AC 2012-4082: INTEGRATING SENSING TECHNOLOGY AND BUILDING INFORMATION MODELING INTO A CONSTRUCTION ENGINEERING CURRICULUM

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John Polasek retired from the Michigan Department of Transportation (MDOT) in 2009 with 39 years of service. He started out as a Student Highway Technician. After graduating from Ferris State University with a degree in highway technology, Polasek went on to pursue his next degree at Michigan State University (MSU). Polasek received his B.S. degree in civil engineering from MSU in 1972 and was hired at MDOT. Over the years, he has worked in the Design Division, as a Staff Engineer for the Local Government Division, as the Kalamazoo District Design Engineer and Project Development Engineer, and as Region System Manager. In June 2003, Polasek was appointed Director of the Bureau of Highway Development, which oversees road and bridge design, including quality assurances and specialty areas such as electrical, hydraulic, and municipal utilities. The bureau is also responsible for administration of federal aid to local agencies and has statewide responsibilities for real estate, utilities, and transport permits. Polasek is a licensed Professional Engineer in the state of Michigan. After his retirement for MDOT in 2009, Polasek accepted a position of Adjunct Faculty in the College of Civil and Construction Engineering at Western Michigan University (WMU). He is the instructor and Coordinator for the capstone senior design program.

Integrating Sensing and Modeling Technology into a Construction Engineering Curriculum

Introduction

As the U.S. construction industry starts exploring and adopting various sensing (3.g., 3D laser scanners) and modeling technologies (e.g., mathematical modeling and optimization, Building Information Modeling) in recent years, a strategic plan of the Construction Engineering program at Western Michigan University is to equip students with relevant knowledge in response to this trend. As shown by multiple pilot studies in the past decade [123], various sensors, such as RFID tags[4] and laser scanners[5], show the potential of collecting real-time observations of construction sites to improve the situational awareness of construction engineers. On the other hand, various Building Information Modeling (BIM) systems (e.g., Autodesk Revit[6]), mathematical modeling packages (e.g., Lingo for Mathematical Modeling and Optimization [7]), and data processing tools (e.g., InnovMetric Polyworks for 3D data processing and reverse engineering [8]) have been adopted in various construction projects to improve the efficiency and effectiveness of information management and collaborative decision making. Overall, effective construction management need both the real-time field observations from job sites (*Sensing*) and various analysis supported by mathematical models, BIM and other virtual models depicting the built environments (*Modeling*). Large and complex construction projects in urban areas specially require these tools for responsive decision making throughout a construction project development cycle. Construction engineers, therefore, need to have comprehensive understanding about sensing and modeling technologies for addressing challenges posed by increasing number of large-scale construction projects.

Even the construction industry is aware of the potentials of various sensing and modeling technologies, effective integration of these technologies into the design-construction process is still challenging due to technical and organizational barriers. On the technical aspect, various sensors and modeling tools are available on the market while new sensors are being developed. The learning curves for most of these technologies are steep, so that the time and resources needed for training engineers to effectively use them are not trivial. On the organizational aspect, most existing construction engineering programs provide students hands-on experiences of selected sensors and BIM tools[910], while systematical introductions about how these technologies can transform the construction practice are limited. As a result, students may know these technologies, while lacking a comprehensive understanding on the relationships among construction practice, data collection (Sensing), and information management (Modeling). In addition, most construction programs currently focus more on product modeling (modeling the buildings using BIM); fewer efforts have been invested into construction process modeling and optimization. Limited understanding about how to optimize the construction process as a production system impedes engineers from identifying the bottlenecks of a construction process and choosing the most suitable technologies to address those bottlenecks. The lack of a systematical view of construction production system, therefore, is becoming a critical issue that needs to be addressed for educating engineers capable of adopting new tools according to a variety of construction engineering's domain needs.

