF, and MSR to investigate whether feature points can be detected and matched across these pairs. In all cases, these algorithms worked poorly or did not work at all (in most cases resulted in detection of less than 10 corresponding feature points). This is due to typical low resolution of thermal images, lack of distinct features, and significant radial distortion in thermal imagery. Thermal cameras use gradient color coding to capture thermal performance which smoothen all surface intensities. As a result, there is no distinct visual feature that can be detected. To overcome this challenge, we first compute the intrinsic parameters of the thermal camera by using a *thermal calibration rig* (550*mm*×700*mm*) using 42 small LED lights located on the intersections of the conventional

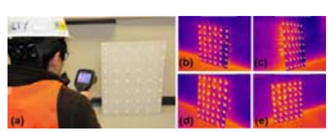

Figure 3. Thermal camera

checkerboard (See Figure 3a). Prior to calibration, the temperature range for thermal map color coding is fixed to make sure each gradient of color is corresponding to an absolute temperature value. Since the thermal camera only identifies thermal differences, they cannot clearly distinguish conventional checkerboard intersections. Once the LED lights are on, they generate heat, and the thermal camera which has thermal sensitivity of $0.05°C$ can easily distinct the heat points (See Figure 3b-e). Since the thermal camera lens is always fixed, this process only needs to be conducted once per camera and does not need to be repeated for different experiments. Through this process, the thermal camera is internally calibrated (i.e., the focal length and radial distortion parameters are calculated). Next, we extract the extrinsic parameters of thermal cameras (the location and orientation) from the results of the SfM step conducted on corresponding digital images. This process is valid for most new thermal cameras as they enable simultaneous capturing of digital and thermal images. Subsequently, using the intrinsic camera parameters, the thermal images are undistorted. The undistorted thermal images along with camera projection matrices which consist of the intrinsic and extrinsic parameters are then fed into the dense 3D reconstruction pipelines (MVS and VCL), resulting in a dense 3D thermal model. Finally, the 3D thermal and image-based point cloud models are automatically superimposed to generate the actual 3D spatio-thermal model (details in Ham and Golparvar-Fard 2012).

CFD simulation - To create the 3D geometric model of enclosed spaces for CFD analysis, we extract the 3D coordinates from the generated 3D image-based point clouds. As a proof of concept, in this paper, the boundary points (e.g., corners of windows) are manually extracted from the 3D point cloud model. Meshing the model and specifying each building component are then followed for energy simulation.

Analyzing deviations between the actual and expected thermal performances - The raw CFD result from simulation is first converted to Virtual Reality Modeling Language (VRML) format which is a graphics interchange format that allows export of 3D geometrical entities. The resulting CFD model needs to be aligned with the actual 3D spatio-thermal model so that the actual and expected performance deviations can be identified. Superimposition includes geometric transformations (e.g., uniform scaling, rotation, and translation) to overlay the VRML with 3D spatio-thermal model. In our approach, the 3D spatio-thermal and VRML based CFD model have the same Cartesian coordinate systems since the 3D coordinates used to create a 3D geometry for CFD analysis were directly extracted from the 3D image-based point clouds. As a result, the two models are automatically superimposed. The final step of our work is to compare the actual thermal performance from 3D thermal model with the expected thermal performance from the CFD model in a single augmented reality environment. For this purpose, we modified the D^4AR – 4D Augmented Reality Model viewer (Golparvar-Fard et al. 2009) to EPAR visualizer to enable visualization of the actual and simulated performance models, in addition to digital and thermal imagery. Details of this process can be found in (Ham and Golparvar-Fard 2012).

EXPERIMENTAL RESULTS

Data collection and model assumptions – To validate the proposed method, several

case studies were performed on an office of an existing facility on campus of Virginia Tech. In these experiments, digital and thermal images are captured using an E60 FLIR Systems thermal camera which has a built-in digital camera. Gambit 2.2.30 and Fluent 6.2.16 are respectively used for both simulation model-setup and CFD analysis. Building physical components are modeled in 3D as follows: The ceiling is modeled as gypsum board, interior walls and floor modeled as concrete masonry units and concrete respectively, and interior doors and windows modeled as closings. Table 1 shows the detailed specifications of the camera and the model assumptions for the CFD analysis.

