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ENGINEERING MANAGEMENT THEORIES AND METHODOLOGIES

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Situational Awareness in Construction and Facility Management

Abstract Engineers and managers involved in construction and facility/infrastructure operations need situational awareness about the as-is conditions when making daily decisions and developing short- and long-term plans. Yet, currently situational awareness of engineers is often challenged due to missing data and the available data not being in a format that is easily accessible and actionable. Advances in reality capture technologies, such as 3-dimensional (3D) imaging, in-situ sensing, equipment on-board instrumentation and electronic tagging, streamline the capturing of the as-is conditions on job sites. The data collected from these technologies, integrated with building information models depicting the as-planned conditions, can help in creating and storing the history of as-is conditions of a facility to support a variety of decisions that engineers and managers need to make. While the opportunities associated with integrating building information models and data capture technologies are compelling, several challenges need to be addressed through research for effective usage of these technologies. Such challenges include assessing the accuracy of the data collected at the field, developing and evaluating data processing and data fusion approaches, formalizing integrated representation of building information models and sensor and other relevant data, and investigating and developing approaches for analyzing and visualizing such integrated information models. This paper provides examples of recent research studies done at the Civil and Environmental Engineering Department at Carnegie Mellon University that demonstrate opportunities associated with integrating building information models and sensor information for facility operations.

Keywords: building information models (BIM), sensors, facility operations and management, construction management, situational awareness

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1 Introduction

Ever increasing complexity in construction projects and facility design challenges the situational awareness of engineers and operators who are managing these projects and facilities. The lack of situational awareness mostly stems from information bottlenecks during the life-cycle of facilities and hence not having the right information at the right time with the right format. As a result, engineers and managers waste signification amount of time and money in searching for information or trying to make decisions with limited information. For example, trades people require information about the as-is conditions of a facility when performing maintenance and repair (M & R) work. When such information is not available, they end up relying on their memories or simply stay idle. A study by Gallaher et al. (2004) estimated the cost of not having accurate and up-to-date information for facility owners and operators to be approximately $1.5 billion a year within the United Stated alone. Similarly, during the operations and maintenance of heating ventilation and air conditioning (HVAC) systems, incomplete or inaccurate understanding of the as-is conditions can result in misdiagnosis of different types of faults, such as biased or drifted sensors, malfunctioning controllers, stuck dampers and fouled coils (Liddament, 1999; Liu & Clairidge, 2002; Mansson & McIntyre, 1997; Roth & Westphalen, 2005), which in turn contributes to energy wastes associated with HVAC systems (EIA, 2008).

Several advancements in recent information and communication technologies available for the architecture/engineering/construction/facility management (A/E/C/FM) can help in alleviating some of the existing information bottlenecks and the wastes associated with them, and increasing the situational awareness of engineers and managers. For example, a building information model (BIM), which is defined by National BIM (NBIM) Standard as “a digital representation of physical and functional characteristics of a facility and as such serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle from inception onward” (NBIM 2014), provides necessary information to perform virtual analyses before construction and facility operations. There have been many documented benefits of using BIM during the life-cycle of a facility, such as mechanical, electrical and plumbing (MEP) coordination (Khanzode, Fischer, & Reed, 2008; Kunz & Fischer, 2007; Tocci, 2001), 4-dimensional (4D) scheduling (Issa, Flood, & O’ Brien, 2003; Staub-French & Khanzode, 2007), model-based estimating (Shen & Issa, 2010), and design for facility operations and maintenance (Akinci, 2006; Eastman, 2008; Issa, Flood, & O’Brien, 2003; Khanzode, Fischer, & Reed, 2008; Shen & Issa, 2010). While many benefits of using BIM exist, a major challenge associated with using BIM is to ensure that the information that it contains gets updated frequently and is able to reflect the reality accurately.

At the same time, reality capture technologies provide an opportunity for capturing data about the as-is conditions. For example, modern phase-shift laser scanners can capture high-fidelity data depicting the spatial conditions of a facility in less than 10 minutes per scan. For a scanning project on one of our test-bed research facilities composed of three rooms, we obtained an average file size for each scan to be around 320 MB (Gao, 2014). Similarly, nowadays modern buildings come with advanced sensing and building automation systems. For example, in a building, there are sensors with data collection frequency of about 10 Hz for HVAC systems alone generating about 1 GB of data per month (Akin, 2012). All of these sensors provide an opportunity to capture as-is data about a facility and they are currently mainly used for diagnosis and control (Roth & Westphalen, 2005), and in generating corresponding dashboards for different stakeholders, such as occupants and facility operators to increase their situational awareness (Budike Jr., 2011). However, the analysis of such sensor data can be further augmented by providing information about context under which data is collected, which can be obtained through BIM.

