EXPERIMENTAL INVESTIGATION OF THE INTEGRATION OF VIRTUAL MODELS AND THE PHYSICAL CONSTRUCTION

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ABSTRACT

There have been several approaches to integrating virtual models and the physical construction for progress monitoring using RFID tags. However, these existing integrated approaches do not adequately support bi-directional coordination between these components and the virtual models or Building Information Models. Also, these approaches still involve manual input of status information into the tags and do not support tracking the permanent installed position of tagged components for consistency maintenance between the as-built and the as-planned models. As such, there are difficulties with ensuring accurate and timely updating of building information models and tag information during the construction process. This is considered necessary for lifecycle management of the constructed facility. A major bottleneck in achieving this integration is the choice of appropriate mechanisms for binding physical components with their virtual representations. This paper describes experiments that investigate approaches to integrating virtual models and the physical construction using RFID tags. Specialized real-time location sensing (RTLS) tags were used for tracking the position and status of installed/uninstalled components. The experiments showed that these RTLS tags were more effective than standard RFID tags for position sensing and for updating the virtual model. This approach also showed significant opportunities for enhancing real-time construction consistency checking, thereby enabling proactive decision making and project control. The key benefits of this approach are also highlighted in the paper.

Keywords: Bi-directional Coordination, Building Information Models, Physical Components, RTLS Tags

INTRODUCTION

Accurate and real-time construction progress monitoring enables project managers to detect any schedule delays early, and make corrective decisions (Turkan et al., 2010). Virtual models play an important role in construction progress monitoring as a means of visualizing the construction process. Also, virtual models contain virtual representations of building components which can be linked to their physical representations on the construction site. As a facility moves through the life cycle from planning to design to construction and to facility management, some information can be embedded in the virtual building components and this provides another integrated database of relevant information that can be used by the project team during the construction and post construction phases of the constructed facility. This potential of virtual models is evident in the research by Anumba et al. (2010), Sorensen et al. (2008) and Motamedi and Hammad (2009) which identified that integrating virtual models and the physical construction can improve the information and knowledge handling from design to construction and maintenance, hence enhancing control of the construction process.

A number of researchers (Chin et al., 2008; Chin et al., 2008; Motamedi and Hammad, 2009) have investigated the integration of virtual models and the physical construction for progress monitoring using radio frequency identification (RFID) tags. However, these approaches still involve manual input of status information (such as installed or uninstalled) into the tags and do not enable tracking the permanent installed position of tagged components on the construction site. As such, there are difficulties with ensuring accurate and timely updating of building information models during the construction process. Being able to track the permanent installed positions of tagged components enhances consistency maintenance between building information models and the physical construction. Also, there is scope for the use of these models for enhancing real-time bi-directional coordination between the design team and personnel on the construction site (Akanmu et al., 2011). This will enable documentation of as-built information which is necessary for lifecycle management of the constructed facility as well as serving as a basis for the active control of installed components such as light fixtures (Akanmu et al., 2010).

Integrating the virtual models and the physical construction (for consistency maintenance and bi-directional coordination) requires the use of specialized real-time location sensing (RTLS) tags capable of both position sensing and data storage capability. These RFID tags are specialized real-time location sensing (RTLS) tags capable of tracking the position of tagged components and storing information for integrating virtual models and the physical components. This paper describes an experimental approach to integrating virtual models and the physical construction using RTLS tags. It starts by describing key enabling technologies for enhancing the integration between virtual models and the physical construction.

ENABLING TECHNOLOGIES

The key enabling technologies for enhancing bi-directional coordination between virtual models and the physical components for progress monitoring and as-built documentation are discussed as follows:

Real-Time Location Sensing (RTLS) System

A real-time location sensing system is critical for bi-directional coordination between physical components and the virtual model, as it is very important to know the exact location of the key components being tracked. The RTLS system used in this research was obtained from Identec Solutions and consists of real-time location sensing (RTLS) tags (i-Q350 RTLS), RTLS reader (i-PORT M 350 RTLS), satellite nodes (i-SAT 300 RTLS) and an ‘i-Share’ position server.

i-Q350 RTLS Tags

The RTLS tags (shown in Figure 1) have position sensing and data storage capability (32 Kbyte read/write memory). These tags have a very long communication range of up to 500m (1600ft) and enable the automated identification, tracking and tracing of assets and people in areas as large as a steel construction workshop without human intervention (Identec Solutions, 2010). Nine RTLS tags were used for the experiment.