Table 1. Camera Technical Data and Initial Boundary Conditions

Contents	Value
Digital Image Resolution	2048×1536 Pixels
Thermal Image Resolution	320×240 Pixels
Thermal Sensitivity	0.05 °*C*
Thermal Measurement Accuracy	±3.6 °*F*
Viscous Model	Standard *k-ε* model
Temperature of Inlet Air (Heating System)	305 °*K*
Velocity of Inlet Air (Heating System)	0.2 *m/s*
Air Thermal Conductivity	0.0242 *W/m.K*
Concrete Thermal Conductivity	0.7 *W/m.K*
Glass Thermal Conductivity	0.96 *W/m.K*
Gypsum Board Thermal Conductivity	0.17 *W/m.K*

Results – Figure 4a shows the actual 3D spatio-thermal model which is the superimposition of the image-based 3D reconstructed scene (8,488,888 points from 429 digital images) (Figure 4b) with the dense 3D thermal model (2,064,662 points from 429 thermal images) (Figure 4c). Figure 4d presents the result of the CFD analysis using the 3D wireframe and the resulting mesh models (Figure 4e and f). This model contains the expected thermal performance data. Figure 4g, h, and i show the actual and simulated energy performance from the same camera viewpoint in a single 3D environment. Once a registered camera is visited in the augmented reality environment (Figure 4a and d), the frustum of the camera is automatically texture-mapped with a full resolution of each thermal (Figure 4h) or digital image (Figure 4i). The user can interactively acquire information related to thermal performance and building condition of the area under study. In Figure 5a-c, EPAR models (simultaneous registration of the actual and simulated energy performance models) are visually illustrated. The EPAR models can provide critical information about how temperature values are spatially distributed in a given space and can identify thermal performance deviations at the time when digital and thermal images are captured.

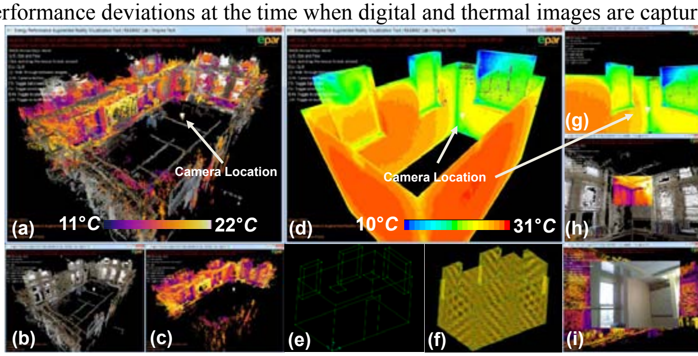

Figure 4. Actual 3D spatio-thermal and the CFD simulation models

Table 2. The deviations between the actual and simulated thermal performance

Temperature of Point Clouds(°C)	Section1 μ	Section1 σ	Section2 μ	Section2 σ	Section3 μ	Section3 σ
Actual Measurement	11.2	0.35	15.1	0.32	16.7	0.16
Simulated Result	14.8	0.29	16.7	0.1	18.1	0.17
Deviations+	(3.47, 3.72)		(0.41, 1.31)		(0.66, 0.7)	

+ $\Delta(\mu\text{-}2.05\sigma, \mu\text{+}2.05\sigma)_i$ where i is each section

As a proof of concept, we chose three areas for comparison between actual and expected thermal performance models (See Figure 5c): 1) An area in the corner of two intersecting walls, 2) an area around a window, and 3) a flat surface of the inside of an exterior wall. The temperature values from both actual and simulated models were measured by collecting 20 points within the selected areas. Each point cloud is color-coded in RGB values wherein each color indicates a distinct temperature. Table 2 reports the deviations between the actual and simulated temperatures in form of mean (μ) and standard deviation (σ) from all 20 points readings per each area. In this case, the deviation is reported by considering a 96% confidence in measurement accuracy (i.e., $\mu \pm 2.05\sigma$). These differences found between the two measurements can enhance practitioner's ability to find potential candidates for existing building retrofit. More experimental results can be found at www.raamac.cee.vt.edu/epar.

