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SCENARIOS FOR CYBER-PHYSICAL SYSTEMS INTEGRATION IN CONSTRUCTION

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SUMMARY: *There is an increasing growth in the use of virtual models in the construction industry but this use is often limited to the design and tendering/bidding stage. Much more benefit can be derived from these models by extending their use to the construction and operations and maintenance phases of a facility's lifecycle. A good way of achieving this involves real-time bi-directional coordination between virtual models and the physical construction. This will enable improvements in progress monitoring, construction process control, as-built documentation and sustainable building practices. To maintain bi-directional coordination, computational resources are required to tightly integrate the virtual models and the physical construction such that changes in one environment are automatically reflected in the other. This paper focuses on describing the role of bi-directional coordination in improving the construction project delivery process. A system architecture is presented, which illustrates the necessary technologies and sub-systems needed to facilitate the two way coordination. Future deployment scenarios are also presented to illustrate the potential benefits to the construction industry.*

KEYWORDS: *Bi-directional coordination, Virtual Model, Physical construction, RFID, Cyber-Physical Systems*

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1. INTRODUCTION

Estimates indicate that up to about 30% of construction cost is lost to inefficiencies, mistakes, delays, and poor communications (Dimakis 2010).Delays could be as a result of design mistakes, changes or updates to the design model and unless communicated to the construction site in real-time, can result in risks to cost and time overrun. Thus, access to design model updates in real-time, can help project managers make informed decisions. Also, changes made on site need to be updated in the as-built model for lifecycle management of buildings. As-built models are presently manually updated after construction and as such are prone to errors as not all the changes are adequately captured. Virtual models offer huge benefit in enabling documentation of as-built information, collaboration between project team, visualization of construction progress but their use is still limited primarily to the preconstruction phase. Examples of virtual models include computer aided design (CAD) models and building information models (BIM). 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. It has been identified that integration between virtual models and the physical construction can improve information and knowledge handling from design to construction and maintenance, hence enhancing control of the construction process (Akanmu et al. 2010; Shen et al. 2010; Chin et al. 2005; Motamedi and Hammad 2009).

A number of researchers Chin et al. 2008; Golparvar-Fard et al. 2009; Motamedi and Hammad 2009; Sorensen et al. 2009) have attempted to link virtual models and the physical construction using different data acquisition technologies (e.g. digital cameras, laser scanners, radio frequency identification tags). However, the existing approaches do not offer opportunities for two-way integration or communication between the virtual models and the physical construction. This two-way integration/communication is important for enhancing feedback or controlling the constructed facility. A good way of providing feedback or control involves real-time bi-directional coordination between virtual models and the physical construction. Bi-directional coordination is a two-way integration of virtual models and physical artefacts such that changes in one are automatically reflected in the other. Furthermore, to maintain bi-directional coordination, computational resources are required to tightly integrate the virtual models and the physical construction such that changes in one environment are automatically reflected in the other. This is termed a cyber-physical systems approach. In the context of this research, cyber-physical system is taken to mean tight integration and coordination between virtual models and the physical construction. Cyber-physical systems bridge the cyber world (e.g. information, communication and intelligence) to the physical world through the use of sensors (Wu et al. 2011). The cyber-physical systems approach will enable improvements in progress monitoring, construction process control, as-built documentation and sustainable building practices.

It has been suggested that the most appropriate path to the realization of cyber-physical systems in construction lies in the adoption of a 'system of systems' approach (Bulbul et al. 2009). Systems integration has been identified as one of the key approaches to help the construction industry to improve its productivity and efficiency (Shen et al. 2010). This is particularly important as it supports design-build and other integrated project delivery methods.

This paper seeks to describe the role of the cyber-physical systems approach in improving the construction project delivery process through enhancing bi-directional coordination between virtual models and the physical construction. To enhance understanding of the potential of cyber-physical systems in construction, it focuses on the development and validation of deployment scenarios for these systems. The paper starts by describing key enabling technologies for the cyber-physical systems approach. It then presents a system architecture, which integrates the key enabling technologies and sub-systems needed to facilitate the bi-directional coordination. Triggers for bi-directional coordination are discussed and illustrated in the deployment scenarios that illustrate the potential benefits of bi-directional coordination in the construction industry. Possible impacts and implementation considerations are discussed in the concluding section of the paper.

2. RELATED INTERGRATION EFFORTS

In recent years, a number of researchers have investigated the integration of virtual models and the physical construction using different data acquisition technologies such as photographs, laser scanners and RFID tags. Some of these integration efforts and their limitations are briefly discussed here. Memon et al. (2004) developed a Digitalizing Construction Monitoring (DCM) Model which is a system that integrates 3D CAD models and digital images for project progress monitoring. The model estimates the percentage of progress by integrating the digital images and the 3D model to develop progress bar charts. The digital images are captured from the construction site and the 3D model is developed using Photomodeler software. The 3D CAD information is created using AutoCAD. Golparvar-Fard et al. (2009) investigated the integration of digital cameras and 4D CAD for the visualization of progress deviations in construction projects. This approach involves the superimposition of the as-planned 4D CAD model into time-lapse photography and videotaping of the as-built progress data collection. Boche et al. (2008) developed an approach which involves integrating 3D CAD models and time-stamped 3D laser scanned data for automated project progress tracking. The approach enables an automated recognition of 3D CAD model objects from site laser scans. The major draw-back of the use of laser scan and digital photographs is that a number of images will need to be taken to fully capture the construction activities and further processing of the images is required, thus hindering access to real-time information. Also, digital photographs cannot be taken in bad weather.

A number of researchers have utilized RFID tags for integrating virtual models and the physical construction: Chin et al. (2005) examined the use of 4D CAD and RFID tags for progress monitoring in supply chain management. RFID tags were placed on structural elements such as structural steel and curtain walls, to sense their status from the ordering stage through the delivery, receipt, and finally to the erection stage. The sensed status was captured in a 3D model to indicate progress status. Wenfa (2008) developed an integrated model of RFID and 4D CAD for tracking the status of construction components. Construction components (such as pipes, equipment, steel columns and beams) are tagged with RFID passive tags and an RFID reader is used to track their status from the manufacturing or fabrication plant to the construction site where they are installed. The disadvantage of the approach by Chin et al. (2005) and Wenfa (2008) is that access to installation status or progress information is dependent on when the construction personnel embeds information into the tags. Motamedi and Hammad (2009) investigated the use of RFID tags and BIM for lifecycle management of facility components. The authors proposed permanently attaching RFID tags to facility components where the memory of the tags is populated with BIM information. There has also being attempts by the industry to integrating field BIM and precast concrete installation using RFID tags (Sawyer 2008) The status of tagged precast concrete pieces was tracked from the fabrication yard to installation. The pieces are identified through the use of a RFID reader communicating with a Tablet PC that has Vela Systems Materials Tracking software installed.

The aforementioned research projects have demonstrated the capability of integration of virtual models and the physical construction for better modeling of proposed facility, tracking of components on the construction site and progress monitoring. However, these integration approaches do not provide opportunity for providing feedback or control of construction activities; specifically, there are still little or no mechanisms for ensuring bi-directional coordination between the virtual models and the physical construction. For example, when a key component or sub-assembly is constructed/ changed in the physical environment, there is no means of automatically updating the virtual model to reflect this. Conversely, if the design or erection sequence of a set of steel members is altered in the virtual model, there is no real time communication of this change to the construction personnel on site. There is also a lost opportunity for the use of sensors and other embedded instrumentation to control the construction process/constructed facility.

