Case Study

Case Study of BIM and Cloud–Enabled Real-Time RFID Indoor Localization for Construction Management Applications

Yihai Fang, S.M.ASCE[1]; Yong K. Cho, A.M.ASCE[2]; Sijie Zhang[3]; and Esau Perez[4]

Abstract: In the field of construction, indoor localization of mobile construction resources remains a universal challenge. Although discussions have focused on the tracking accuracy and affordability of indoor localization technologies, few efforts have focused on practical criteria such as ease of use, latency, and data visualization and remote sharing. To close this gap in knowledge, this study introduces a building information modeling (BIM) and cloud-enabled radio-frequency identification (RFID) localization system. The system consists of three main components: the passive RFID localization system, the BIM visualization system, and the cloud computing system. The proposed system is tested in a full-scale implementation on an actual construction site. The test was designed and conducted to evaluate the localization accuracy, data latency, and real-time data processing and visualization for remote monitoring. A comprehensive analysis is made of various practical issues based on the test results and panel discussion. The findings in this study indicate that the BIM and cloud-enable RFID indoor localization solution has a great potential in practical applications such as site security control, safety management, asset management, and productivity monitoring. **DOI:** **10.1061/(ASCE)CO.1943-7862.0001125.** © *2016 American Society of Civil Engineers.*

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Introduction

Location information is the basis of many applications such as navigation, transportation, manufacturing, and logistics. While global positioning systems (GPS) have been widely adopted for outdoor localization, no robust solution is ready yet for widespread implementation in indoor environments. In sharp contrast, many industries have shown growing demands for indoor localization (Lu et al. 2011). Recently, information technology has dramatically changed the way a construction project is executed. Various tasks in the phases of planning, designing, and execution heavily rely on a wide range of location data, such as worker and equipment location data for safety planning and management, and material location data for progress tracking. Since a majority of construction activities in building projects take place in indoor environment, indoor location data of workers, materials, and other construction resources have a significant impact on the quality, safety, and productivity of project execution.

Various technologies have been investigated for indoor localization. Most popular technologies in this category include inertial navigation systems (INS), ultra-wide-band (UWB), wireless local area network (WLAN), Bluetooth, and radio frequency identification (RFID). INS-based solutions utilize inertial measurement sensors such as accelerometers and gyroscopes to estimate location. This method does not require any infrastructure besides a sensor unit carried by the tracked subject. Since the location estimations are obtained through a double integration from acceleration measurement, this technology suffers from its large and distance-proportional drifting error (Jiménez et al. 2009). UWB is a sensing technology for precise location tracking. Compared to RFID technology, it transmits data over a large bandwidth, which makes it less prone to signal interference and easier to pass through walls. Although UWB-based localization technology can theoretically achieve centimeter-level accuracy, many studies showed that the accuracy of a UWB system highly depends on a clear line-of-sight from readers to tracked subjects (Cho et al. 2010). Furthermore, the biggest disadvantage of implementing UWB for indoor localization is its expensive hardware investment of \$140 per m^2 (Li and Becerik-Gerber 2011). WLAN-based method takes advantage of existing WLAN infrastructure in the facility. This makes it one of the most cost-effective localization technologies (Behzadan et al. 2008). However, this technology is hard to implement on sites under construction where no WLAN infrastructure is available. For this reason, Cho et al. (2006, 2010) used a fully untethered self-powered WLAN system that is mainly designed for construction sites or places that may not have communication infrastructure installed. RFID systems typically consist of a number of RFID readers, antennas, and tags. RFID readers are strategically placed around the sensing area and tags are placed on subjects that need to be localized. A RFID antenna reads data from tags, and a reader transmits the collected data to a host computer for further data processing and analyses. An active RFID tag has an on-board battery and periodically transmits its ID signal. A passive tag is cheaper and smaller and it uses the radio energy transmitted by the reader. Both active and passive tags have internal memory for

[1]Ph.D. Student, School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlanta Dr. N.W., Atlanta, GA 30332-0355. E-mail: yihaifang@gatech.edu

[2]Associate Professor, School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlanta Dr. N.W., Atlanta, GA 30332-0355 (corresponding author). E-mail: yong.cho@ce.gatech.edu

[3]HES Research Engineer, Chevron ETC, 1200 Smith, St. Houston, TX 77002. E-mail: sijie.zhang@chevron.com

[4]Workforce Safety Team Lead, Chevron ETC, 1200 Smith, St. Houston, TX 77002. E-mail: esau.perez@chevron.com

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Table 1. Characteristics of Indoor Localization Technologies (Adapted from Li and Becerik-Gerber 2011)

Technology	Accuracy	Affordability ($\$/m^2$)	No line of sight required	Wireless communication	Context-independence	Built-in power supply
Indoor GPS	1–2 cm	380	—	—	—	Yes
INS	1.1–4.2 m	20	Yes	—	Yes	Yes
Infrared	30–50 cm	17		Yes	—	—
UWB	6–50 cm	140	Yes	Yes	—	—
WLAN	4.5–6.9 m	3	Yes	Yes	—	—
RFID (passive)	1.6–3.1 m	25	Yes	Yes	—	—
RFID (active)	1–2 m[a]	N/A	Yes	Yes	—	Yes

[a]Accuracy data of active RFID is from (Liu et al. 2007).

storing unique tag ID and other necessary information. Table 1 summarizes the characteristics of different indoor localization technologies based on the evaluation criteria proposed by Li and Becerik-Gerber (2011).