All of these indicate an opportunity to integrate BIMs with the data collected from sensors so that sensor data can augment a BIM and help to keep it up-to-date and realistic, and at the same time BIMs can provide context to the data collected from sensors to support more detailed and accurate analytics. In other words, these two categories of technologies can be combined for delivering the right information at the right time to increase situational awareness during construction and facility operations. This paper overviews several recent research projects that integrate BIM and sensor data to increase situational awareness to support construction and facility/infrastructure operations.

2 Overview of research projects

2.1 Progressive scanning to support accurate and detailed as-built BIMs (Gao, 2014)

Point cloud data collected using laser scanners provide accurate 3-dimensional (3D) depiction of building conditions when appropriate scan settings are used. Therefore, point cloud data obtained during construction can be used as the reference to periodically update a given “as-designed” BIM with existing conditions and to generate accurate and up-to-date as-built BIM (Gao, Akinci, Ergan, & Garrett Jr., 2012). However, the update process, which requires integration of the point cloud data collected by laser scanners with a BIM generated during design, has two main challenges. First, matching segments of point cloud data with an as-designed BIM can be difficult due to the fact that a building component may have different shapes, dimensions, and locations during construction as compared to how it is modeled in an as-designed BIM. Second, some chunks of building geometric information can be missing in point cloud data due to occlusions and inability to perform a scan at a particular location due to the onset of some site activity at that time, which further challenges the matching of the captured as-is data using laser scanners with the components represented in BIM. It is possible to have more scanning to be performed periodically throughout a construction project to have a more complete picture, and yet such additional scans will result in a very large file size making it difficult to process. Hence, this situation warrants an approach to achieve a trade-off between the richness of the information provided by combining many different point clouds and the file size of the corresponding combined data

In addressing the challenges associated with matching of point cloud and BIM described above, we identified a general set of features contained in point clouds and BIMs that can be applied to recognize point cloud and BIM correspondences. We implemented different approaches which use these features to match point cloud segments to various BIM components to evaluate the performances of these matching approaches in how effective they enable the matching process.

Building on previous related research studies, we identified 21 features associated with BIMs and 29 features associated with point clouds. These features have been extracted at varying levels of detail (e.g., point to entity to system of entities) from point clouds and BIMs. These features can also be the basis of developing hybrid approaches that involve utilizing/combining different features before mapping point clouds to BIMs.

Four feature matching approaches based on specific types of features associated with point clouds and BIMs were developed. These approaches are 2D overlap area matching approach, spatial relationship based graph-matching approach, distribution based 2D shape matching approach, and distribution based 3D shape matching approach. We tested these approaches in their capability to match point clouds and BIMs under various kinds of discrepancies which were randomly generated in a BIM. The results of those experiments showed that each of these approaches worked for specific types of discrepancies and none of them displayed the capability to identify all correct matches between point cloud and BIM data in the virtual experiments that we did within (Gao, Akinci, Ergan, & Garrett Jr., 2013). Each of the developed feature matching approach was robust to certain types of discrepancies, and at the same time was sensitive to the others. To ensure a better matching, we formalized two hybrid approaches combining multiple types of features together, within which the effectiveness of the matching process, described using metrics of recall and precision, got much higher than using a single feature-based matching approach.

The experimental analysis we conducted gives a general idea regarding the performance of different types of features under many discrepancy conditions when used to match point cloud segments to BIM components. This knowledge could be a useful reference for the development of more advanced/hybrid matching approaches that utilize or combine different features to remove or mitigate the negative effects of discrepancies on matching results, and hence enable integration of virtual world depicted using BIM with the real-world data collected through laser scanners.

To address the challenge associated with increasing the completeness of the geometric information to be extracted from laser scan data in expense to have large file sizes which in turn might impede the processing of the collected data, we developed an information-gain based approach comprised of two modules: content assessment module and content improvement module. While the content assessment module targets the quantification of the geometric information each point cloud possesses that could be useful in updating/modeling target building components in a BIM; the content improvement module computes the information gain resulting from the addition of a new point cloud to an initial baseline point cloud. With this process, it is possible to identify the specific point clouds that would increase the completeness of the geometric information to be extracted in a given scene without increasing the file size unnecessarily. The validation studies demonstrated the effectiveness of the developed information-gain based approach in identifying the right combination of point clouds to achieve a larger goal of putting together a more complete set of geometric information while minimizing the increase in file size.