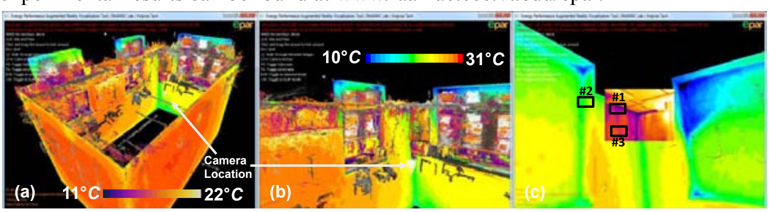

Figure 5. Energy Performance Augmented Reality (EPAR) model

CONCLUSIONS AND FUTURE WORK

Energy performance estimations obtained from energy simulation tools typically deviate from the actual building energy performances. To identify and quantify the deviations (the potential building retrofit candidates), we presented a new rapid and cost-effective 3D thermal mapping approach which uses digital and thermal imagery, in addition to CFD analysis. The proposed method visually highlights building energy performance deviations. It can also help reduce the time and cost required for retrofit through easy identification of energy problems in existing buildings. Our future works involve implementing extensive experiments and creating an algorithm for fully automated quantification and visualization of performance deviations using multiple data sets collected over time. These areas are currently being explored as part of our ongoing research.

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Assessing IECC Energy Saving Potential for Residential Construction in Florida

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ABSTRACT

Florida has become the third largest consumer of electricity in the United States. Its residential energy demand is about 1400 trillion BTU which is among the highest in the country. In an effort to reduce residential energy consumption, the State of Florida is conducting extensive efforts to improve the energy efficiency of existing building codes. One of the recent developments in this regard includes its decision to use more elements of the 2009 International Energy Conservation Code (IECC) as the foundation. The aim of this paper is to study the energy savings potential of the proposed 2012 IECC for residential construction as compared to the current Florida Energy Efficiency Building Code (FEEBC). A baseline model of a single family house was developed using BIM and simulations were conducted using different geographical locations in Florida with varying number of cooling degree days. After performing the energy analyses of the model for the selected cities using FEECBC, it was modified based on the proposed IECC 2012. The two sets of analyses were then compared to check the impact of those modifications on the overall energy performance of the baseline model house in each selected city. This research further strengthens the idea that the recent advancements in BIM/Simulation technologies play an important role in energy efficieny decision making.

INTRODUCTION

A rapidly growing demand for better energy performance in buildings is leading to an ongoing development of strategies and technologies to improve energy efficiency in construction without compromising on comfort, cost, aesthetics and other performance considerations. The focus of the world's attention on environmental issues in recent years has stimulated responses in many countries which have led to a closer examination of energy conservation strategies for conventional fossil fuels. Buildings are important consumers of energy and thus important contributors to emissions of greenhouse gases into the global atmosphere (Pitts 1994). For the past 40 years, due to low energy prices in the United States, there was little concern for energy-efficient design of buildings. With the oil shocks of the 70s, an increased awareness of energy and the environment led to greater interest and research in the use of energy in buildings and its environmental consequences

(Diamond 2001). There is still a lot of work to be done for establishing and practicing the performance standards to evaluate structures according to the international standards (Raheem 2011).

According to U.S. Energy Information Administration, Florida's per capita residential electricity demand is among the highest in the country, due in part to high air-conditioning use during the hot summer months and the widespread use of electricity for home heating during the winter months. In 2006, Florida residential energy consumption was 767.6 trillion Btu and that was almost doubled at the end of 2007 and it rose to 1,294 trillion Btu in 2009 (U.S. EIA 2011). Energy consumed for space heating was 5 million Btu per household and the average amount spent for space heating is $83 per household. Electricity consumed for air conditioning is 13 million Btu per household and the average amount spent for air conditioning is $322 per household (RECS 2011).

With the current domestic energy consumption scenario, this expenditure will likely to increase in the future. In Florida due to high temperatures and humid climate electrical energy consumption is relatively higher. As described by FPSC "the residential customers' electrical usage varies more throughout the day than commercial usage and shows more pronounced peaks in the early evening in the summer and in the mid-morning and late evening in the winter" (FPSC 2009).

ROLE OF TECHNOLOGICAL ADVANCEMENTS IN DECISION MAKING

Over the past few years, there has been an undeniably rapid development in computer technology. These recent developments in information technology have enhanced the capabilities of the construction industry leading towards more energy efficient solutions. There are many energy simulation programs available in the market which provides users with key building performance indicators such as energy use and demand, temperature, humidity, and costs (Crawley et al. 2008). These technological advancements are helping the construction world keep up with the ever changing energy demands by providing help in making timely decisions.