Although RFID technology has shown great potential in applications such as supply chain management and site access control, several critical challenges hindered its further adoption for mobile resource tracking on construction sites. To enhance efficiency and effectiveness of construction resources tracking in indoor construction environment, this study introduces a building information modeling (BIM) and cloud-enabled RFID localization solution. To further illustrate this enhanced localization solution, this paper starts with a review of the challenges in current RFID localization systems and envisions the benefits of integrating BIM and cloud computing. It then introduces the design and components of the proposed system followed by a demonstration of a full-scale implementation of the proposed system in an ongoing construction project. The analysis and validation on localization accuracy, data latency, and real-time data processing and visualization is reported and the test results and the limitations of the proposed system are further discussed.

Related Work

Indoor Localization Technologies

Compared to the other aforementioned indoor localization technologies, RFID technology draws more attention from researchers and practitioners in the construction field because of its technological maturity and comparatively cost-efficient infrastructure. As one of the early pioneers, Jaselskis et al. (1995) envisioned a wide range of applications for RFID technology in the construction industry. These applications include concrete processing and handling, cost coding for labor and equipment, and material control. Domdouzis et al. (2007) anticipated a wide influence of RFID technology in construction practices such as pipe spool tracking, onsite inspection, and localizing buried assets. Following these expectations, researchers have been exploring and expanding the applications of RFID technology to material management (Jaselskis and El-Misalami 2003), quality inspection and management (Wang 2008), facility management (Ergen et al. 2007), construction progress monitoring (Chin et al. 2008), and construction resource localization (Domdouzis et al. 2007).

Among these applications of RFID technology, construction resources localization is the center of interest as it provides essential location data to various applications such as productivity analysis, inventory management, safety management (Lee et al. 2012), and first responder events (Guerrieri et al. 2006). Costin et al. (2012) attempted to use RFID for construction resources localization (i.e., personnel, equipment, material) in a high-rise building project. By placing RFID readers at the elevator gates and RFID tags on worker hardhats, materials, and equipment, they analyzed the efficiency of vertical transportation of construction resources. As being struck by construction equipment is one of the major causes of construction-worker fatalities, Chae and Yoshida (2010) developed a RFID system to prevent collision accidents with heavy equipment. This system collects the distance between equipment, surrounding objects, and workers to prevent accidents caused by insufficient awareness.

Despite much effort on exploring the applications of RFID localization technology in resource tracking, integrating this technology in construction processes still faces many challenges. The four most prominent challenges are as follows:

Poor System Scalability for Full-Scale Implementation on Arbitrary Sites

System scalability is one of the most critical characteristics of any localization system (Li and Becerik-Gerber 2011). The scalability of a localization system can be affected by technology limitations such as limited sensing range, expensive infrastructure, or signal interference (Cho et al. 2010). In addition, system scalability can also be impaired by poor design from reader and antenna placement (Liu et al. 2007).

Heavy Infrastructure on Site for Data Processing and Visualization

Configuring hardware required for onsite data processing and visualization is another challenge as devices such as laptops and power supplies are not always available during construction. Additionally, as construction proceeds, system configurations need to be changed and updated according to new localization needs. When inadequately placed, furthermore, the data and power cables on floors can be hazardous. For existing localization systems, reconfiguration involves redesigning reader and antenna layout, and increasing or reducing the amount of devices, associated cables, and power supplies.

Lack of Effective Strategy for Visualizing Location Information

Another challenge is how to effectively visualize the location information of construction resources. First of all, the location information needs to be visualized in real-time with minimum delays. Secondly, the location information needs to be visualized in a way that is effective for support of timely decision making.

Limited Capability for Sharing Location Data of Construction Resources across Remote Users

The last challenge identified in existing localization systems is the limited capability of data sharing to decision-makers in a timely manner (Zhang and Amin 2013). Location information collected by the system is first processed by the onsite computer that cross-checks the worker database to translate tag ID to worker ID and associated authority information. This information is then reported to the management team through the site network or more likely in the form of paper reports. This linear transportation not only delays the timeliness of information, but also loses data integrity in the process (Wang 2008).

Concept of Cloud Computing

Cloud computing has been a trending topic in both research and practice for several decades (Armbrust et al. 2010). The National Institute of Standards and Technology (NIST) defines cloud computing as "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction" (Mell and Grance 2011). Usually, a cloud model is composed of five essential characteristics (i.e., on-demand self-service, broad network access, resource pooling, rapid elasticity, and measured service), three service models (i.e., software as a service, platform as a service, and infrastructure as a service), and four deployment models (i.e., private cloud, community cloud, public cloud, and hybrid cloud (Mell and Grance 2011). Currently there are only a few implementations of a cloud computing framework in the construction industry. However, some researchers have attempted to build a software-as-a-service (SaaS)-based framework for construction applications leveraging standard web services technologies (Kumar et al. 2010).

Building Information Modeling (BIM)

BIM use has rapidly gained popularity in both the academic research and field implementation across the architecture, engineering, construction, and facility management (AECFM) industry. Integrating information such as schedule and cost, BIM is able to assist decision-making during design, planning, construction, and operation phases. In the construction phase particularly, BIM provides essential information for analysis and monitoring processes such as clash resolution, construction progress monitoring, and construction resources tracking. It significantly improves the efficiency in communication and coordination between management team and field crews.

Methods

To address the challenges in existing localization systems, this study investigated a BIM and cloud-enabled RFID indoor localization system. Fig. 1 shows a system framework consisting of three components: (1) RFID system for indoor localization, (2) BIM-enabled system for system configuration and data visualization, and (3) cloud computing system for data processing and sharing. The design and functionalities of these three components will be introduced in the following section.

RFID Localization System for Indoor Localization

The RFID localization system is designed to collect worker location data in an indoor construction environment. According to the sensing range and characteristics of different antennas, the RFID system can be configured with different kind of antennas and readers in order to cover a site area of any specific geometry. The RFID localization system in this study is composed of the following five components.