3. BI-DIRECTIONAL COORDINATION

3.1 The Concept

The concept of bi-directional coordination (shown in Figure 1) in cyber-physical systems is used to describe the two-way integration of virtual models and physical artefacts such that changes in one are automatically reflected in the other. In construction, this includes enabling active monitoring and control of construction activities such that as building components are erected on site, the corresponding virtual model is updated to reflect the changed status of the component. Conversely, when changes are made to the virtual models, appropriate updates can be automatically sent to the relevant physical components in real time. Virtual models (such as BIM models) have long proved their worth in construction industry as a means of visualizing the construction process. These models contain virtual representations of building components which can be linked to the corresponding physical components on the construction site and in the constructed facility. As a facility moves through the life cycle from planning to design to construction and to facility management, changes in the status of physical components can be automatically updated in the virtual representations of the 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. Integrating virtual models with the physical components on the job site offers opportunities for improving information handling, thus enhancing access to real-time information or communication between the design and construction team (Sorensen et al. 2008). With bidirectional coordination, construction personnel can have access to 'component level' design model updates, make queries about components and receive responses to time critical issues, thus reducing delays to projects.

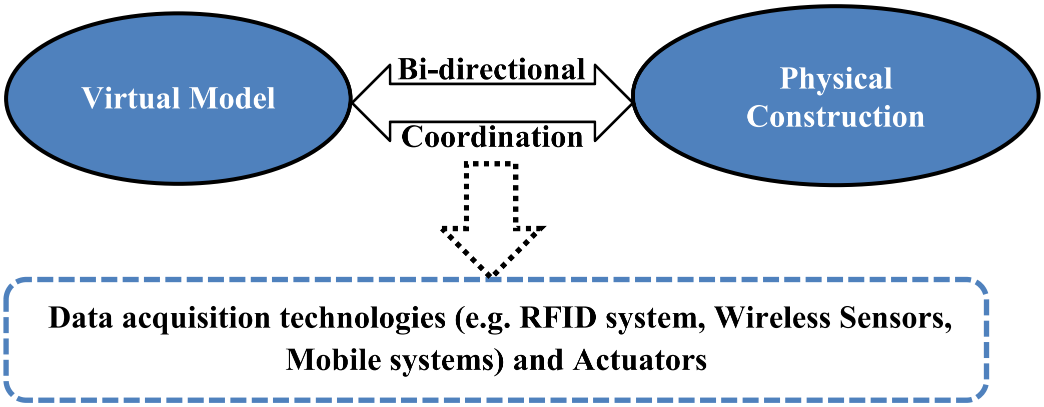

FIG. 1: Bi-directional coordination between Virtual models and the Physical construction

3.2 Triggers for Bi-Directional Coordination between Virtual Models and the Physical Construction

There are several situations that trigger the need for bi-directional coordination between virtual model and the physical construction. Based on content analysis of literature, the following triggers were identified: design changes, tracking and control of building components, changes in site conditions, and temporal conditions required for constructability. These are briefly described below:

3.2.1 Design changes

During construction, design changes occur and these changes can be owner-induced, or due to design mistakes or unforeseen site conditions etc. These changes constitute major causes of delays, disruption and disputes, and it is widely accepted that the effects of such changes are difficult to quantify (Motawa et al. 2007). When these changes occur, they need to be shared accurately, consistently and in a timely manner between the project team members and the construction site so as to reduce risks such as time and cost overruns (Chin et al. 2008). These changes can be effected in the virtual model and communicated to the affected components on site. Conversely, critical information can also be communicated from the physical components on the job site to their virtual representation in the model. For example, changes to sizes of steel members can be made to the virtual model and the steel erectors can access this from the tagged pieces on site before installation/erection. This will go a long way to help reduce rework, as critical information is received at the point of need.

3.2.2 Tracking and control of building components

Building components such as light fixtures are identical and as such, not distinguishable. Being able to track each light fixture in a constructed facility will enhance the ability to identify and control each fixture, thus offering the potential to improve facilities management and energy management. Binding each physical component with its corresponding virtual component will enable facility managers/owners to differentiate each component in the model and use the model to remotely control each component. Also, facility managers can track damaged or faulty components remotely instead of the usual physical maintenance checks.

3.2.3 Changes in site conditions

Changes in site conditions have been identified as one of the major causes of delays in construction projects (Domdouziz 2007). These changes from the original assumptions in the model/design need to be communicated to the design team in time and in an effective way so that appropriate decisions can be made. Also, changes in site conditions could result in changes (for example, to the original/as-planned layout/positions of physical components) being made on site. These changes need to be documented in the virtual model for 'as-built' documentation, which is vital for the operation and maintenance of the building facility.

3.2.4 Temporal conditions required for constructability

During the pre-construction phase, certain temporal conditions required for construction may not be accurately predicted and, as such, not fully provided for in the design. These temporal conditions usually result in a re-evaluation of the design before construction can proceed. For example, during the steel erection process, large mechanical equipment may need to be lowered into the building, and this could require that some steel members be left out. The structural engineer will need to be informed of the particular pieces to be left out so that he can determine the capability of the remaining structure to support the loads temporarily. The steel contractor could communicate the affected steel members to the structural engineer by flagging and embedding information in the virtual components. This will enable the structural engineer visually identify the affected pieces and also have access to real time information from the jobsite, thereby enhancing reduction in project cost and schedule.

3.3 Enabling Technologies

The key enabling technologies for enhancing bi-directional coordination between virtual models and the physical construction are discussed below:

3.3.1 Virtual Prototyping

Virtual prototyping is the exploitation of simulation processes for the testing, evaluation and modification of prototypes in virtual design environments (Brandon and Kocaturk 2005). Virtual prototyping involves creating digital models of products to be analyzed in 3D and 4D using software such as Autodesk Revit, VICO Software, and Bentley Architecture etc. These digital models, also known as virtual models, enable the visualization of proposed buildings to be constructed, thus enabling identification and correction of conflicts before construction (Huang 2006). . A 3D virtual model when linked to the construction schedule creates 4D models. These 4D models are necessary for graphically simulating the construction process, thereby allowing the user to control the appearance of objects in the 4D simulation in terms of timing, colors, materials, speed etc. 4D models also create a basis for comparison between the 'as-planned' and 'as-built' construction for consistency checking.

Virtual prototyping technology also involves information based models called Building Information Models (BIM) which have the capacity to store embedded information that can be analyzed and utilized throughout the lifecycle of a facility. The National Building Information Modeling Standards (NBIMS) Committee defines BIM as a digital representation of physical and functional characteristics of a facility. This digital representative feature of BIM provides a basis for linkage with the actual physical components. Thus, providing opportunities for automatically capturing and monitoring the status of components, communicating critical design changes between the virtual and the physical components and controlling the physical components in the constructed facility.