2.2 Integration of work-orders and BIM to support facility operations (Akcamete, 2011)

Over the life-cycle of a facility, several changes, such as repairs and retrofits, take place. Hence, the as-is conditions mostly do not remain the same as they were initially designed. The changes that occur throughout the life-cycle of a facility should be captured and stored so that facility operators and managers have up-to-date information about as-is conditions when they are performing repairs or planning and scheduling maintenance activities. If the changes are not captured and stored, there is a need to recreate/revalidate the information which is a costly process, and it is estimated that such activities cost around $5 billion per year to facility owners and operated in the US alone (Gallaher, O' Connor, Dettbarn Jr., & Gilday, 2004). Also, when changes are not captured and stored, facility related information repositories become obsolete, and any scheduled operations or maintenance activity will need to be undertaken on the basis of this outdated data and tacit knowledge of the field personnel. In the absence of as-is information for maintenance planning, operation and maintenance personnel stay idle for prolonged periods indirectly costing an estimated $1.5 billion per year in the US capital facilities industry (Gallaher et al. 2004). Moreover, in the absence of change history due to M & R work, most of the maintenance activities are done in a reactive manner, which is known to cost three to four times more than planned maintenance (Franklin, 2008; Mobley, 2008).

In order to address some of the problems described above, we developed an approach that formally captures information items relating to changes done in a facility as a result of M & R work, and that links M & R work change history to a BIM to support querying and identifying spatial patterns of changes occurring within a facility. To develop, verify and validate this approach, we implemented a prototype that enables customized template generation, work history integration with BIM, and spatial querying and visualizing maintenance and performance patterns.

This research highlighted the need to capture information items reflecting the changes due to various M & R activities along with the existing information capture gap in the capture approaches that result in information loss. To address this need, we categorized M & R work types and related changes and their corresponding information requirements, and developed a formalism which in turn was found to support generation of customized information templates. We observed six such generic categories covering facility changes attributed to M & R work: additions, removals, replacements, alterations, assessments, and adjustments. Subsequently, we developed information modules for each category to collect relevant change information in the field. The collected information is then integrated to BIM through associated components and spaces to store the change history. This integrated model allows a user to query and observe history, as well as visualize spatial information of interest. The user studies demonstrated how such an integrated environment of BIM with work-order data helps in identifying location of major changes and highlighting the need to update the corresponding BIM in those areas.

2.3 Integration of sensors and BIM to support fault detection and diagnosis of HVAC systems (Liu , 2012)

Several advanced information and communication technologies have been developed for HVAC systems to address the growing demands for better indoor air quality control (Schein & Bushby, 2005). Modern HVAC systems are embedded with many pieces of hardware and software components, which create a highly complex system that is challenging to operate, diagnose and manage. At the same time, while HVAC systems are advancing, the current M & R practices are still mostly based on manual inspection and reactive maintenance (Mobley, 2008). As a result of this dichotomy the following issues exist: ① Only faults with significant symptoms attract notice and get resolved (Wang, S. & Wang, J. B., 2002; Xu, 2005); ② the frequency of manual inspection of HVAC systems does not necessarily correspond to the occurrence of faults and could be much lower than the occurrence of the faults, and hence many faults can go undetected (Roth & Westphalen, 2005); ③ ambiguous nature of manual diagnosis coupled with several faults occurring in HVAC systems having similar symptoms can result in misdiagnosis (Schein & Bushby, 2005).

Often, these reasons prevent effective monitoring of performance and fault detection in the HVAC systems thus leading to less efficient operating conditions. To overcome this challenge, several researchers have developed automated performance monitoring algorithms to support fault detection for the last two decades. These algorithms can be classified into self-assessment, self-healing, and self-improvement related algorithms (Liu & Akinci, 2011). Self-assessment algorithms enable HVAC systems to assess their own performance and sift out problems due to inefficient operations. Self-healing algorithms target finding ways to address certain faults simply by modifying the configuration of HVAC control systems. Self-improvement algorithms identify strategies for energy efficiency based on the characteristics of a given building and HVAC system.

Though these algorithms can greatly help in effective HVAC operation and management, the deployment of them in real-life settings has been hindered by not having correct and thorough knowledge of the configuration of building, which is an input requirement for some of these algorithms to ensure adaptive control of systems as per their outputs. In relation to this, we aimed at developing an automated framework to manage the information requirements of the performance analysis algorithms and support the system operator in a facility deployment scenario. Towards this goal, the developed multi-module framework contained self-recognition and self-monitoring modules that automatically acquire the necessary inputs from a BIM and sensor data, a self-configuration module that automates the task of processing outputs of the algorithms, and an information mediator layer encompassing an integrated information repository to manage the information requirements of different algorithms (see *Figure 1*).