METHODOLOGY

A baseline model of a single family house was developed using BIM and it was simulated using different geographical locations with varying number of cooling degree days in Florida. The general data of the baseline model were taken from two resources: 1. Energy Information Administration (EIA) - for general characteristics of single family houses in U.S. 2. Florida Energy Efficiency Code For Building Construction (FEECBC) -for insulation and equipment efficiency values in Florida. The total square footage of the baseline house was 2275 square feet. U.S. Census data (2010) show that the size and number of dwelling units per building in new single family units has decreased by about 2% in 2009 due to the increased trend in building energy efficient housing. After performing the energy analyses of the model for the selected cities using the Florida Energy Efficiency Building Code (FEEBC) 2010, it was modified based on the proposed IECC 2012 requirements. The two sets of analyses were then compared to check the impact of those modifications on the overall energy performance of the baseline model house in each selected city.

BASE MODEL CHARACTERISTICS

Number of Stories: 1
Floor space: Heating space (SF) = 1950, Cooling space (SF) = 2100
Footprint and height= 65’ x 35’, Floor-ceiling height= 8.5ft
Perimeter=200’
Garage 2-car
Foundation: Concrete slab
Rooms: Bed rooms: 2, Common room: 1, Full bathroom: 1, Half bathroom: 1
Windows Area (SF): 192, Number: 12, Type: Double pane, Low E (e3=.2)
Insulation: FEEBC

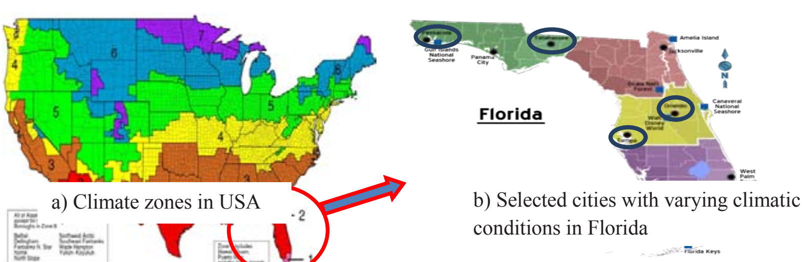
CLIMATIC LOCATIONS USED IN ENERGY SIMULATIONS:

Figure 1 shows the IECC Climate Zone map describing a widely recognized system that helps defining climate conditions particular to the buildings in any specific climatic zone. This map served as the basis for energy-related requirements for our baseline model. Five different locations were selected having variety range of cooling and heating degree days. The cities selected were Orlando, Tampa, Tallahassee, Pensacola and Miami (Table 1). Hour-by-hour energy consumption was calculated over an entire year (8760 hours) using hourly weather data for each selected city.

Table 1. Selected Cities with Cooling and Heating Degree Days (Adapted from: HomeInsight Year 2011)

City	Cooling Degree Days*	Heating Degree Days*
Orlando	3,426	566
Tampa	3,427	725
Tallahassee	3,105	560
Pensacola	3,124	760
Miami	3,339	656

*Base 68F



a) Climate zones in USA

b) Selected cities with varying climatic conditions in Florida

Figure 1. U.S. Climate zones (Source: U.S. Department of Energy 2009)

IECC IMPROVEMENTS

The focus of IECC 2012 proposed improvements is on the building envelope so it sets more stringent insulation and fenestration levels requirements. Figure 2 shows the proposed R-values, fenestration values and solar heat gain coefficient values for various envelop components within different climatic zone (Fig 2). A major part of the Florida comes under zone 2 except the extreme southern part which is covered under zone 1 including Hawaii, Guam, Puerto Rico and Virgin Islands.