Figure 1: i-Q350 RTLS tag

i-SAT 300 RTLS

The i-SAT 300 RTLS (shown in Figure 2) operates a reference point for the localization of the RTLS tags. The i-SAT 300 RTLS senses information about identity and location of RTLS tags. The i-Q350 RTLS in conjunction with the i-SAT 300 RTLS reference generator allows localization down to a few feet. It operates stand-alone only with power supply.

Figure 2: i-SAT 300 RTLS

i-PORT RTLS Reader

The i-PORT M 350 RTLS reader shown in Figure 3, acts as a combination of a RTLS reader (with up to 500m read/write range) and a satellite node (i-SAT 300 RTLS), capable of about 400 localizations per minute (Identec Solutions, 2002). This means it serves as a reference node as well as an interrogator to retrieve the RTLS ranging data from the tags. When building materials and components are tagged with the RTLS tags, the tags control the communications to the i-SAT nodes. The i-SAT nodes provide position information of the tagged component to the RTLS tag, which then communicates this position information to the RTLS reader.

Figure 3: i-PORT M 350 RTLS Reader

i-SHARE Positioning Software

i-SHARE Edgeware is a server application with the primary goal of filtering data to and from the i-PORT M350 RTLS reader installation. The i-SHARE Edgeware handles various RFID situations like position calculation and sensor data. In addition to this, the server controls the system status and exposes tag communication to business applications. In order to reduce the effort for system integration and avoid typical interface problems like serialization issues, all available interfaces are Web-services based (Identec Solutions, 2010).

The location information captured by the RTLS reader is collected in the i-SHARE positioning software. The i-SHARE positioning software computes the actual position of the tagged component with respect to the reference i-SAT nodes and the RFID reader. Likewise information written to the RTLS tags can be captured by the RTLS reader and stored in the i-SHARE software. The positioning software can be integrated with BIM and other project management applications for as-built documentation and for visualizing progress information.

Mobile Devices

Mobile devices have long demonstrated opportunities for improving the construction delivery process through providing access to information on site and means of collaboration between project participants. Mobile devices such as tablet computers and personal digital assistant (PDA) have display screen for capturing information about design changes, comments and relevant information that needs to be relayed to the construction team in real-time. The construction team can also use the mobile devices for embedding information in the tags or directly to the i-SHARE software to be captured in the BIM in the office. The mobile devices serve as a great tool to communicate back and forth the construction site and the office. In the context of this research, a tablet PC was used. This was used to access model updates and changes. The tablet PC also provided means of embedding information in the tags to be updated in the model.

Communication Network

The communication network, such as Ethernet and Wi-Fi, plays an important role in enhancing effective integration between BIM and the physical construction. The RTLS reader connects to the positioning server using the Ethernet. The positioning server can be accessed by the project team using the Internet. The mobile devices can also be linked using Wi-Fi to enable information sharing and collaboration between the project team.

OVERVIEW OF THE EXPERIMENTAL APPROACH

A prototype system was developed for integrating virtual models and the physical construction using the enabling technologies described above. The steps involved in the prototype system development include the following:

Development of Virtual Model

An Autodesk Navisworks model of a small scale building was developed. The model serves the purpose of enabling visualization of the status of tracked building components and the information captured from the project site. The model also enables embedding of model updates or critical information that needs to be communicated to the construction site in real-time.

Development of Physical Prototype

A laboratory scale physical prototype of the Navisworks model was constructed. The physical prototype (Figure 4) consists of nine detachable components. The components of the laboratory scale physical building prototype were tagged with RTLS tags as shown in Figure 4.

Figure 4: Laboratory scale physical prototype (tagged)

Application Development

Two applications were developed for this implementation using Visual Studio.Net. These applications are described in more detail below:

- **CPSPlugin:** This is the main entry point into Navisworks. This plug-in was used to invoke the features of Navisworks such as color and property values.
- **Client Application Development:** A client application was developed to fetch information from, and write to, the tags. This application captures the information written to the tag and writes it to an Access database, to be read by the Navisworks plug-in.