Aiming at addressing the barriers described above, we are initiating efforts on systematically integrating sensing and modeling technologies into the Construction Engineering curriculum at Western Michigan University. In an engineering design course offered to freshmen, we introduce scheduling and BIM tools and their implications for the design-construction integration. In a series of construction engineering courses (e.g., Planning and Scheduling, Construction Cost Estimating, Construction Project Management) offered in the junior and senior years, we expose students to various sensing and BIM tools in various application scenarios (e.g., Construction Productivity Monitoring, Time-Cost Trade-Off Analysis). This program concludes with a comprehensive course "Sensing and Modeling for Construction Management" in the senior year to provide students a systematical view of the roles of sensing and modeling technologies for responsive management of complex construction projects, as well as senior design projects for students to apply the skills learned from these courses in real-world projects.

The following sections are organized into four sections: first, we presents an overview of a construction project development cycle and a number of engineering tasks posing challenges to construction engineers; second, we describes a number of sensing and modeling technologies that can address the challenges described in the previous section; third, we discusses what changes we had made on our curriculum to incorporate these identified technologies into the learning process; finally, we summarize the lessons learned and presents a plan for keeping on this systematical updates of the presented Construction Engineering curriculum.

Construction Project Development Cycle: A Landscape

A typical construction project development cycle is composed of four stages, as shown in Figure 1: design, construction, operation & maintenance, and renovation (disposal). Each stage involves collaborations in both the "virtual world" and "physical world." The physical world includes the physical conditions of the anticipated construction sites for developing designs and construction plans, the real-time physical conditions of job sites during the construction process for construction project control, and the physical conditions of constructed facilities for long-term facility operation and maintenance. In the physical world, participants of construction projects need to collect, process, interpret, and share data with each other to ensure that their activities would not have spatial or temporal conflictions. For instance, constructors working on installing roofs using a crane need to collaborate with others to ensure that the crane operations would not damage any constructed components and would not conflict with other construction activities.

The virtual world contains models describing the designs of the buildings (*Design Model*), the actual conditions on construction sites (*As-is Model*), the construction and operation processes (*Process Model*), and knowledge related to construction inspection and building performance management (*Code Model*). In other words, a virtual world contains digital models based on which project participants can collaborate with each other. These digital models contain both the design information and the as-is information. Engineers use the as-designed models to express the ideal conditions of the jobsite, while using the as-is models to communicate the actual jobsite conditions for decision making. Various sensing technologies acquire as-is information from the physical world to facilitate the interactions between the virtual and physical worlds, and enable engineers to collaborate with each other. For example, 3D laser scanners can capture the as-built conditions of construction sites, so that designers and constructors will have good understanding about the current construction progress and the as-is geometries of the workspace to safely carry out various construction operations[11].

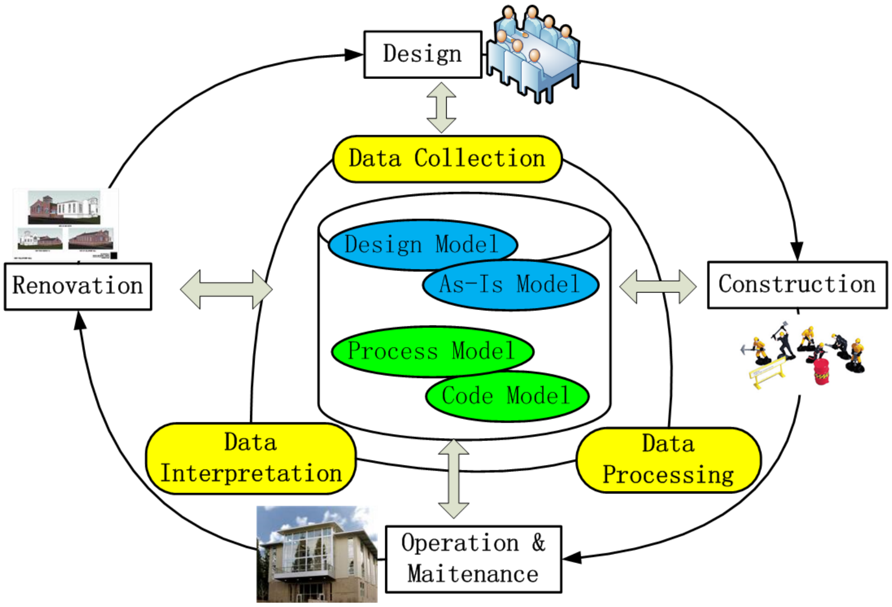

Figure 1 Roles of sensory data and information models in a construction project development cycle