3.3.2 Wireless Sensors

Sensors are being deployed to obtain information about facilities that are being constructed, processes and equipment that are being utilized in constructing these facilities, and monitoring the as-is condition of an infrastructure throughout its service life (Akinci and Anumba 2008). Wireless sensors offers increased flexibility in terms of placement, reduced cost of installation and maintenance compared with wired sensors; this makes it suitable for adoption in the construction industry. Examples of wireless sensors used in the construction industry include Radio frequency identification (RFID) technology, temperature, humidity, magnetic sensors etc. The Radio-Frequency Identification (RFID) technology is a wireless sensor technology which is based on the detection of electromagnetic signals (McCarthy et al. 2003). The RFID technology consists of the RFID tags and readers. RFID tags makes it possible to assign unique identification numbers to components that they are attached and information can written to them to be accessed by personnel on the construction site using RFID readers (which may be fixed or mobile).

RFID tags are classified as passive and active tags (Erabuild 2006). Their classification is based on the means in which they receive power for transmission. Passive tags are the most popular type of RFID tags because of their low cost. They do not have a battery, but they get their power from the RFID reader. Passive tags can be read if brought in close proximity to a reader. These passive RFID tags can be used to track the status and location of bulk components such as light fixtures (during construction). And the tags can be linked to as-built BIM for identifying, distinguishing and controlling the bulk components during the facility lifecycle. Opportunities exist for also capturing and monitoring the energy use of facilities from the BIM. On the other hand, active tags have an on-tag power supply like a battery, which emits a constant signal containing identification information but they are expensive. Depending on the type, active RFD tags have read/write and location sensing capability e.g. the real-time location sensing (RTLS) tags. RFID tags have been utilized in the construction industry for tracking construction materials or components on site (Assaf and Al-hejji 2006; Goodrum et al. 2006) logistics and safety monitoring (Domdouzis 2007) and for material management and resource tracking (Kasim 2008). Integrating RFID tagged components with their virtual representation in the model will enable as-built information stored in this tags on site to be accessed in the model (in the office). Also design changes made to virtual components in the model can be communicated to the tagged components for access by the construction personnel on site. Furthermore, the location sensing capability of the RFID tags can be useful for automated position and status tracking of installed/uninstalled components instead of the manual approach of embedding status information in the tags. The ability to identify tagged components in the model will also enable facility managers to control key components in the constructed facility.

3.3.3 Mobile Devices

Mobile devices are portable/small sized computing devices having a display screen for reading and writing information. Mobile devices have long been found useful in the construction industry for progress monitoring (El-Omari and Moselhi 2008; Leung et al. 2008; Sawyer 2008), managing punch lists (Menzel et al. 2002)], maintenance (Kim et al. 2008) and safety applications (Wu et al. 2011). Examples of such mobile devices include personal data assistant (PDA), smart-phones and tablet PCs. The tablet PCs offers several advantages compared with the PDAs and smart phones: Tablet PCs are capable of accommodating several kinds of information such as project models and specifications. Tablet PCs have large screen (unlike the PDA and smart phones) which can be used to navigate models and provides easily and quick entry of construction data. The major drawback of PDAs is the small screen size and limited ability to easily and quickly enter data. Most mobile devices have external features for data capture such as barcode scanners and RFID readers. Construction personnel can easily embed information through the screen to be written to RFID tags before installing/erecting building components. They can also scan the tags and barcodes using the embedded RFID and barcodes readers respectively, to read the tag information. Another important feature of mobile devices is the wireless connectivity. Data captured using mobile devices can be transferred wirelessly to a local or remote server.

3.3.4 Communication Networks

The communication network is one of the most important technologies for enhancing bi-directional coordination between virtual models and the physical construction, as it enables the transfer and exchange of information between mobile and fixed devices (Bulbul et al. 2009; Sorensen et al. 2009; Chin et al. 2008). Examples of some communication networks being used in the construction industry include the internet, wireless local area network (WLAN, Wi-Fi) and the wireless personal area network (WPAN) comprising ultra wide band, Zigbee and Bluetooth. With these communication networks, data can be transferred or exchanged wirelessly between devices on the construction site, and between the construction site and the remote office, thus enhancing collaboration amongst the project team. In the context of this research, data or information from the construction site can be transferred through the communication networks to the virtual model in the remote office and vice versa. The choice of communication network depends on a number of factors such as range, cost, data transfer rate, network topology and battery life (Xuesong et al. 2008).

The role of the above enabling technologies in the cyber-physical systems approach to bi-directional coordination is described in more detail in the next section.

4. THE CYBER-PHYSICAL SYSTEMS APPROACH

4.1 Overview

Cyber-physical systems approach has long been adopted in information systems research in other industry sectors. A number of authors have defined the term in the following ways:

- Cyber-physical systems are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core (Rajkumar et al., 2010).
- Cyber-Physical Systems are networked, component- based, real-time systems that control and monitor the physical world (Crenshaw et al., 2007).
- A Cyber-Physical System are systems that integrate physical devices (e.g., sensors, cameras) with cyber (or informational) components to form a situation-integrated analytical system that responds intelligently to dynamic changes of the real-world scenarios (Tang et al., 2010).
- Cyber-physical systems are dynamic systems that integrate physical processes with computation, often in feedback loops, where physical processes affect computations and vice-versa (Lee, 2008).

From the above definitions, the key elements of a cyber-physical system include integration and coordination. Thus, for a system to function as a cyber-physical system, its subsystems must be tightly integrated and coordinated. Hence, in the context of construction, a cyber-physical systems approach can be defined as a tight integration and coordination between virtual models and the physical construction/constructed facility such as to enable bi-directional coordination. A key feature of a cyber-physical systems approach is the presence of both a 'cyber-to-physical' bridge and a 'physical-to-cyber' bridge as shown in Figure 2 (Wu et al. 2011). The 'physical–to-cyber' bridge is the sensing process, which involves the use of sensing systems to identify, distinguish, locate and bind the physical components to the virtual representation. On the other hand, the 'cyber-to-physical' bridge represents the actuation process, which shows how the sensed information is acted upon by 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 control the physical components.