Prototype System

Figure 5 shows an overview of the developed prototype system. Each i-SAT node determines the proximity of each tagged component and sends the coordinate information to the RTLS tags. The individual coordinate data are read from the RTLS tags by the RTLS reader and transferred to the i-Share software. The i-Share software computes the relative distance of each tag in space and sends this to a Web interface. The database is constantly updated with data from the Web interface. The CPSPlugin collects the position data from the database and updates the status of the affected elements in the model. Whenever there is a design change or model update, the CPSPlugin captures this change and stores it in a database and in the Web interface where it is received by the i-Share software. The RTLS reader collects this information and writes it to the associated RTLS tag where it can be accessed on site using a mobile device. Also, the tag can be read and updated using a client application installed on the mobile device. The client reads and writes to that tag by connecting to the Web interface. Information written to the Web interface is collected and stored in the Access database where the CPSPlugin updates the associated element with the change.

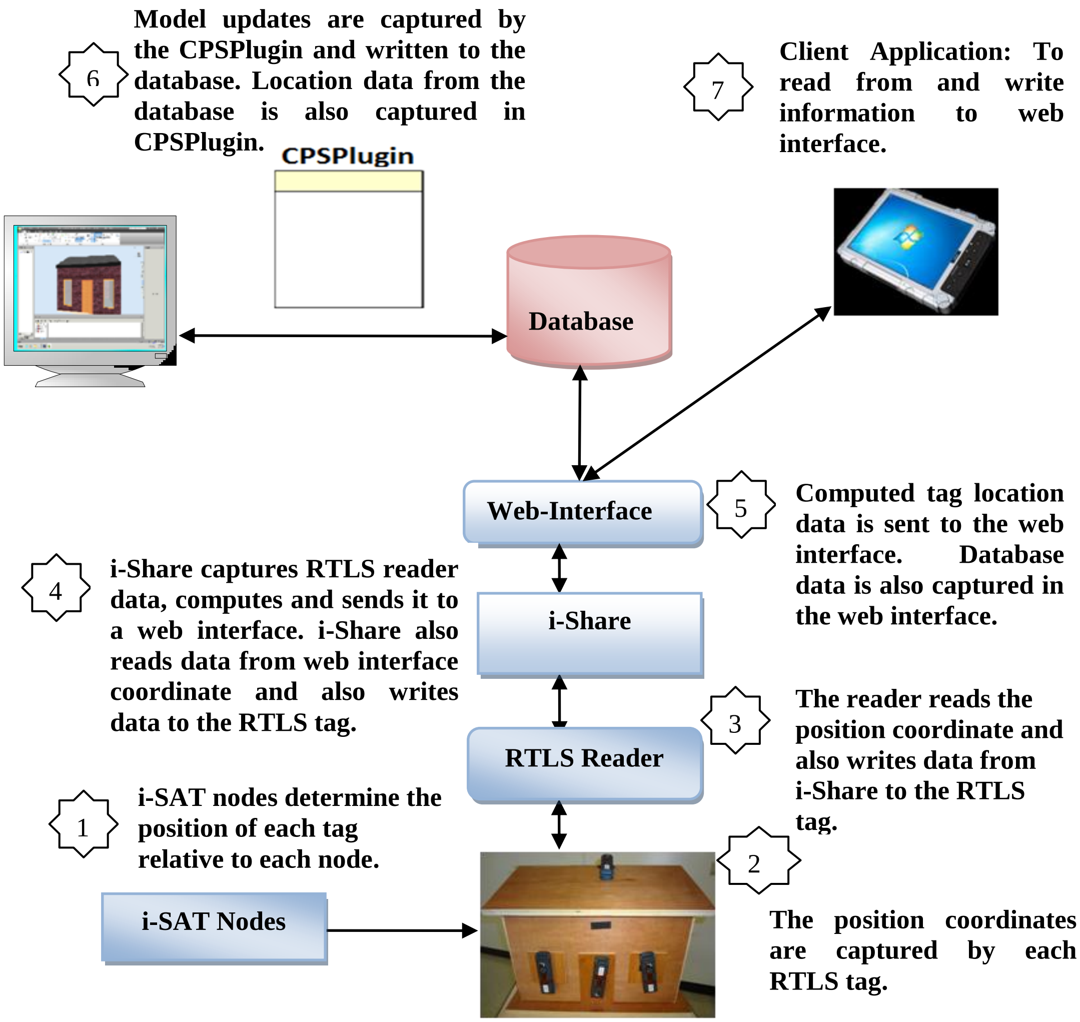


Figure 5: Overview of Prototype System

PROTOTYPE SYSTEM IMPLEMENTATION

One of the aims of the developing the prototype system was to track when tagged components are installed and uninstalled. The principle adopted here is that the as-built locations (position coordinates) of the tagged components must be known. These as-built locations are input into the developed Navisworks plug-in as the tagged component's final 'installed' location. As the tagged components are moved around the site/test location, the plug-in compares the captured location coordinates with the final 'installed' location. If these coordinates are the same, the tagged component is considered to be 'installed' and the model is updated to reflect this (as shown in Figure 6). Conversely, if the coordinates are different, the tagged component is considered 'uninstalled' and the model is updated to that effect (as shown in Figure 7).