RFID Reader

The system employs two types of commercially available readers, Astra-NA and Mercury 6 from ThingMagic (Woburn, Massachusetts). The Astra readers integrate an antenna in the unit so it can serve as both a reader and an antenna. Mercury 6 readers can connect up to four antennas of different ranges. Therefore, they are more suitable for covering an individual area with a large and irregular footprint.

RFID Antenna

Three types of antenna are available in the system for configuring sensing areas of different characteristics. The MT 242 and MT 262 from Mti (Rosh-Ha'Ayin, Israel) can connect to the Mercury 6 reader and the oval sensing range makes it possible to cover a large sensing area by directionally placing the antennas. The built-in antenna in Astra reader/antennas has a circular sensing range that is shorter compared to Mti antennas. This feature enables the Astra reader/antennas to efficiently cover a small area or serve as a virtual gate.

Passive RFID Tag

The system uses passive RFID tags with the operating frequency of 860–960 MHz. Three tags were placed around each hard hat to ensure that at least one tag can be sensed by the antennas from any direction.

Wi-Fi Router

Since the Mercury 6 and Astra readers transmit data wirelessly through WLAN, Wi-Fi routers can be used to establish an ad hoc local network for data transmission between local readers and a computer. At the same time, the location data collected by the RFID system need to be pushed to the cloud server through the internet for remote monitoring. Hence, a hotspot was used in this system to server as both a Wi-Fi router (NETGEAR, San Jose, California) and source of internet access.

Local Computer with Monitoring and Alert Program

Although all the location data will be pushed to the cloud server for processing, a local computer was used for configuring and calibrating the system in emergency cases.

The developed RFID system consists of multiple types of RFID antennas, RFID readers, and RFID tags. Table 2 lists these devices' model, manufacturer, cost, and individual characteristics.

Worker location data obtained by the RFID localization system contains raw sensing data including tag number, entry time stamp, received signal strength indication (RSSI), antenna ID, etc. The RFID antennas emit radio waves continuously and collect tag information at a frequency of 10 Hz. The system streams the location data to the cloud computing system in real-time after each data entry.

The proposed RFID system localizes tracked subjects based on their proximity to antennas. This method does not use the RSSI value to estimate the travel distance of the signal. Instead, it uses RSSI value to compare the nearness of the adjacent antennas to the tracked subjects. In another word, the proximity to a particular antenna will indicate which predefined zone in which the worker is located, and thus the location of the worker will be determined. Therefore, this method is less sensitive to problems such as wave propagation and diffused reflection.

BIM-Enabled System for System Configuration and Data Visualization

Containing geometry data of building components, BIM enables spatial reasoning for applications such as design code checking (Eastman et al. 2009), construction workspace identification

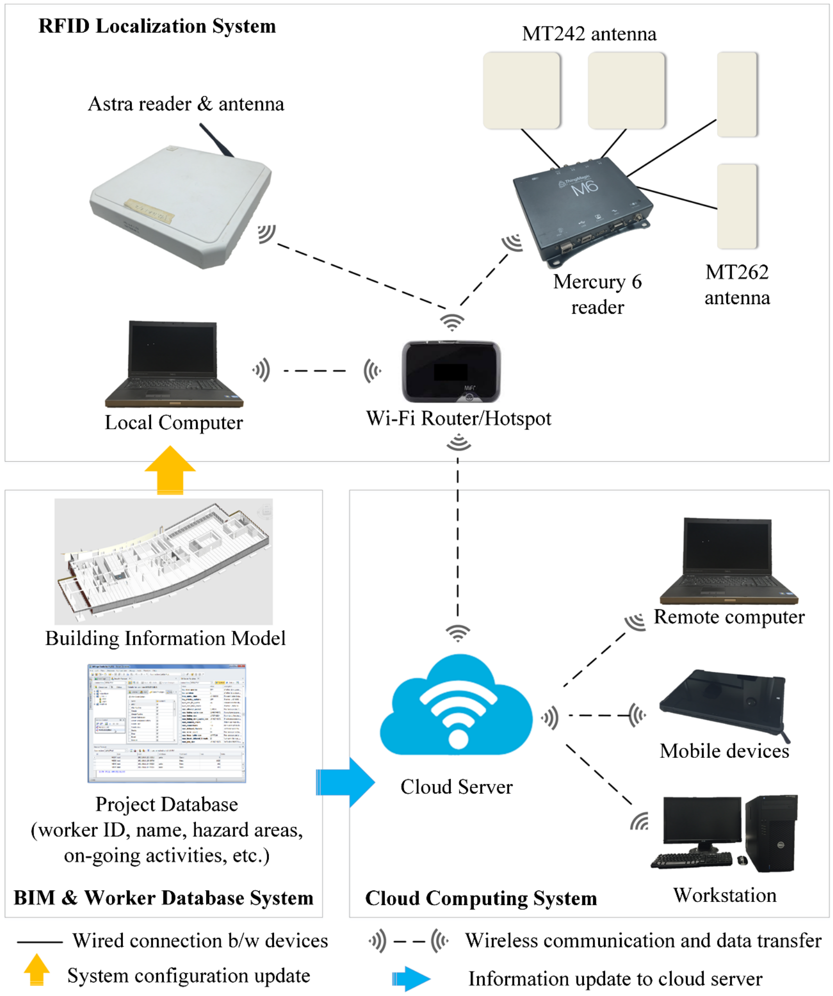

Fig. 1. Framework of the BIM and cloud-enabled RFID localization system

Table 2. Devices Adopted in the RFID Localization System

Device	Model	Manufacturer	Cost	Note
RFID antenna	Astra-NA-antenna	ThingMagic	N/A	902–928 MHz
	MT242043	Mti	\$153	865–956 MHz
	MT262006	Mti	\$153	902–928 MHz
RFID reader	Mercury 6	ThingMagic	\$1,495	Up to 4 antennas
	Astra-NA-reader	ThingMagic	\$495	Built-in antenna
RFID tags	N/A	N/A	\$0.1	Passive
Wi-Fi router	WGR614	Netgear	\$25	N/A