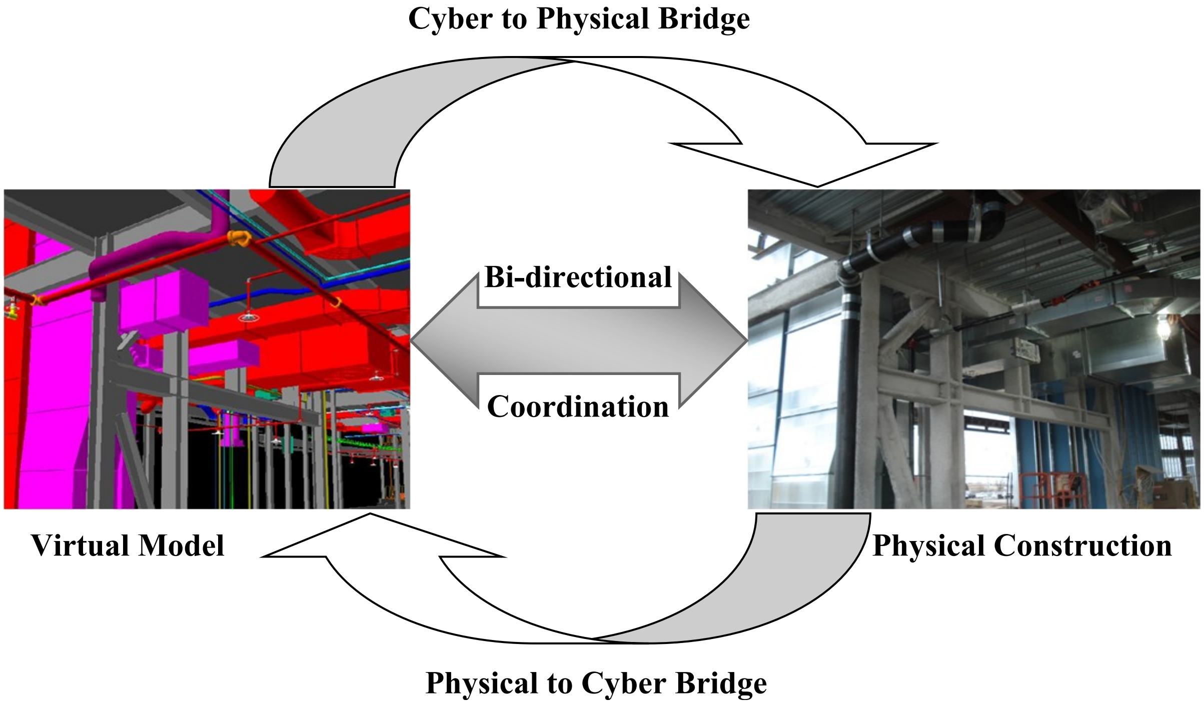

FIG. 2: Cyber-Physical Systems Integration Concept

4.2 System Architecture

As discussed earlier, in a construction context, the critical issue is how to integrate the virtual models with the physical building components so that there can be bi-directional coordination between them for a variety of purposes. To demonstrate the application of the CPS approach to this issue, a system architecture (shown in Figure 3) and a set of deployment scenarios have been developed. The system architecture is presented below prior to a description of the deployment scenarios. The architecture is based on multiple layers, which are explained as follows:

4.2.1 Sensing Layer

The sensing layer consists of sensors which monitor different aspects of the construction process/constructed facility e.g. the temperature sensor (for monitoring temperature of a space), RFID tags and readers (for identifying and storing information about components), and placement sensors (for tracking component placement). Depending on the type of sensor used, this layer can also provide the construction personnel access to control decisions (e.g. information captured in the RFID tag memory or information that can be accessed through the RFID tag id).

4.2.2 Device Layer

This layer consists of the client devices (such as PDAs, tablet PCs, iPADs and smart phones) through which the end user (e.g. construction personnel on site) can interact with the system. This layer serves two purposes: it provides access to sensed data from the sensing layer, and enables the entry of information through the user interface.

4.2.3 Communication Layer

This layer contains the Internet and wireless communication networks: wireless personal area networks, WPAN (e.g. Zigbee and Bluetooth), wide area networks (WAN) and local area networks, LANs (which use Wi-Fi to enable access to the Internet). These communication networks connect mobile and other devices to allow for collaboration and information sharing between construction personnel on site and with the design offices of the consultants. The communication networks also allow the data collected through the mobile devices to be transferred through the Internet to the database in the contents and application layer.

4.2.4 Contents and Application Layer

The contents and application layer contains the local database, database server and the control application. The type of control application depends on the context application to which the system is put. This layer stores, analyses and is constantly updated with information collected from both the communication and actuation layers. The stored information includes project management data (such as component type, as-built information, model update information, component lifecycle data and application specific data). The control applications use the sensed data from the database to make control decisions which can be visualized using the virtual prototype in the actuation layer.

4.2.5 Actuation Layer

The actuation layer contains the virtual prototype which is accessed through the user interface. The virtual prototype enables the user to visualize how the sensed information (from the contents and storage layer) affects the system. The user interface enables the user to visualize and monitor the sensed information from the contents and storage layer. The user can also embed control decisions into the virtual prototype using the mobile devices in the device layer.

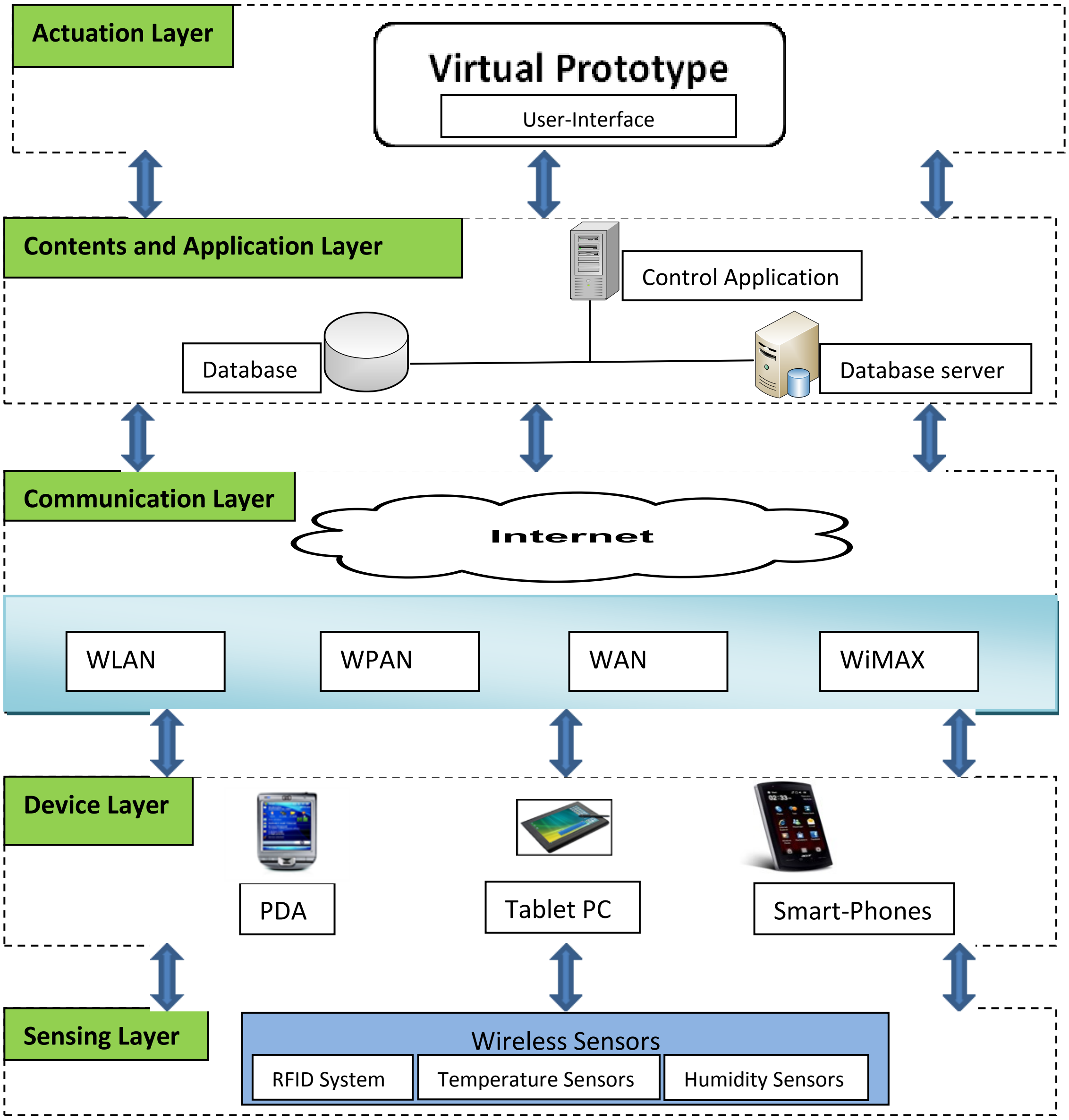

FIG. 3: The Cyber-Physical Systems Architecture

4.3. APPLICATION SCENARIOS

Four scenarios, illustrating the application of bi-directional coordination between virtual models and the physical construction, are presented here to show the practical application of the proposed cyber-physical systems approach. The scenarios were developed to address the different broad categories of building components (as defined by CII, 1999): Engineered materials (pump size change), Bulk materials (light fixture monitoring and control) and Prefabricated materials (doors change on a retrofit site and steel placement).