In developing an integrated framework that supports in-

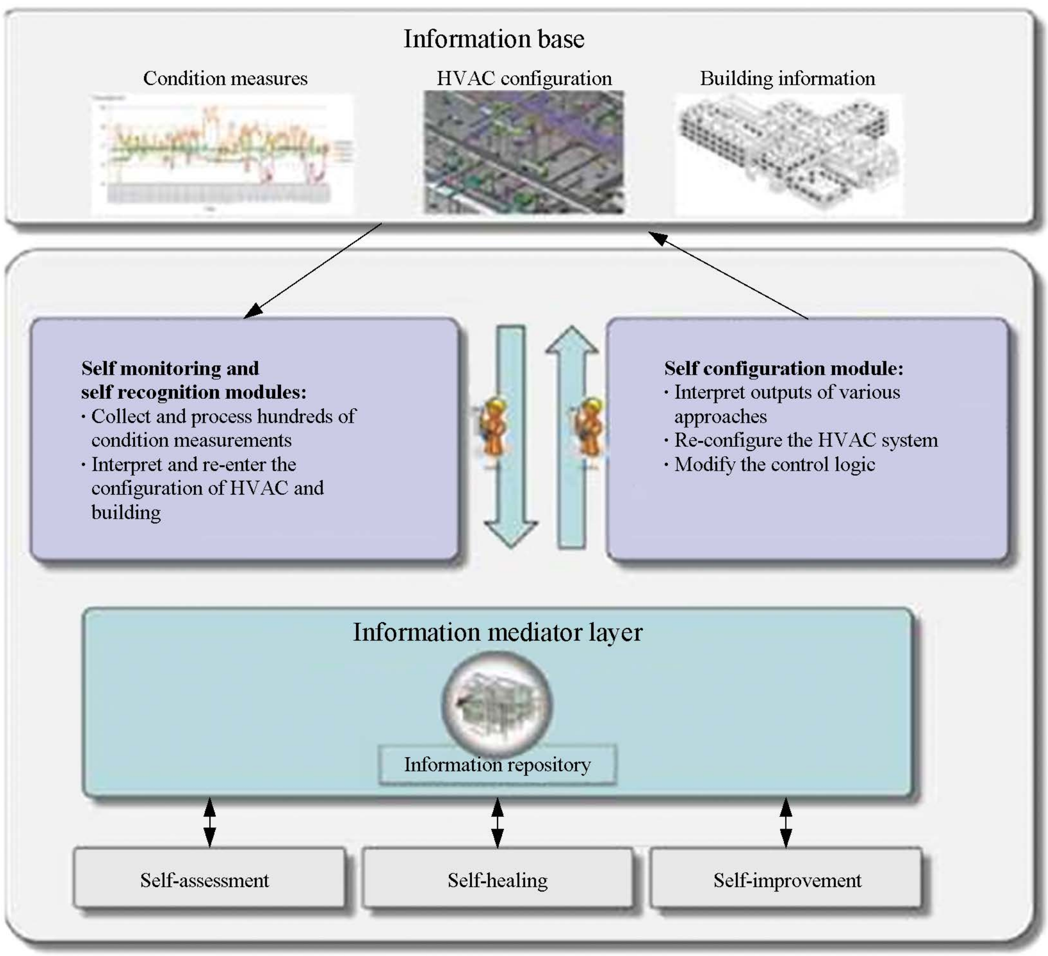

Figure 1. Automated multi-module framework supporting performance analysis algorithms and operators after deploying in a facility. Adapted from thesis presentation of Liu X. (2012).

formation for these algorithms, we extended the information delivery manual approach developed by Build SMART (2010) to identify and list a general set of information items required by various analysis algorithms. These information requirements were validated for their generality, and provided foundational step towards automating information integration and retrieval process.

At the same time, we explored existing query languages to retrieve the information required by the existing algorithms; however, they could not sufficiently support the framework because the information requirements HVAC domain-specific terminology and functional relationships. To address this issue, we developed a customized query language, centered on HVAC domain, specifying the lexicon and syntax required to represent the information requirements. This also included a library of formal query mechanisms to parse the user-defined queries, decipher the information needs, and automatically retrieve the information.

In summary, this research demonstrated that many algorithms have already existed in actively monitoring, diagnosing and managing HVAC systems and yet they are not being used due to the information bottlenecks that require data from different sources to be fused. Integrating data from BIM and sensors existing on HVAC systems enables running many of these existing algorithms simultaneously effectively.