CLIMATE ZONE	FENESTRATION U-FACTOR[b]	SKYLIGHT[b] U-FACTOR	GLAZED FENESTRATION SHGC[b, e]	CEILING R-VALUE	WOOD FRAME WALL R-VALUE	MASS WALL R-VALUE[i]	FLOOR R-VALUE	BASEMENT[c] WALL R-VALUE	SLAB[d] R-VALUE & DEPTH	CRAWL SPACE[c] WALL R-VALUE
1	NR	0.75	0.25	30	13	3/4	13	0	0	0
2	0.40	0.65	0.25	38	13	4/6	13	0	0	0
3	0.35	0.55	0.25	38	20 or 13+5[h]	8/13	19	5/13[f]	0	5/13
4 except Marine	0.35	0.55	0.40	49	20 or 13+5[h]	8/13	19	10 /13	10, 2 ft	10/13
5 and Marine 4	0.32	0.55	NR	49	20 or 13+5[h]	13/17	30[g]	15/19	10, 2 ft	15/19
6	0.32	0.55	NR	49	20+5 or 13+10[h]	15/20	30[g]	15/19	10, 4 ft	15/19
7 and 8	0.32	0.55	NR	49	20+5 or 13+10[h]	19/21	38[g]	15/19	10, 4 ft	15/19

Figure 2. Proposed IECC 2012 Insulation, fenestration and SHGC requirements by components for each climate zone (Source: U.S. DOE 2011)

ENERGY SIMULATION:

The baseline model was first simulated using the 2012 Florida Building codes with weather data from the five selected cities in Florida. The results showed that the house in Miami consumed the highest KWh of electricity per year (Figure 3). This was anticipated due to the pretty hot and humid climatic conditions (longer cooling degree days) found in Miami.

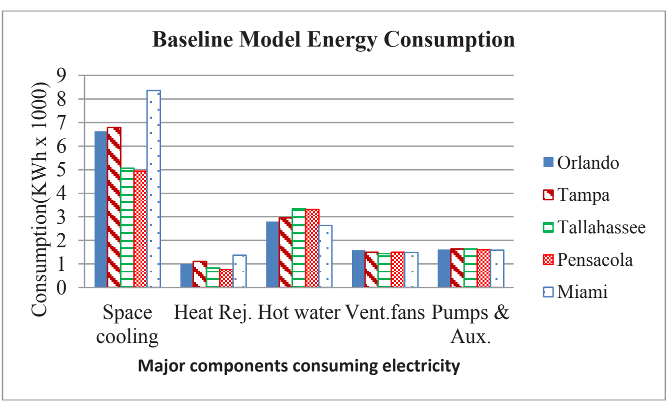


Figure 3. Energy consumption of baseline model using FEEBC

On the other hand the house simulated with the Pensacola weather file consumed the least KWh of electricity per year (Figure 3). Space cooling is the major electricity consuming component in each city contributing about 30% to the yearly electricity bill. The impact of the 2012 IECC code requirements were quantified by analyzing baseline models representing the envelope, lighting and mechanical requirements. After modifying the baseline model according to the proposed IECC requirements, it was simulated again using five different weather files for the selected cities in Florida. The results, as shown in Figure 4, indicated that there would be a savings of KWh of electricity by incorporating the IECC improvements.

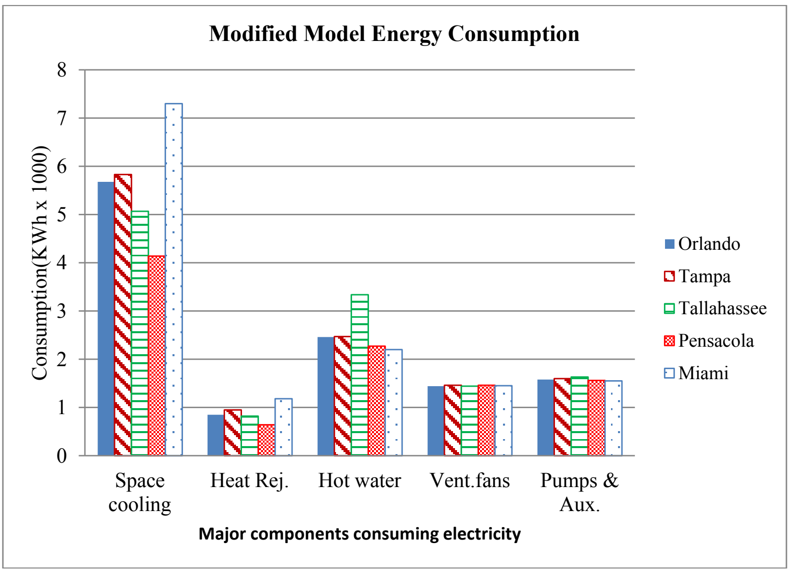


Figure 4. Energy consumption of baseline model using proposed IECC 2012 improvements

TOTAL ELECTRICITY CONSUMPTION AND SAVINGS

The baseline model simulated with Miami weather file came out to be the highest electricity consuming residence as compared to other cities but with the further analysis incorporating IECC 2012 proposal, it came out to be capable of saving 13.6% of KWh per year. The amount of savings ranges from 13.6% to 15% within these selected cities (Table 2).