4.3.1 Steel Placement

This scenario describes how bi-directional coordination between the virtual model with the physical construction will enhance the installation of structural steel members. Each member is tagged using active RFID tags with embedded information on the erection sequence for the installation of the steel members. This is intended to avoid the problems that can occur when a member is in line for installation before the supporting members have been erected. The virtual model reflects the status of the steel erection (i.e. it can highlight which members have and have not been installed to date). The model also contains information about dependencies (i.e. which members need to be installed before others). The following numbers illustrate the sequence of actions and correspond to the numbers in Figure 4.

1. After steel members have been fabricated, a change is made to the design (or a mistake is found). The structural engineer corrects this change, but it has an impact on the sizes of several other members.
2. Information regarding the changed/affected member sizes is communicated to the construction site and written to the RFID tags: The information from the model is initially captured in the database server, transferred through the internet and read by a fixed RFID reader (which has read and write capability). The reader/writer writes the information to the RFID tags of the affected members so that the contractor knows which pieces can be installed and which need to be replaced with larger members. Since the virtual model also contains dependencies, if the original installation sequence changes, the new sequence is also communicated to the RFID tags of the affected members.
3. Before erecting each steel member, the steel erector scans the RFID tag with a PDA (having an in-built reader with read and write capability) and reads off embedded information.
4. As each steel member is erected on site, the steel erector updates the status of the RFID tags (from ‘on-site’ to ‘installed’ or ‘erected’) on the members by writing to the tags using the PDA.
5. The status change is detected by the fixed reader and communicated through the Internet to a project database. A control application (running on the remote office computer) loops through the database for new information and updates the virtual model with the new status, resulting in the affected member being highlighted (e.g. by a color change). This color change in the virtual model enables the model coordinator /project manager to monitor the progress of the structural steel erection from the remote office.
6. If a large mechanical equipment needs to be lowered into the building later during construction and this requires some steel members to be left out, the steel erector can identify the steel members and write this change to their tags.
7. The tag information is detected by the fixed reader through the radio frequency from the tags and communicated through the database to the virtual model, which is then updated with the new information, resulting in that member being highlighted. The role of the color change is to inform the structural engineer of the updated information relating to a steel member.

The structural engineer reads the information in the model, and evaluates whether the remainder of the structure is adequate to support the loads temporarily.

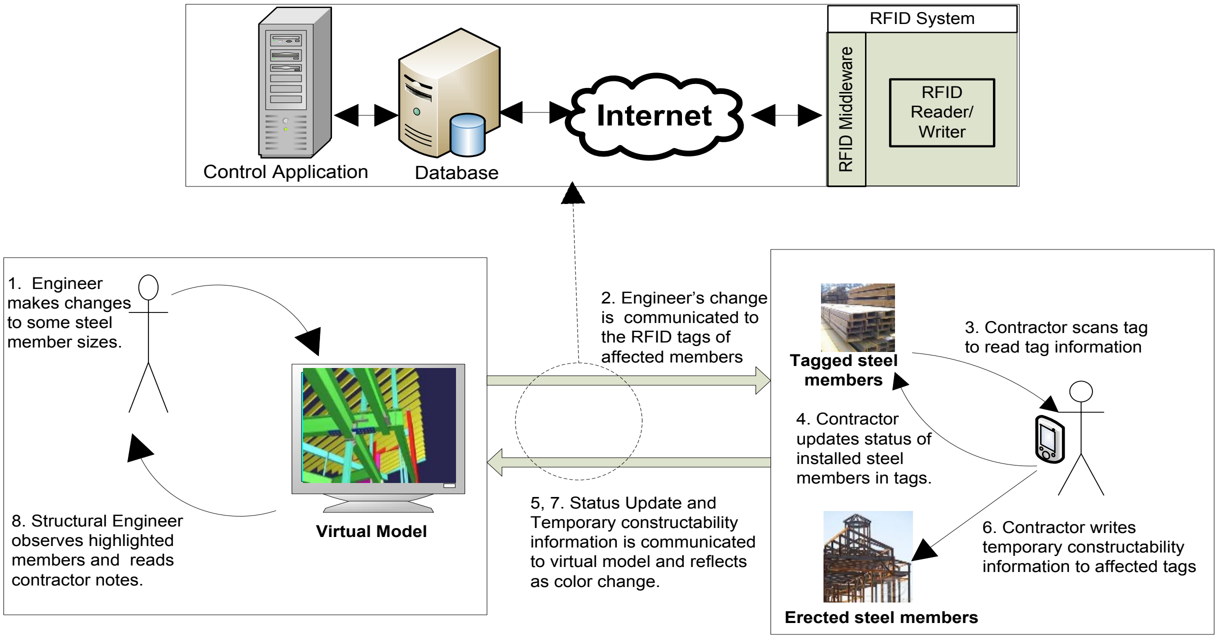

FIG. 4: Steel Placement Scenario

4.3.2 Door Change on Retrofit Site

In this scenario, bi-directional coordination is used on a retrofit site for tracking design and construction site changes and documenting as-built information. The following numbers correspond to the sequence of activities in Figure 5.

1. In this scenario, after design is complete, the owner requests a change to the room layout so that the door location moves to an adjacent wall. The architect in the design office updates the virtual model with the change in the door location.
2. The change is communicated to the construction site and written to the tag on the affected door (which has not yet been installed): The design change from the model is initially captured in the database server, transferred through the Internet and read by a fixed RFID reader. The reader/writer writes the information to the RFID tags of the affected door.
3. Before installing the door, the contractor scans the door tag and observes that the door location has been changed. A notice of the change can also be communicated to the contractor so that he knows that a change has occurred before he proceeds with installing the door.
4. Furthermore, on examination at the site, the contractor discovers that the new door location is in one of the interior walls that is load bearing. The original door location corresponded to a door with a 1-hour fire rating (for non-load bearing assemblies), but now needs to change to a 2-hour fire rating (for load bearing assemblies). The contractor writes this change to the door tag.