(Akinci et al. 2002), and safety analysis (Kim and Cho 2015; Zhang et al. 2013). Such spatial reasoning capability empowered by BIM makes it possible to automatically generate sensing zones and antenna layout plan for the RFID localization system given predefined sensing ranges of different types of antennas. Knowing the number and type of antennas that are most suitable for a particular site at planning phase leads to quick and more-prepared installation, and thus will minimize disturbance of the RFID system to normal construction activities. This BIM-enabled site zoning and system configuration also greatly improves the scalability of the RFID system. It is simple to change the zoning and system configurations as the construction proceeds by updating the BIM model according to actual schedule and reconfiguring the system in the updated BIM model. The workflow of planning the RFID system configuration is presented in Fig. 2.

In addition to supporting system configuration in the planning phase, BIM serves as essential visualization component in the real-time monitoring application. Raw data collected by the RFID localization system does not contain any contextual information. It tells when (i.e., entry time stamp) a particular tag is sensed by which antenna (i.e., antenna ID), but without knowing where exactly these antennas are located on site, the raw information alone would not be of benefit to decision-makers. Integrating the three-dimensional (3D) BIM model in the visualization application in the cloud computing system offers situational awareness of worker's location and thus provides valuable contextual knowledge to the users.

Cloud Computing System for Data Processing and Sharing

Handling location data locally at a construction site is computationally expensive and inconvenient for data sharing and collaboration. In order to minimize the burden and delay in data communication, the proposed system shifts the data processing and sharing tasks from a local computer to the cloud computing system. The cloud computing system is composed of a Wi-Fi hotspot, a cloud server, and client devices. The Wi-Fi hotspot receives location data from the RFID localization system and pushes the data to the cloud server through the internet. The cloud server provides service in the concept of software-as-a-service (SaaS). A dedicated program on the cloud server processes and links the location data with the