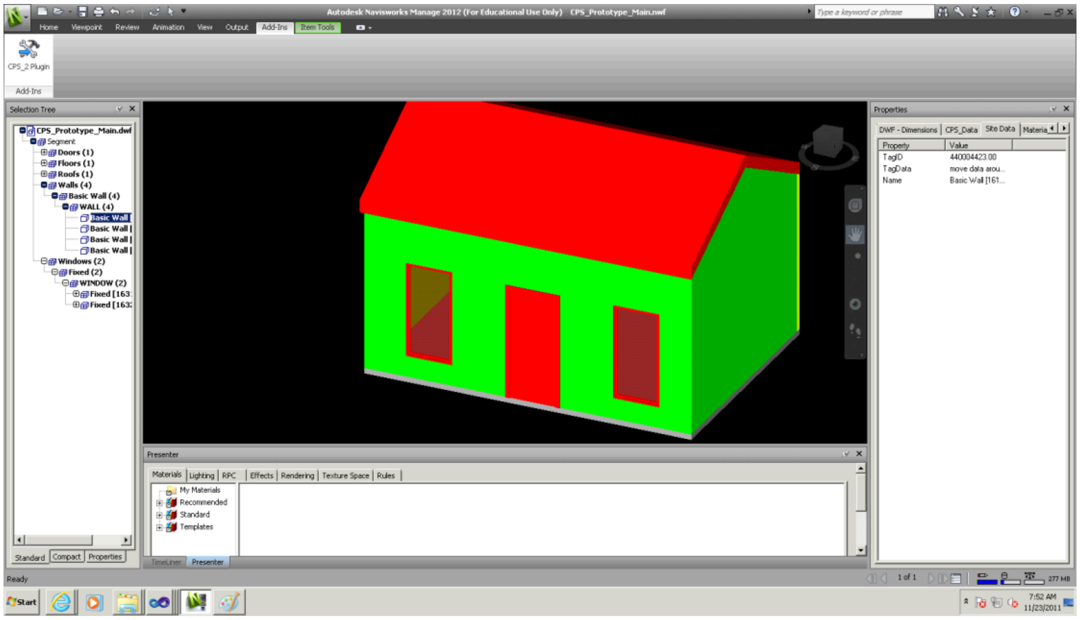


Figure 6: Door and Roof element status changed to ‘uninstalled’ (red)