Above discussions shows the roles of sensing and modeling technologies in a construction project development cycle. Sensing technologies collect data capturing the as-is information of construction sites, such that engineers can process and interpret these data to obtain as-is models. Modeling technologies generate the virtual world to support various analyses, so that engineers can exchange design, process, and other information to complete their tasks during a project development cycle. Table 1 lists seven engineering tasks occurring during a typical project development cycle, which involve various analyses that can benefit from sensing and modeling technologies, as will be detailed later. We identified these tasks based on our teaching practice, detailed analyses of our construction engineering curriculum, and feedbacks of our students about what are the most-needed skills for their career development in the construction industry.

Sensing and Modeling Technologies for Construction Project Development

The seven engineering tasks listed in Table 2 pose various challenges to construction engineers during a project development cycle. These challenges include: 1) *time constraints*, construction sites change frequently and it is challenging for engineers to collect, process, and interpret large amounts of data for large construction sites; 2) *resource constraints*, spaces, labor, and other resources for collecting, processing and interpreting data are limited, and it is challenging for engineers to acquire as-is information within stringent resource constraints; 3) *information quality constraints*, most engineering tasks have certain requirements about the accuracies and levels of details of the as-is information, and it is challenging to acquire detailed and accurate information on construction sites within time and resource limits; 4) *information integration*, as the data and information models are of different formats, it is challenging to streamline the process of integrating multiple data/information sources for supporting various analyses. Previous studies reveal that BIM is a platform addressing the information integration related challenges [10], but the discussions on the first three aspects are still limited.

Table 1 Engineering tasks potentially requiring supports from sensing and modeling technologies and engineering analyses related to them

Engineering Tasks	Engineering Analyses and Domain Requirements
Design development	Assist engineers to effectively conduct value engineering analysis [12] and budget cost estimating
Construction Scheduling	Assist engineers to efficiently develop, simulate, analyze and optimize construction schedules in terms of time/spatial conflictions and other risks
Construction Cost Estimating and Analysis	Assist engineers to efficiently develop, update, analyze, and optimize construction cost estimates, and acquire quantitative awareness of the implications of various changes in the design-construction workflow
Construction Project Control	Assist engineers to efficiently acquire and analyze as-is conditions of construction sites for monitoring the construction progress, quality, safety
Material Management	Assist engineers to quickly and precisely location materials and equipments on construction sites for efficient and effective resource allocations according to the needs on jobsites; assist engineers to track components and equipments in the supply chain during the life-cycle of them for detailed analyses of the histories of building components as well as constructed facilities
Life-Cycle Cost Management	Assist engineers to analyze and optimize the life-cycle costs of various facilities throughout a project development cycle
Sustainability and Maintenance Analysis	Assist engineers to monitor the conditions of constructed facilities, and analyze and optimize the resource allocations for maintaining constructed facilities

In this study, we conducted systematical analysis about seven engineering tasks listed in Table 1, and found that all these tasks have time, resource, and information constraints. Table 2 shows the analysis results, which indicate that in addition to BIM, two other modeling techniques, process modeling and optimization techniques have the potential for addressing challenges brought by these constraints[13]. On the other hand, our construction engineering curriculum has not yet integrated process modeling and optimization techniques. Table 2 also shows that different engineering tasks require different as-is information, which can be best acquired by different sensing technologies. For example, for task "Design Development," the imaging technology can capture the detailed as-is geometries of the job site for developing the design, while for task "Material Management," RFID technology is more suitable as these tasks require history information of components in the supply chain, rather than detailed geometries of them [14]. In our curriculum updating process, Table 2 serves as a strategic view guiding our decisions about which technology should be introduced in which courses to form a systematical integration of sensing and modeling technologies into our Construction Engineering curriculum.