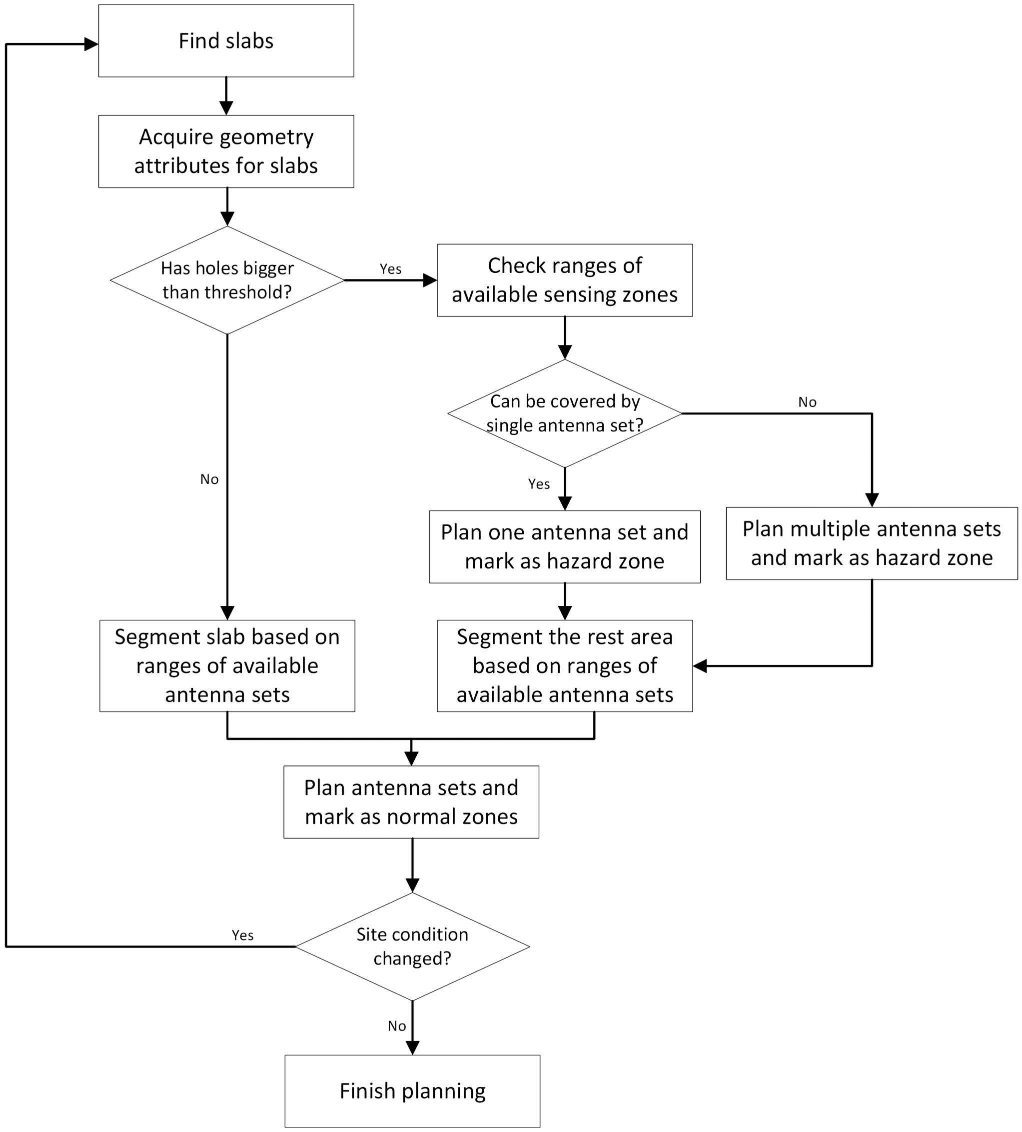

Fig. 2. Flowchart of BIM-enabled automated planning of RFID localization system

project database. It also monitors the working status of the RFID localization system. The SaaS requires setting up the program and the database on the cloud server in advance. In addition to the database, floorplans generated from the BIM model are integrated in the cloud server to provide contextual location visualization. The cloud service is deployed as a community cloud where the visualized live worker location information can be accessed by simply launching a web browser on various kinds of client devices. For example, a safety manager can monitor the worker location from a laptop in the office or using a tablet when conducting a field inspection on the site. In addition to viewing worker location information in real-time, the system is capable of storing the historical location data on the server for further data analyses if necessary.

Validation in Field Test

Field Test Overview

To evaluate the performance of the proposed RFID localization system in a real construction environment, a building construction site was selected for a field test. The test site features a 5-floor cast-in-place concrete building [Fig. 3(a)]. The test areas are located on the third and fourth floors, which are vertically connected by a temporary staircase [Fig. 3(b)]. The test area on the third floor is 32×12 m and the test area on fourth floor is 21×20 m. At the time of the test, the main structure was complete and the MEP system installation was on-going on the third and fourth floors.

The quantity of each device used in the RFID localization system was determined by analyzing the geometry of the test areas in the BIM model and the actual sensing range of RFID antennas. To cover the test area on the third and fourth floors, 10 Astra reader/antennas, 4 MT 242 antennas, 4 MT 262 antennas, and 2 Mercury 6 readers were strategically deployed. A Wi-Fi router/hotspot was placed on the third floor to receive sensing data from the readers on the third and fourth floors. This configuration facilitated the data transmission to a local laptop and data push to the cloud server. The laptop placed on the third floor was used to configure the system at the beginning of the test.

Antenna Layout and Zoning

Prior to the field test, range tests for each antenna were conducted to determine the actual sensing range of each type of antenna.

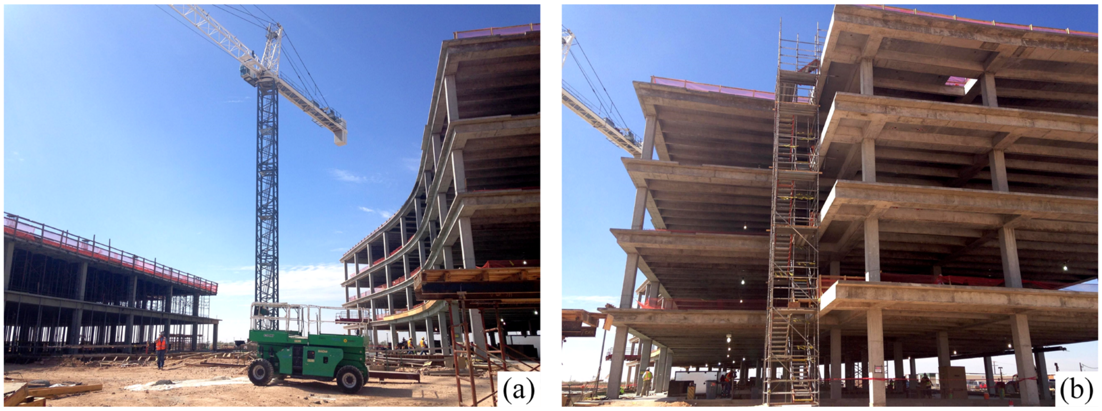

Fig. 3. Construction site for field test: (a) overview; (b) test area on third and fourth floors (images by Esau Perez)