Table 2. Percentage Electricity Savings per year

City	Electricity use per yr. (KWh x 1000) Baseline Model	Electricity use per yr. (KWh x 1000) After Modification	%age saving
Orlando	25.34	21.74	14.2
Tampa	25.66	22.03	14.14
Tallahassee	24.07	20.57	14.5
Pensacola	23.84	20.35	15
Miami	27.11	23.41	13.6

TOTAL DOLLAR SAVINGS PER YEAR

To assess the economic impacts of the 2012 IECC requirements, electricity rates per KWh were collected from different electricity provider companies in the selected cities and the averaged values were used to calculate yearly dollar savings after reducing electricity consumption due to 2012 IECC proposed improvements in U-values, R-values and SHGCs.

The results showed that there was a relatively consistent dollar savings across selected cities. It was observed that a single family household could save approximately $250 to $430 per year in the selected five cities. The electricity rate in Miami was the highest so the savings were the most evident (Fig 5).

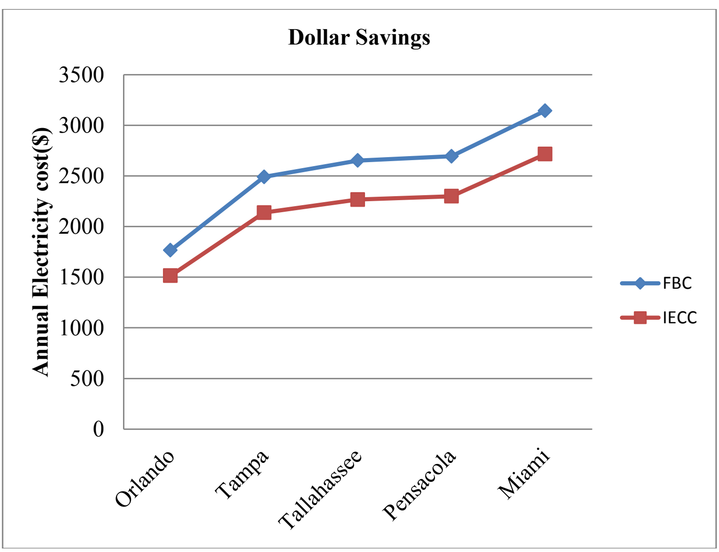


Figure 5. Dollar savings FEEBC vs. IECC

Table 3 shows the electricity rates per KWh and relative dollar savings in the selected cities in Florida. Miami electricity rates are the highest whereas Orlando has the lowest electricity rates among the sample cities. There was a substantial savings from the projected requirements of 2012 IECC in comparison to the baseline of the FEEBC.

Table 3. Total Savings per Year

City	Cost of electricity /KWh (cents)	Savings per year($)
Orlando	6.97	250.92
Tampa	9.706	352.32
Tallahassee	11.02	385.70
Pensacola	11.3	394.37
Miami	11.6	429.2

CONCLUSIONS

The importance of advanced simulation technologies for efficient decision making process is undeniable especially for the construction industry which is one of the highest energy consuming sectors. This research enabled the authors to assess the effects of 2012 IECC proposed improvements in different cities of Florida. It has been clearly deduced from the detailed energy analysis that 2012 IECC proposed improvements have a huge potential of KWh savings per year in Florida. These improvements propose strict emphasis on the efficient envelope design in terms of improved thermal resistance, thermal transmittance and solar heat gain coefficients and it is evident from the simulation results that in the selected five cities there was an average saving of 14% KWh of electricity per year. That means an average saving of \$360 per year. So to curb the ever increasing residential energy demand especially in Florida, it is imperative to incorporate the most efficient codes within the industry practice. By doing this the projected growth of residential energy consumption in Florida can be potentially reduced and the practice can set Florida on a way toward a more sustainable and prosperous energy future.

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