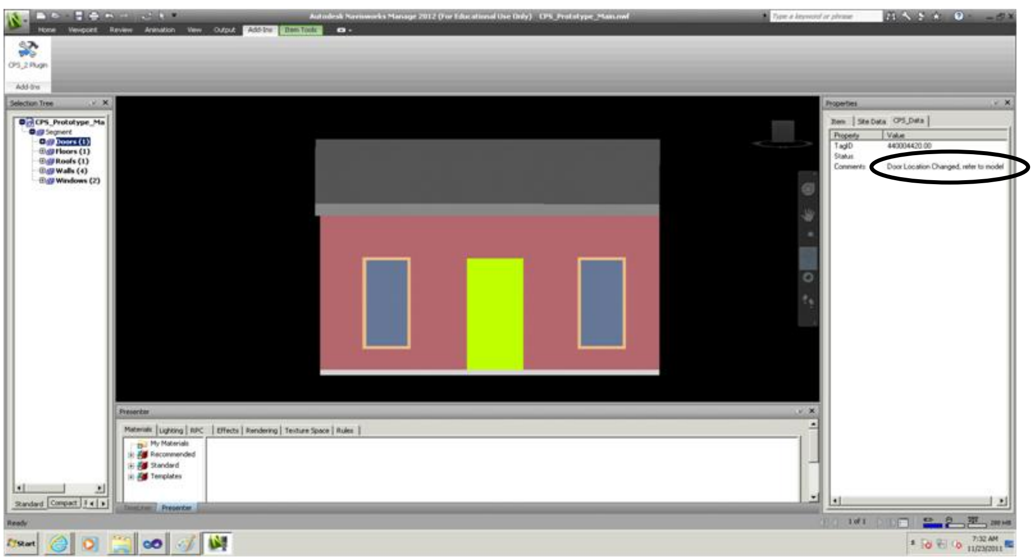


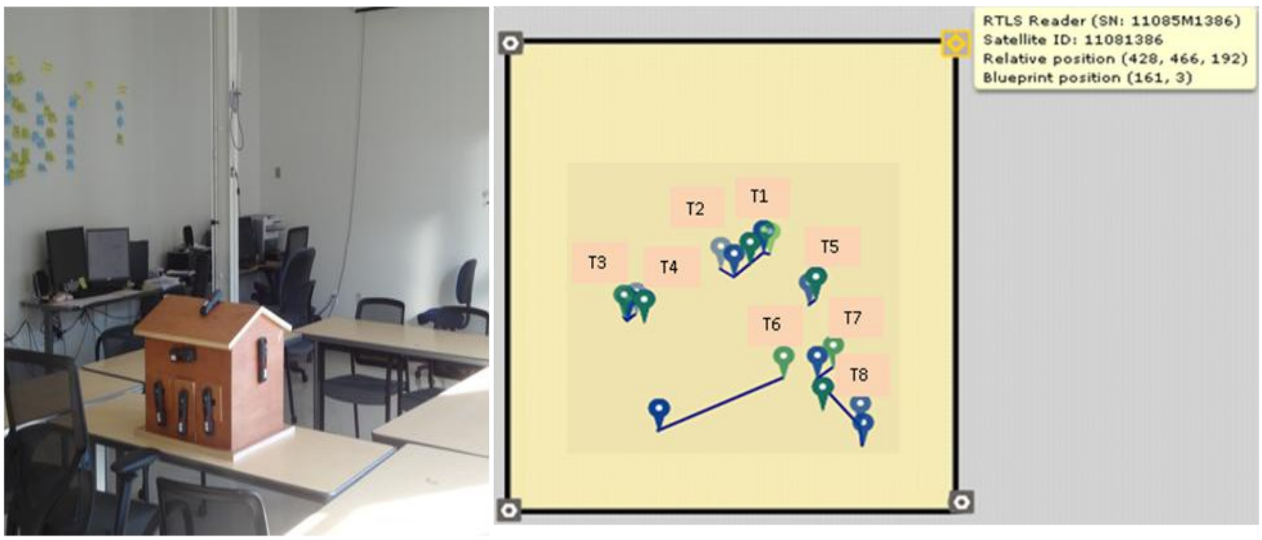
Figure 7: Element highlighted and TagData property updated with information

The developed prototype system was tested on two different sites (indoors and outdoors).

Indoor Test

The developed system was initially tested indoors in the Intelligent Systems Laboratory in the Department of Architectural Engineering at the Pennsylvania State University as shown in Figure 8a. The i-SAT nodes and RTLS reader were attached to steel columns at a height of 1.76m. The tagged laboratory scale prototype was placed on a table at a height of about 0.61m.

During the indoor test, false movements (multipath effects) were noticed from the RTLS tags while the tagged components were stationary. These false movements resulted in a number of false updates recorded in the model. The false movements can be observed in the RTLS event map shown in Figure 8b. The map represents a layout or plan of the indoor test location. The RTLS tags are represented by the green and blue icons in the figure. The blue line between each green and blue tag represents a movement of the RTLS tags. During the indoor test, the tags were kept stationary but they appeared to be moving as shown in the figure. This is as a result of interference from a large number of wireless networks in the vicinity of the laboratory. This led to an exploration of outdoor tests.