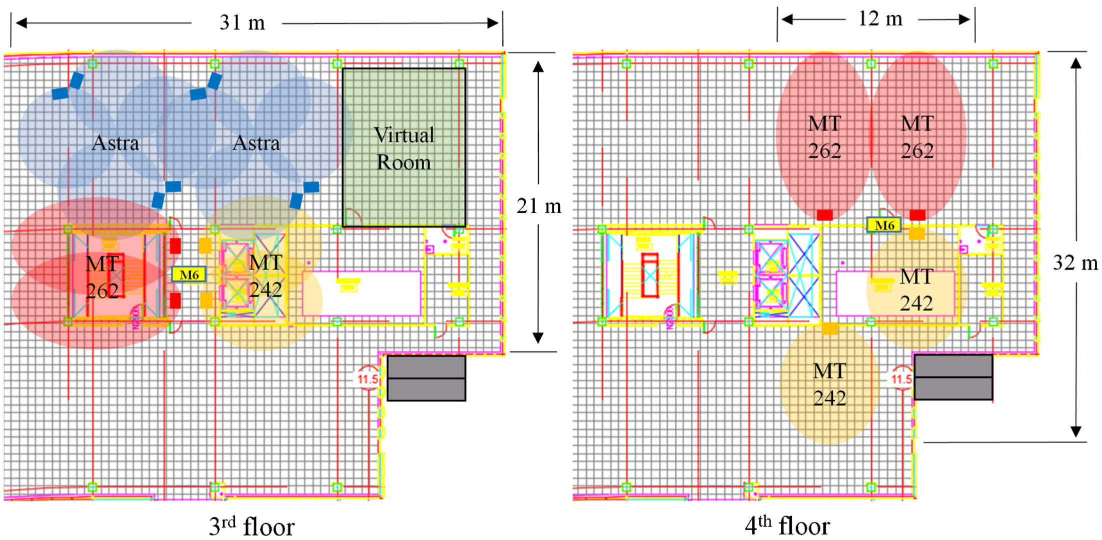

Fig. 4. RFID antenna and reader layout on site on the third and fourth floors

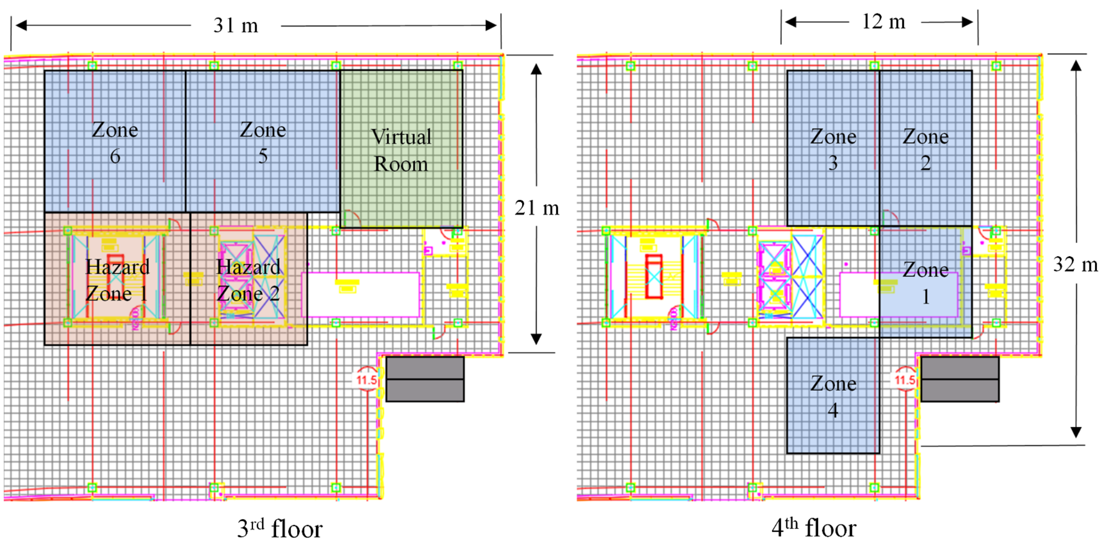

Fig. 5. Location and classification of sensing zone on site third and fourth floors

Fig. 6. (a and b) RFID antenna installation for zone setup; (c) virtual room setup; (d) passive tags mounted on a hardhat (images by Yihai Fang)

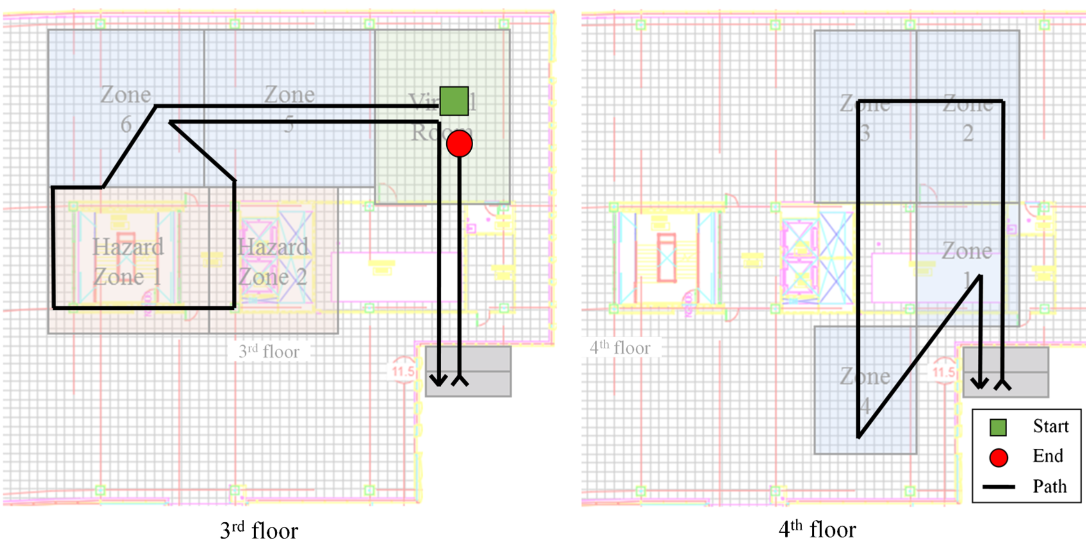

Fig. 7. Test Scenario 1: System accuracy and coverage test

Based on the test site geometry obtained from BIM model and the sensing range of each type of RFID antenna used in the test, an efficient antenna layout plan was designed as shown in Fig. 4. For instance, as the sensing zone of Astra reader/antennas feature a circular area, four Astra reader/antennas were used to construct a rectangle sensing zone by overlapping the sensing area of each antenna. In addition to optimizing the sensing range, another critical issue in the antenna placement is to minimize the feel of presence of the RFID system. It is important to ensure minimal interruption to the normal construction activities and ensure no additional hazards (e.g., tripping) are introduced. Given these considerations, 18 antennas and 7 readers were placed strategically on the third and fourth floors.