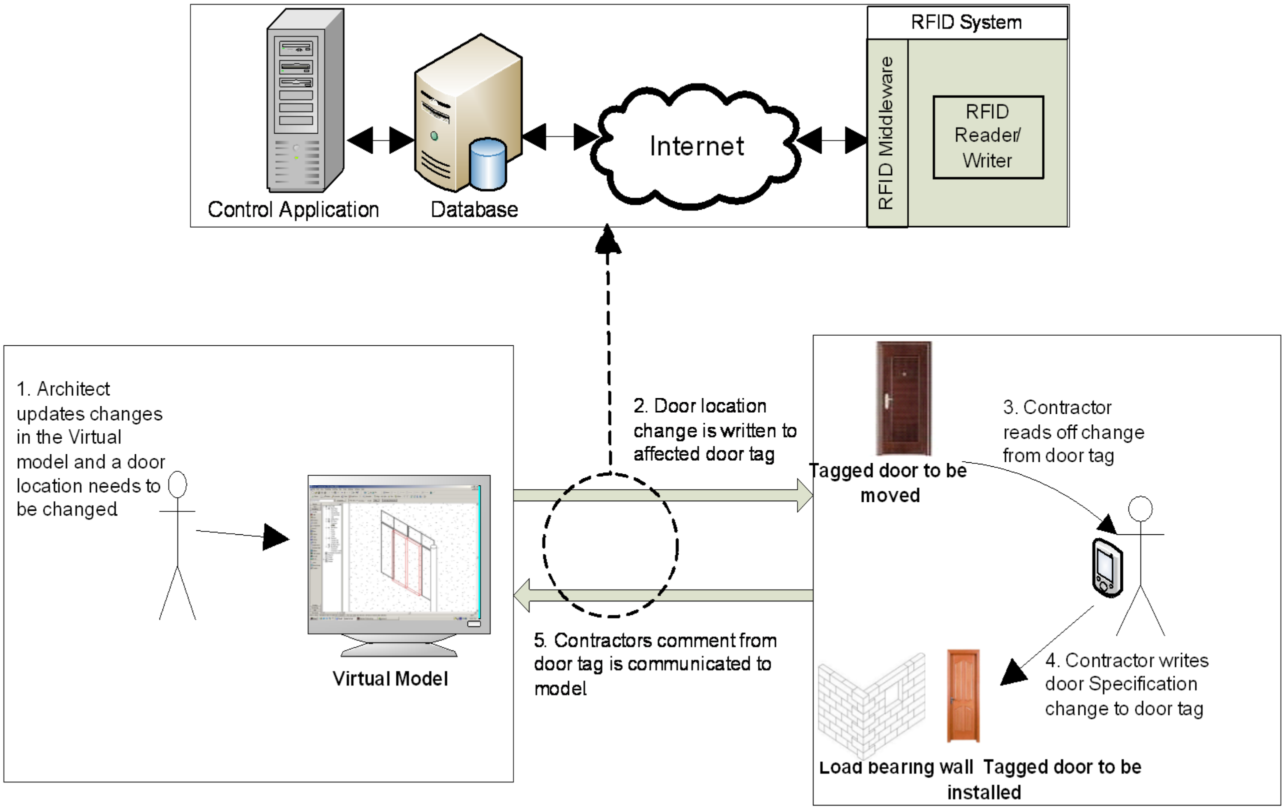

FIG. 5: Changes on Retrofit site scenario

5. The tag information is detected by the fixed reader and communicated through the database to the virtual model, which is then updated with the new information, resulting in the door member being highlighted. This update to the model serves as a way of archiving as-built status and informing the architect of the different site condition. The architect inspects the site to confirm the observation of the contractor. He specifies and orders a new door type and frame for the load bearing wall. Depending on the contractual agreement, the architect and contractor can both assess the cost implications of installing the new door. Once the cost of the change is agreed upon, the architect can issue a notice to proceed with the drawings, specifications and instructions to execute the change.

4.3.3 Pump Size Change

This scenario involves tracking design changes on the construction site and documenting as-built status in the virtual model. The sequence of activities in figure 6 illustrates this scenario.

1. After design is complete, the MEP engineer (in the design office) makes a change to the virtual model that requires a larger pump size for one of the water lines. This change specifies the use of a specific pump or equivalent type.
2. The change is communicated to the construction site and written to the active RFID tag on the pump: the design change is initially captured in the database server, transferred wirelessly and read by a fixed RFID reader. The reader/writer then writes the information to the RFID tag of the affected pump. If the inlet and outlet pipes are affected by the change in pump size, the MEP engineer also effects this change in the virtual model and the change is captured in the database server from where it is transferred wirelessly and read by the fixed RFID reader on site. This change is then written to the RFID tags on the affected pipes. A

notice of the change can also be communicated to the contractor's PDA so that he is aware of the change before proceeding with the installation.