Table 2 Sensing and modeling technologies for supporting the engineering analyses required by various engineering tasks in a typical construction project development cycle

	Sensing Technology	**Modeling Technology**	
		Information Modeling	**Decision Science**
Design Development	Imaging Technology for Site Modeling	Building Information Modeling (BIM) and Clash Detection	Design Optimization
Construction Scheduling	Imaging Technology for Site Modeling	Product and Process Modeling, BIM, 4D CAD	Construction Plan Optimization, Simulation
Construction Cost Estimating and Analysis	Imaging Technology for Site Modeling	BIM for Cost Estimating	Time Series of Cost Indices
Construction Project Control	Imaging Technology for Progress Monitoring	BIM for Construction Coordination	Data Collection Optimization
Material Management	Radio Frequency Identification (RFID) for Tracking Materials	BIM for Construction Site Control	Inventory Model and Optimization
Life-Cycle Cost Management	Energy Sensors, Occupancy Sensors, Imaging Technology for Building Performance Monitoring	BIM for Energy Performance Simulation and Evaluation	Economic Analysis, Life-Cycle Cost Optimization, Simulation
Sustainability and Maintenance Analysis	Imaging Technology, Contact Sensors	BIM and GIS for Construction Site Selection	Optimization of the Maintenance Strategy of Constructed Facilities

Curriculum Design for Integrating Sensing and Modeling Technology

The analyses of engineering tasks in a typical construction project development cycle and technologies needed by various engineering tasks motivate a number of changes in the Construction Engineering curriculum at Western Michigan University. Table 3 lists the courses that have been updated so far, the technologies incorporated into the course materials, and the software tools that we had used for teaching those technologies. Among courses listed in Table 3, the first four courses (Introduction to Engineering Design, Construction Planning and Scheduling, Construction Cost Estimating and Control, Construction Project Management) focus on introducing various engineering analyses and how various sensing and modeling tools can support these analyses. We have two lectures of each of these four courses as lab sessions in computer labs so that students can have hands-on experiences of using modeling and data processing tools to solve problems defined by the instructors. Course projects of these courses must show the uses of sensing and modeling tools for solving the engineering problems.

The last two courses in Table 3 involve extensive introductions of various sensing and modeling tools and hands-on experiences with data collection, processing, and information modeling.

Figure 2 shows an example result produced by a senior design group in Spring 2011. In this Capstone design project, three undergraduate students used a 3D laser scanner to collect 3D point clouds capturing detailed as-built conditions of a campus building (College of Engineering and Applied Science at Western Michigan University) and compare the as-built data against a Building Information Model created by the Facilities Management group at Western Michigan University based on as-built drawings. The students found a number of errors of the Building Information Model. For example, they found that in this figure, the top right corner have large deviations indicating significant angular error of this model: the angle between two wings of this building is actually 119 degree, slightly smaller than the 120 degree specified in the as-built drawings. Extensive hands-on experiences acquired through the last two courses listed in Table 3 build up students' background in collecting and processing data in real-world scenarios, and most students gave very positive comments about such extensive sensing and modeling experiences.