On the third floor, one M6 reader connected two MT262 and two MT242 antennas. This setting created four sensing zones covering an area of 32×12 m on the third floor. On the fourth floor, another M6 reader connected two MT262 and two MT242 antennas, which created two larger sensing zones. This dual zone covers the two slab openings that are considered hazardous zones. Eight Astra reader/antennas created two sensing zones. These four zones covered an area of 21×20 m on the fourth floor. Another pair of Astra reader/antenna created a virtual gate for a virtual room on the fourth floor. As shown on Fig. 5, this antenna and reader

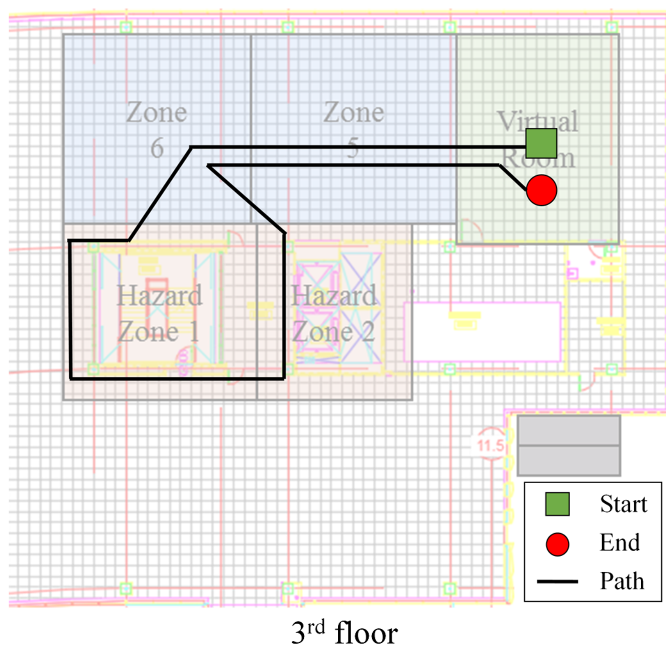

Fig. 8. Test Scenario 2: System scalability test

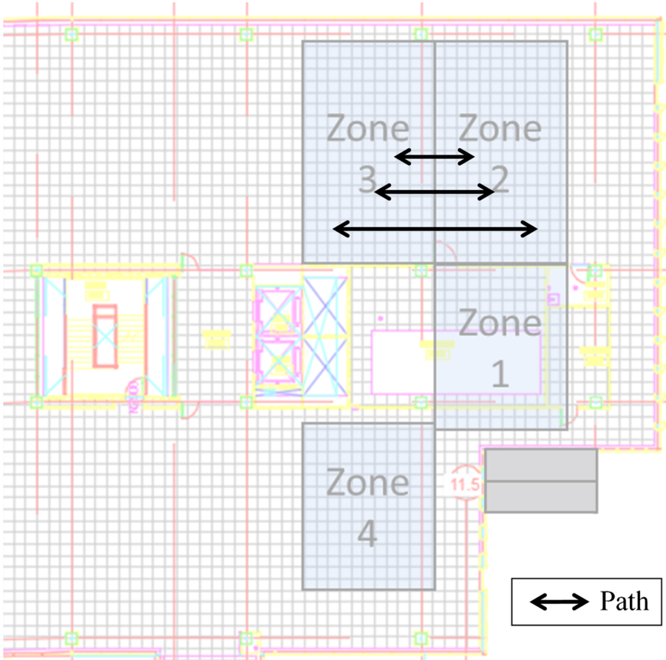

Fig. 9. Test Scenario 3: System latency test

configuration created in total nine virtual zones on the two test floors. Among these nine virtual zones, four are normal zones (Zones 1 to 4), two are hazardous zones, two are high-accuracy zones (Zones 5 and 6), and the last one is a virtual room.

System Installation

During the construction phase, a construction site is usually very congested and limited space is available to configure the localization system. To create sensing zones on the test site, RFID antennas were mounted on a custom-designed pole and the pole was attached to a tripod at normal zones [Fig. 6(a)] or to the guardrail in hazard zones [Fig. 6(b)]. Fig. 6(c) shows the installation of a RFID gate for the virtual room. Three RFID tags were mounted on different sides of each hard hat [Fig. 6(d)].

Test Scenarios

Scenario 1
The purpose of Scenario 1 was to test the positioning accuracy and coverage of the system. One subject followed a predefined path to traverse all virtual zones. As shown in Fig. 7, the path is indicated by a line while the rectangle is the start and the circle is the end.

Scenario 2
The focus of this test scenario was to test if multiple subjects could be positioned at the same time. Three subjects followed the designated path as shown in Fig. 8 with a start interval of 10 s.

Scenario 3
The purpose of Scenario 3 was to test the sensing latency of the developed system when positioning subjects. Two subjects followed zigzag paths by moving back and forth between Zone 2 and Zone 3 (Fig. 9).

Test Results and Analysis

Recognition Rates Evaluation

The performance of the developed system was validated through a manual analysis of the video footage recorded during the experiment. The analysis of the worker location in the video served as ground truth (Fig. 10).

Results from the video analysis and the real-time location data collected and visualized by the system were compared with each other to assess the accuracy, recall, and precision of the developed system as follows:

- True positive (TP) cases are defined as those where both ground truth and system are positive, which means that the worker is in a particular zone and the system also shows that the worker is present there;
- True negative (TN) cases are defined as those where both ground truth and system are negative, which means that the worker is not in a particular zone and the system also shows that the worker is not present there;