a. Indoor site

b. Indoor site blueprint showing the i-SAT nodes and stationary tags

Figure 8: Map from indoor test for stationary tags

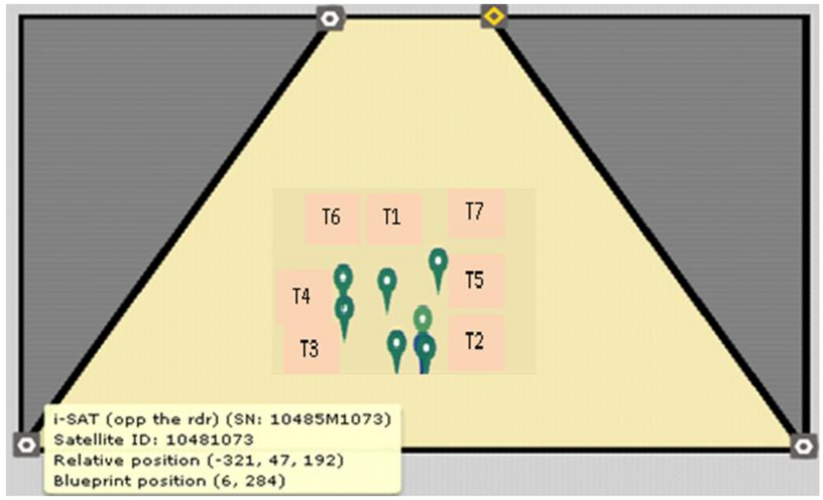
(The notations T1, T2…..T8 on each green and blue icons represent the tags, with the green tag showing the initial location while the blue tag location shows the final location. The line between the RTLS tags represents the path to movement).

Outdoor Test

The developed system was also repeated in an outdoor environment in a park behind the Engineering Unit buildings at the Pennsylvania State University as shown in Figure 9a. The system was set up by installing the i-SAT nodes and RTLS reader at the boundaries of the test sites. The i-SAT nodes and RTLS reader were placed at increased distance apart. The i-SAT nodes were attached to metal poles at a height of 6m.

During, the outdoor test, the surrounding wireless networks were shut off to avoid disruption to the RTLS signals. Less multipath effects were noticed as illustrated in Figure 9b, which shows the RTLS event map from the outdoor test, comprising of stationary tags.

a. Outdoor site



b. Outdoor site blueprint showing the i-SAT nodes and stationary tags

Figure 9: Map from outdoor test for stationary tags

(The notations T1, T2…..T8 on each green icons represent the tags and shows that there was no multipath effect at the outdoor site).

DISCUSSION

The experiment presented in this paper has demonstrated some potential for the use of RTLS system for progress monitoring and as-built documentation during construction. The experiment was implemented indoors and outdoors. The indoor experiment helped to determine the suitability of the RTLS system in enclosed sections (e.g. partially completed buildings) during construction and in the constructed facility during the operations and maintenance phase. The outdoor test also helped to the suitability of RTLS system in an open environment such as a construction site for material tracking, site planning and logistics, and equipment operation and safety. The RTLS system showed tremendous potential for real-time location tracking of the tagged components in the outdoor environment. The RTLS system proved more effective and with less multipath movement when deployed out-doors (with less interferences from wireless networks). The signals from the RTLS system seem to be disrupted indoors, as a result of the interferences from wireless signals (such as the Wi-Fi, Bluetooth and Zigbee) within and outside the laboratory. The disruption can be observed from the false movement/multipath effects of the RTLS tags viewed from the indoor site blueprint. However, this disruption relates to tracking the placement of the tagged components. The issue of communicating changes to the jobsite and obtaining feedback or as-built documentation in the model, proved effective. Changes made on the jobsite can be written to the RTLS tags to be documented in the BIM. Conversely, the project team can embed notification of changes or alerts in virtual components; this can be captured on the project site (either through the RTLS tag or mobile devices). This process of being able to track permanent of tagged components and being able to communicate between the virtual model and the physical construction illustrates the concept of bi-directional coordination. The presented experiment has demonstrated the potential of the RTLS system for bi-directional coordination. Bi-directional coordination is beneficial for access to real-time progress information and decision making. The approach also has great potentials for enhancing as-built documentation which is necessary for lifecycle management of the constructed facility. The outdoor test took place outdoor with walls, trees and less wireless interference compared to the indoor environment. Having demonstrated some potential for bi-directional coordination between virtual models and the physical components, it would be useful to explore the demonstration of the RTLS system on a real construction site.

CONCLUSIONS

This paper has presented an investigation into the use of a specialized RTLS system for integrating virtual models and a physical laboratory-scale prototype building. This investigation was carried out by conducting two tests (outdoor and indoor) to determine the efficacy of bi-directional coordination between virtual model representations of building components and the physical components themselves. The RTLS system proved more effective outdoors than indoors, as the location coordinates were more stable outdoors than in the indoor situation where high multipath movements were recorded, when the tagged components were stationary. However, despite the multipath effects encountered, the use of RTLS tags for tracking model updates/design changes on the site and also updating the model with as-built information, was successful in both the indoor and outdoor environment. This bi-directional coordination is considered very important in the deployment of cyber-physical systems in the construction industry. Thus, there is considerable potential for the application of the RTLS system to other aspects of the construction project delivery process, facility management, and other operations.

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