2.4 Indoor positioning through integration of BIM and various sensors (Taneja, 2013)

Several indoor work environments, these days, require accurate, reliable and streamlined tracking and positioning of occupants and field personnel. The criticality of this requirement increases with the complexity of the environment. The proven approaches associated with using satellite-based technologies often will not work well for indoor environments, as it normally does for outdoor environments due to weak penetration power of the satellite signals. Research in the indoor localization area progressed with broadcast-based and motion-based approaches as possible solutions to this problem. However, they had several limitations. The broadcast-based technologies, such as wireless local area networks (WLAN) and radio frequency identification (RFID), suffered in terms of accuracy due to signal attenuation and multipath propagation, and at the same time the drift errors in indoor environments severely affected the capabilities of inertial navigation technology. Further, indoor environments have not been able to leverage any robust geometrical and topological knowledge to correct erroneous positioning data in a way we could do in an outdoor environment like road network with the help of global positioning system (GPS) and geographic information system (GIS) databases. With the development and usage of BIM, it is now possible to create spatial models that explicitly and automatically represent the geometrical and topological information of the indoor environments.

We developed a framework that contains a library of spatial models, fusion algorithms, and a reasoning mechanism to select and generate the most appropriate spatial model representing geometrical and topological information of a given indoor environment (see *Figure 2*). In order to develop such a reasoning mechanism, we evaluated several categories of various spatial models in terms of how well they support the selected fusion algorithms in correcting erroneous positioning data. We also used industry foundation class (IFC)-based BIM files and developed different algorithms to correct positioning data given in different formats in an automated manner. Here, the generality and extensibility of categorization of different spatial models are validated using the theory of diminishing returns by identifying spatial models used in multiple domains through rigorous literature review. We utilized several buildings with different shapes and usages as

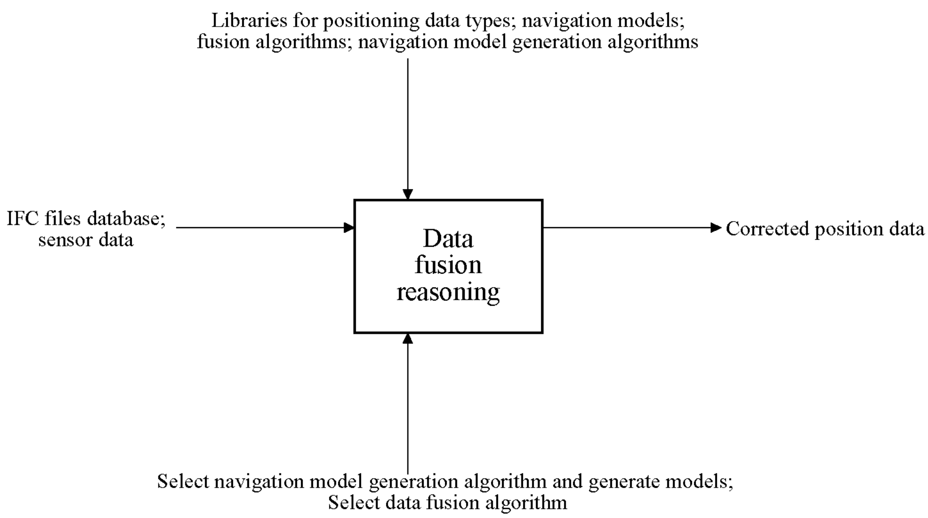

Figure 2. Envisioned framework to evaluate the performance of map-matching algorithms for indoor positioning data when different navigation models are used.

test-beds to validate research factors such as size and layout of the buildings, which affect the spatial model generation and correspondingly the accuracy of the indoor positioning. The experiments conducted at different real-life building test-beds demonstrated an improvement obtained in indoor localization by using spatial models generated from BIM and merging that with the data obtained from different sensor systems to support auto-correction of positions.

3 Conclusions

Effective managements of construction projects and facilities require that engineers and managers have good situational awareness of existing conditions and hence are able to make effective situation assessment. However, currently situational awareness of engineers and managers is challenged by information bottlenecks and lack of information. BIMs integrated with data collected through reality capture technologies, i.e., sensors, provide an information- and data-rich environment that can support many different types of decisions and effective management strategies throughout the life-cycle of facilities. The example projects described in this paper demonstrate a wide range of decisions and management tasks that could be supported through such integration. These include, but not limited to, accurate and up-to-date as-built models at the end of construction, capturing change history during facility operations for identifying effective management strategies, active HVAC diagnosis, and indoor localization to support location based services. Future studies need to be done to quantify the impact of decisions made in such information-rich environments in order to assess the value of information.

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