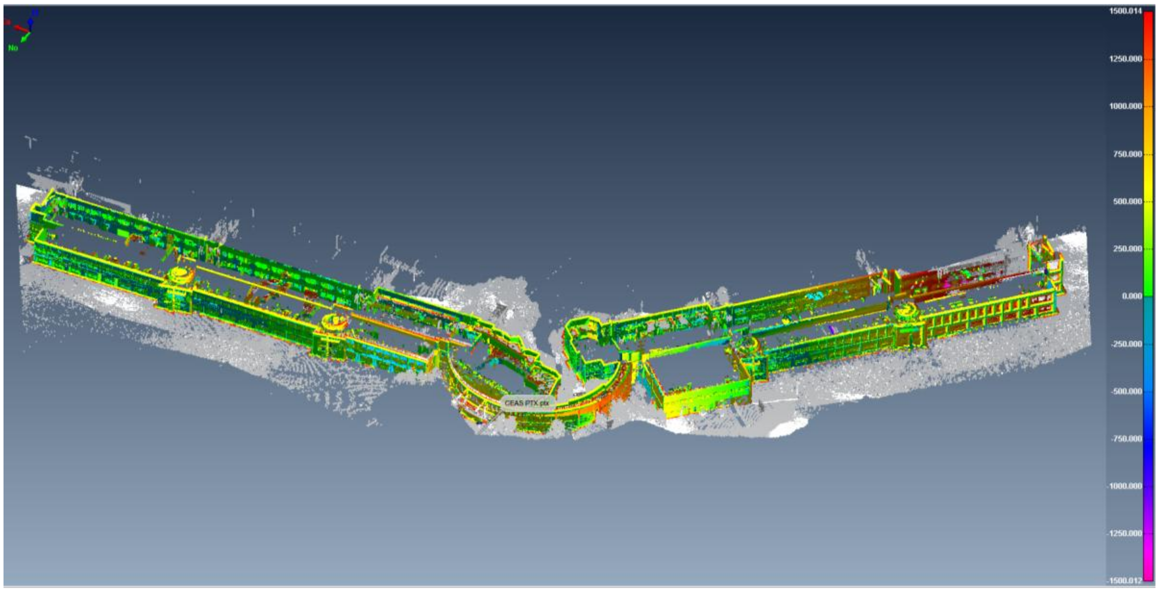

Figure 2 A Senior Project Result: Integrating 3D Laser-Scanned Point Clouds with a Building Information Model

We started these changes in the Fall of 2010, and is continuously collecting and analyzing data about the learning experiences of students. We expect to have substantial amounts of data for quantitatively evaluating the impacts of these curriculum changes on the knowledge structure of students. In addition, we plan to send out surveying forms to students graduated recently (who have taken updated courses) and students graduated before 2010 (who have not taken the updated courses), and analyze whether the new body of knowledge helps our students to achieve a better performance in their career developments in the construction industry.

Table 3 Curriculum updates of the Construction Engineering program at Western Michigan University for integrating sensing and modeling technologies into the learning process

Courses	Technologies	Tools
Introduction to Engineering Design	Automated Scheduling; Building Information Modeling (BIM)	Microsoft Project; Autodesk Revit
Construction Planning and Scheduling	Scheduling; 4D CAD; BIM	Microsoft Project; Autodesk Revit; Autodesk Navisworks
Construction Cost Estimating and Control	BIM; Automated Cost Estimating; Automated Engineering Economic Analysis; Monte Carlo Simulation	Autodesk Quantity Takeoff; Autodesk Revit; Microsoft Excel (Financial Functions, Simulation plug-in)
Construction Project Management	BIM; Automated Engineering Economic Analysis	Vico Virtual Construction Suite; Autodesk Revit; Microsoft Project
Senior Design Project	BIM; 3D Laser Scanning	Leica Cyclone; CloudCompare; InnoveMetric Polyworks, Autodesk Revit
Sensing and Modeling for Construction Management	BIM; GIS; RFID; 3D Laser Scanning	Weka Data Mining System; Lingo Optimization Environment; Autodesk Revit; Vico Virtual Construction Suite; Tekla BIMsight; Google Earth

Conclusions and Future Work

Through systematical analysis about the needs of construction engineers during a typical construction project development cycle, we found that even though some construction engineering programs start to integrate some BIM and sensing technology related materials, some gaps still exist and impede construction engineers to systematically understanding the roles of these technologies for effective using them in practice. First, we still lack a systematical view about the roles of sensing and modeling technology in a project development cycle. Second, current education practice emphasize the uses of BIM as information integration platform, but limited explorations has been done about process modeling and optimization of construction processes. Third, limited efforts have been invested in helping students to understand the role of sensing technology in a typical project development cycle.

This paper presents a landscape used in our teaching practice for helping students to understand the roles of sensing and modeling technologies in a typical construction project development cycle. Based on that landscape, we systematically analyzed the needs of seven typical engineering tasks that have good potential to be improved through incorporating sensing and modeling technologies. Such analysis results in a better understanding about which technologies are needed for which engineering tasks, and help us to change our curriculum for introducing sensing and modeling technologies in appropriate courses.

This curriculum updating effort started in the Fall of 2010. Under the guidance of the landscape presented in this paper, we have made changes in six courses, and have collected some data using course evaluation systems and face-to-face discussion with students. We plan to update all construction engineering related courses on the curriculum, and finish the first round of updates of all courses in the Fall of 2012. After that, we plan to design a surveying form and send it to students who took the old versions of the changed courses, and students took the new versions. We will thoroughly analyze the data and surveying results for understanding the impacts of the curriculum changes presented in this paper, and further improve the curriculum design in the second round of updates of all construction related courses on the curriculum.

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