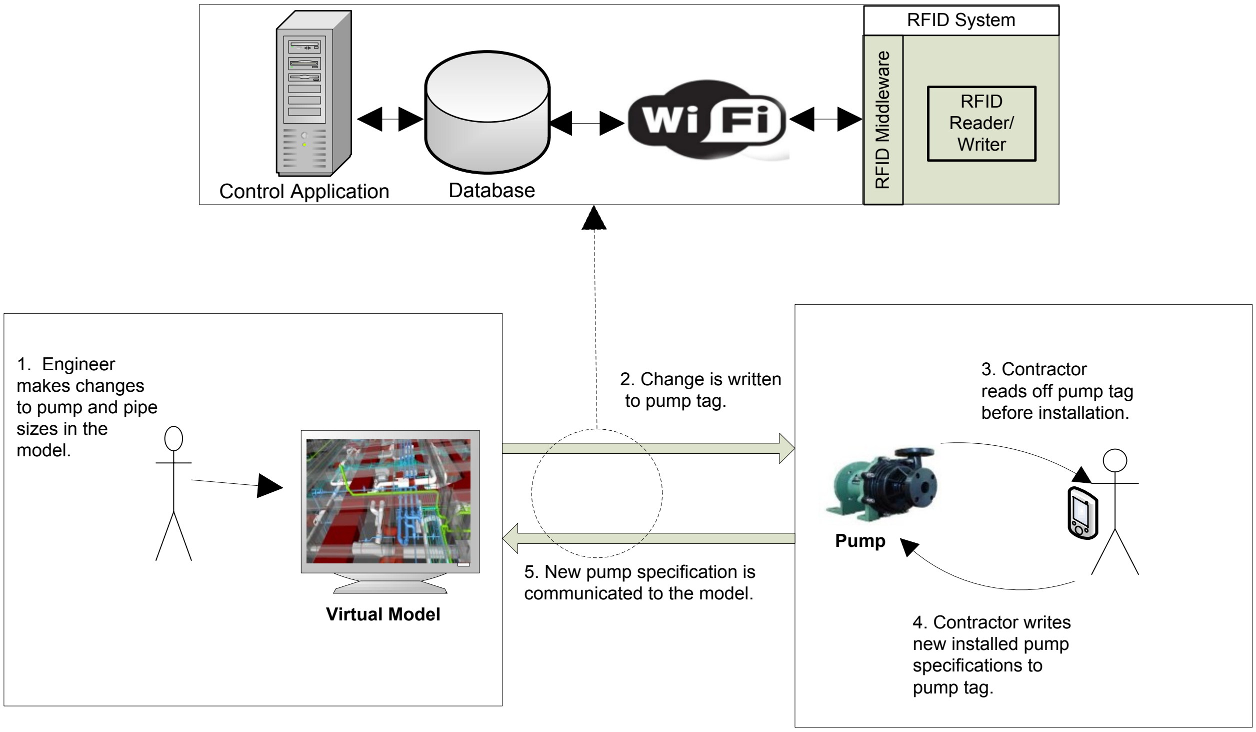

FIG. 6: Pump size change scenario

3. The contractor also scans the tag on the pump before installation; this enables the contractor to know which pump and pipe sizes to install and he can immediately assess any schedule or cost impacts. Once the contractor is informed of the new change, he selects the appropriate pipe sizes and equivalent pump from a different manufacturer. The cost and specification of the selected pump and pipes are submitted to the architect and MEP engineer for approval before the contractor orders the items. The approval authorizes the pump to be released for purchasing and shipment to the job site. This is a quality control process ensuring that the right equipment is ordered prior to being brought to site for installation.
4. Subsequently, since the specification calls for a specific pump or equivalent type, the contractor installs the approved pump type and writes the installed pump specification to the RFID tag on the affected pump.
5. The pump tag information is detected by the fixed reader through the radio frequency from the tags and communicated through the database to the virtual model, which is then updated with the new information, resulting in the affected pump being highlighted. Communicating this change to the virtual model serves as a way of recording as-built condition or actual pump specification, which is necessary during the operation and maintenance phase of the facility.

Writing the pump specifications to the RFID tag ensures that changes are documented during construction and can be later referenced for full documentation of complete specification of the pump.

4.3.4 Light Fixture Monitoring and Control

The locations of individual items of bulk materials (such as light fixtures) within a building are not easily differentiable; as such, facility managers cannot control each item. This scenario (Figure 7) focuses on identifying and tracking the installed locations of light fixtures for the purpose of improving energy management in buildings.

1. On arrival at the site, the light fixtures are tagged with passive RFID tags (if the light fixtures are not already tagged) to identify and differentiate each component.
2. As each tagged fixture is installed, the electrical contractor scans the fixture tag using a tablet PC with an integrated RFID scanner.
3. 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.
4. 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.
5. 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.

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. This concept can be applicable to urban infrastructure street lights, electrical bill boards and similar installations, where the installation of the individual street lights can be monitored remotely for the purpose of distinguishing each fixture and controlling each fixture over the infrastructure lifecycle. Being able to digitally address each light fixture provides an opportunity to digitally address each fixture from the virtual model and to communicate any changes in the status of the physical fixture (e.g. defective) to the virtual model for operational and maintenance purposes.

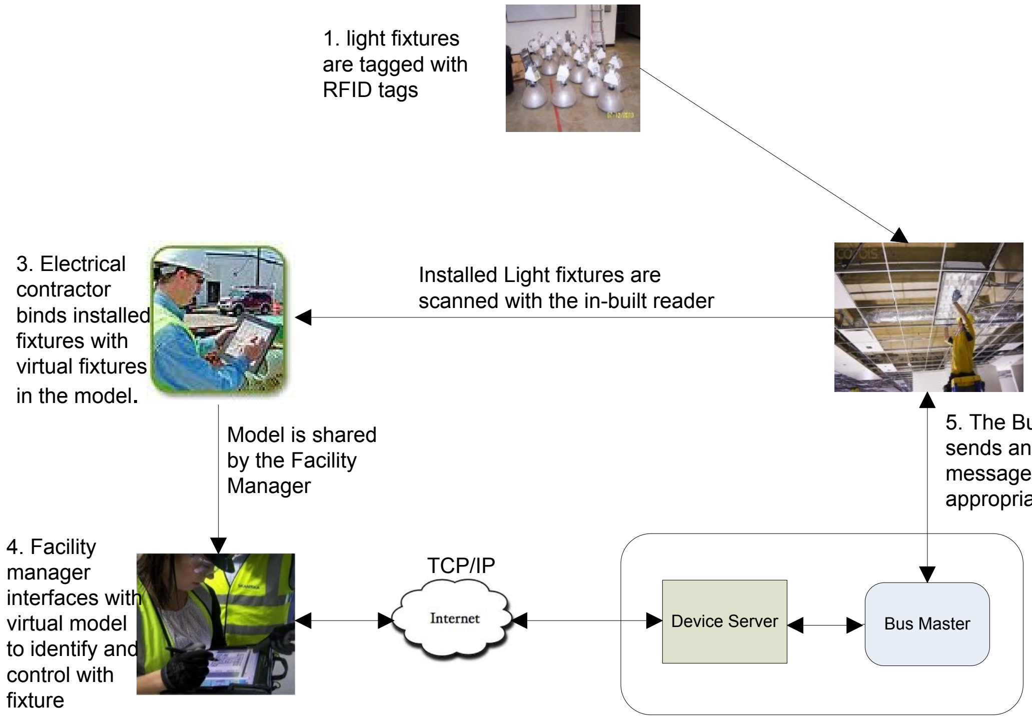

FIG. 7: Bulk material tracking and control

4.4. Scenario Validation

In order to ensure that these were appropriate scenarios for the deployment of the CPS approach, a scenario validation exercise was undertaken using a qualitative research approach. This involved interviewing a number of construction industry practitioners, who would be the potential end-users and beneficiaries of the system. Care was taken to choose people with the right expertise and technical knowledge of the construction industry and related wireless sensing technologies. On average, practitioners with a minimum of five years of industry experience were chosen for the scenario validation. Twelve practitioners were involved in the validation of which five were construction managers, three were project managers and four were facility managers. The validation procedure involved a survey which had both a questionnaire and an interview component. The questionnaire completion was followed up with oral interviews. The interview was performed to follow up the industry practitioners and to explain the scenarios. The involvement of the practitioners ensured that an appropriate construction industry perspective was taken. The practitioners were contacted through email and phone. They were told that no personal information would be collected other than job title and industry experience.

The questionnaire was designed objectively to investigate the role and importance of bi-directional coordination in improving the construction and post-construction phases of a facility lifecycle. Relevant questions relating to how well the scenarios achieved the goal and addressed the triggers for bi-directional coordination were also posed. Other questions related to the usefulness of bi-directional coordination and issues regarding the implementation of the scenarios and how the scenarios could be improved for practical deployment. The respondents were briefed on the scenarios and questionnaire before starting to fill in their answers. This was done to ensure the validity and reliability of the data. After completing the questionnaires, a follow up interview was conducted for clarification of questionnaire responses, to collect additional information, and to eliminate misunderstanding.

4.5 Validation Results

The questionnaire data were analyzed in-order to observe the response patterns. The information gathered from the respondents via the questionnaire and follow up interviews gives a positive indication that the proposed scenarios are appropriate and have potential for practical implementation.

- **Perceived Benefits**

All the respondents liked the concept of bi-direction coordination and considered the scenarios as being realistic. They all agreed that the scenarios are important for communicating construction site changes, work progress to the design team. They also agreed that the scenarios are important for communicating design model updates to the site team, thus improving the construction project delivery. Concerning the requirements for bi-directional coordination, the respondents identified that the scenarios enhance access to real-time information, construction process control, and on site retrieval of relevant model changes or updates. It is important to note that they also considered the scenarios as having some support for as-built documentation by capturing the 'as-built status' of key components and transmitting this to the virtual model. The respondents were also asked to highlight the potential benefits of the proposed approach. Majority of the respondents identified that the proposed approach enables formal capture of changes made late in design or in the field. These changes rarely make it into the formal documents for the owner or are so hidden in the binders of request for information (RFIs) or Change Orders, that they are not readily accessible. Other respondents also identified accurate documentation of the as-built condition as the greatest benefit of the proposed approach. Few reviewers identified the benefits from the facility managers' point of view as being useful for preventative maintenance. This approach has demonstrated potential for enabling tracking and identification of components within the model. However, being able to track the individual items from the model will provide opportunities for condition awareness and possibly control if appropriate sensors are used. They also highlighted that this technology will become more useful when virtual models of all projects become the norm. One of the reviewers identified that if operations data can be stored in the model, this can be easily retrieved when needed.

- **Concerns**

Two of the respondents were concerned about the effect that this approach would have on the current process of tracking and conveying changes to concerned parties during construction. Current practice require that the contractors raise change orders if there is a change in the scope of work, design or conditions on site before the change is implemented. The reviewers also raised the question of how the proposed approach of bi-directional coordination compares with the current practice. They further claimed that the proposed approach will more likely be suitable for design-build project delivery than traditional design-bid-build delivery methods. This is because there is better communication between the design team and the field personnel in the design-build delivery method, thus enhancing the effective flow of changes/model updates to the site and the update of progress or as-built information to the model. Most of the respondents were concerned about the cost of implementing this technology on large construction sites and raised the question of 'who bears the cost?'. The tagging of building components requires that PDAs and Tablet PCs be used, thus increasing the project budget. Also, the cost of these tags is high and as such there will be considerable loss if these tags are stolen, lost or damaged. The lifetime of the tags is an average of five years depending on the frequency of use. Another concern was regarding the technical competency of the workers. Construction workers are typically not accustomed to technology, so considerable training (costs to train) would be required in-order to get them on board with this new technology. The industry experts claim that it would cost a lot to educate the building managers on how to use the technology proposed in 'light fixture monitoring and control' scenario. However, they also recognized that the benefits of being able to track and control bulk items (such as light fixtures) throughout a building lifecycle outweigh the cost of training building managers. Furthermore, the cost of training the building managers is a one-off cost.

- **Other Applications/Scenarios**

The respondents identified other potential applications of bi-directional coordination as being useful for building enclosure tracking, and the tracking of other components (such as window blinds, electrical components, and heating, ventilation and air-conditioning (HVAC) components). These components could be integrated and controlled as a homogenous system.

5. DISCUSSION

The concept of bi-directional coordination described in this paper involves two-way communication between virtual models and the physical construction, such that changes in one can be reflected in another and vice versa. From content analysis of literature, the requirements for this two-way communication were established to include design changes, tracking and control of building components, changes in site conditions and temporal conditions required for constructability. Since the goal of this research was to provide a strong, 2-way link between virtual models and their corresponding physical components, existing technologies were explored as a means of addressing the aforementioned requirements. The image based technologies (laser scanners and digital cameras) will need to be complimented with other technologies to fulfill the requirements or triggers for bi-directional coordination. However, RFID tags proved effective in this regard, given their capacity to identify and track individual physical components. Their real-time location sensing capability makes them suitable for status tracking and automatic update of the virtual model as changes are made to the location, installation status or other important property of the physical components.

The scenarios presented in this paper demonstrate the versatility of the cyber-physical systems integration and the role of RFID tags in facilitating the bi-directional coordination. The scenarios were presented for the different categories of construction components. The 'steel placement' and 'door changes on a retrofit site' scenarios require the use of a specialized RFID tag capable of both location sensing (for automated component placement) and read/write capability (for two way communication between virtual models and the physical components). The 'light fixture monitoring and control' scenario requires a sensing system for identifying and distinguishing each fixture, thus providing opportunities for monitoring and controlling the fixtures. This calls for the use of a passive RFID tag.

For the developed scenarios, it was important to understand the perspective of industry practitioners regarding their feasibility and how the proposed concept would fit into practice. This was done through a validation exercise that included both interviews and a questionnaire survey. The structure of the distributed questionnaire was such as to provide them with detailed information to enable adequate and quality feedback. The nature of the bi-directional concept and low level of awareness about the cyber-physical system integration necessitated follow-up phone interviews. The feedback from the industry practitioners was generally positive with regard to the usefulness of the scenarios. In particular, they were complimentary about the support for real-time component level progress monitoring, supporting as-built documentation by capturing 'as-built' status information, real-time capture and communication of changes to project team members, and the potential for active control of building components (such as light fixtures). The practitioners considered the proposed approach highly suitable for the design-build delivery method; where communication and collaboration are strongly encouraged between the design and construction team. However, the practitioners had concerns about the cost of RFID tags, especially with regard to who bears the cost of the tags and the cost of training for the site personnel that would use the technology. While this is a legitimate concern, it is not the intention that all components on the jobsite will be tagged with this technology – only high value or critical components for which the cost can be justified would need to be bound to their virtual representations. Also, it is expected that the cost prices of these technologies will continue to decrease over time, while the benefits of the cyber-physical systems integration in construction projects become more evident.

There is the need to implement the proposed scenarios on a jobsite to fully investigate the practical, managerial and other considerations in the implementation of the CPS approach in construction projects. This is being addressed in the next phase of the research. Opportunities also exist for investigating the potential and suitability of other image based technologies for enhancing the bi-directional coordination approach.

7. SUMMARY AND CONCLUSIONS

With advances in information and communication technologies, the cyber-physical systems approach offers potential opportunities for enhancing bi-directional coordination between virtual models and the physical construction. The CPS approach described in this paper involves the use of RFID tags to capture and store relevant information about tagged components. The sensed information from the tags is used to make management decisions, with the potential to physically control the construction process/constructed facility. This approach has been demonstrated through the development of use-case scenarios. A system architecture was presented, which describes the key enabling technologies (including wireless sensors, mobile devices, communication networks and virtual prototyping technology) and sub-systems needed for cyber-physical systems integration. The key conclusions that can be drawn from this work are:

- Limiting the use of virtual models to the design phase of construction projects misses the huge potential benefits to be gained from their use during the construction and operational phases of the facility life-cycle;
- Maintaining consistency between the virtual model and physical construction components (through bi-directional coordination of information between both representations) offers considerable scope for new tracking and communication mechanisms in project control;
- Bi-directional coordination between virtual models and the physical construction has potential opportunities for improving project monitoring and control of construction process/constructed facility, tracking changes/model updates and communicating these to site in real-time, documentation of as-built status and sustainable practices;
- Triggers for bi-directional coordination have been identified as design changes, tracking and control of bulk materials, different field conditions, and temporal conditions required for constructability;
- The developed scenarios indicate that cyber-physical systems approach can play an important role in enhancing bi-directional coordination between virtual models and the physical construction;
- RTLS-RFID tags can be used to identify components and store information; this makes them suitable for tracking design changes and relaying them to the construction site, and facilitating the capture of as-built information;
- There is considerable potential for the use of cyber-physical systems in various aspects of the construction project delivery process, facility management, and other operations.

Further work on this project involves the development of the CPS system and its deployment on an experimental laboratory-based construction scenario prior to full-scale deployment on a construction site. The latter is expected to identify practical implementation constraints in addition to identifying further benefits and application areas.

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