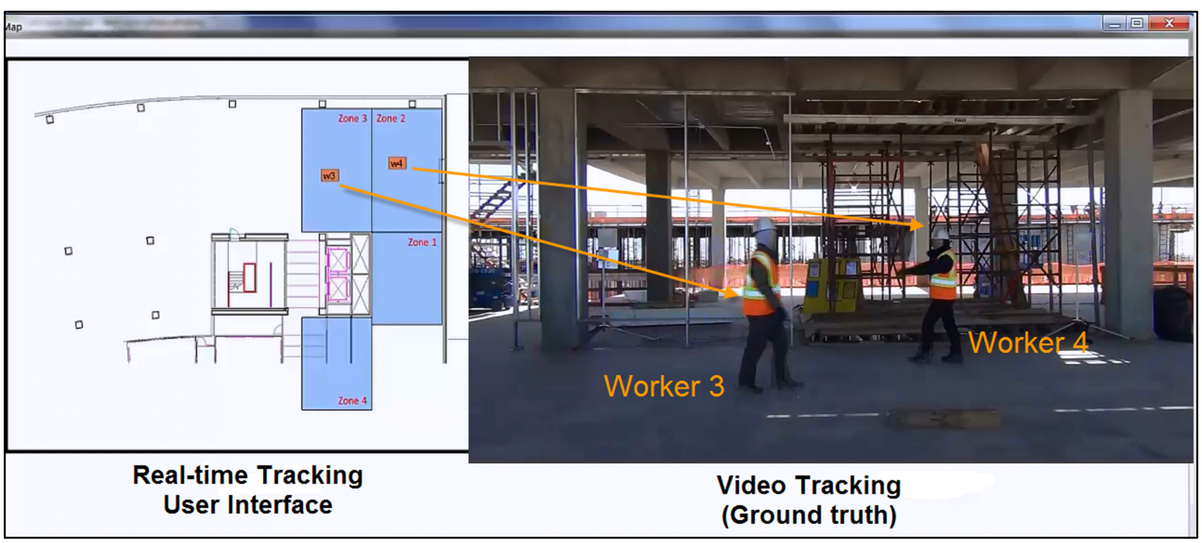

Fig. 10. Recognition rate evaluation by comparing localization results to video recording (images by Yihai Fang)

Identified by system / Observed from video (Ground truth) — Zone 1

	System Positive	System Negative	
Ground Truth Positive	101 (TP)	22 (FN)	Precision = 82.1%
Ground Truth Negative	11 (FP)	86 (TN)	
	Recall = 90.2%		Accuracy = 85.0%

Identified by system / Observed from video (Ground truth) — Zone 2

	System Positive	System Negative	
Ground Truth Positive	158 (TP)	25 (FN)	Precision = 86.3%
Ground Truth Negative	22 (FP)	189 (TN)	
	Recall = 87.8%		Accuracy = 88.1%

Identified by system / Observed from video (Ground truth) — Zone 3

	System Positive	System Negative	
Ground Truth Positive	167 (TP)	28 (FN)	Precision = 85.6%
Ground Truth Negative	25 (FP)	203 (TN)	
	Recall = 87.0%		Accuracy = 87.5%

Identified by system / Observed from video (Ground truth) — Zone 4

	System Positive	System Negative	
Ground Truth Positive	51 (TP)	22 (FN)	Precision =69.9%
Ground Truth Negative	7 (FP)	79 (TN)	
	Recall = 87.9%		Accuracy = 81.8%

Identified by system / Observed from video (Ground truth) — Zone 5

	System Positive	System Negative	
Ground Truth Positive	98 (TP)	13 (FN)	Precision = 88.3%
Ground Truth Negative	10 (FP)	142 (TN)	
	Recall = 90.7%		Accuracy = 91.3%

Identified by system / Observed from video (Ground truth) — Zone 6

	System Positive	System Negative	
Ground Truth Positive	106 (TP)	19 (FN)	Precision = 84.8%
Ground Truth Negative	9 (FP)	162 (TN)	
	Recall = 90.7%		Accuracy = 90.5%

Identified by system / Observed from video (Ground truth) — Hazard zone 1

	System Positive	System Negative	
Ground Truth Positive	156 (TP)	35 (FN)	Precision = 81.7%
Ground Truth Negative	15 (FP)	178 (TN)	
	Recall = 91.2%		Accuracy = 87.0%

Identified by system / Observed from video (Ground truth) — Hazard zone 2

	System Positive	System Negative	
Ground Truth Positive	132 (TP)	21 (FN)	Precision = 86.3%
Ground Truth Negative	25 (FP)	157 (TN)	
	Recall = 84.1%		Accuracy = 86.3%

Identified by system / Observed from video (Ground truth) — Virtual room

	System Positive	System Negative	
Ground Truth Positive	76 (TP)	2 (FN)	Precision = 97.4%
Ground Truth Negative	4 (FP)	55 (TN)	
	Recall = 95.0%		Accuracy = 95.6%

Fig. 11. Results of positioning accuracy and reliability analysis (duration in second)

- False positive (FP) cases are defined as those where the ground truth is negative and the system is positive, which means that the worker is not in a particular zone but the system shows that the worker is present there; and
- False negative (FN) cases are defined as those where the ground truth is positive and the system is negative, which means that the worker is in a particular zone but the system shows that the worker is not present there.

The comparison of the video and the system data is shown in Fig. 11. The figure shows nine confusion matrices (one per zone). These matrices present adequate validation of the comparison. The vertical direction of each confusion matrix describes the ground truth, which shows whether the worker is actually in the particular zone or not. The horizontal direction of the matrix shows the system outcome. The experimental results are as follows:

- On average, the developed system performed accurate positioning of workers, with an average accuracy rate of 88.1%, an average precision of 84.7%, and an average recall of 89.6%;
- It is observed that Zone 5, Zone 6, and the virtual room (92.5%) have higher accuracy than other zones (86.0%). This is mainly because at Zone 5, Zone 6, and the virtual room, Astra reader/antennas were deployed. They have a faster refresh rate for receiving and transferring data than Mercury readers and Mti antennas;

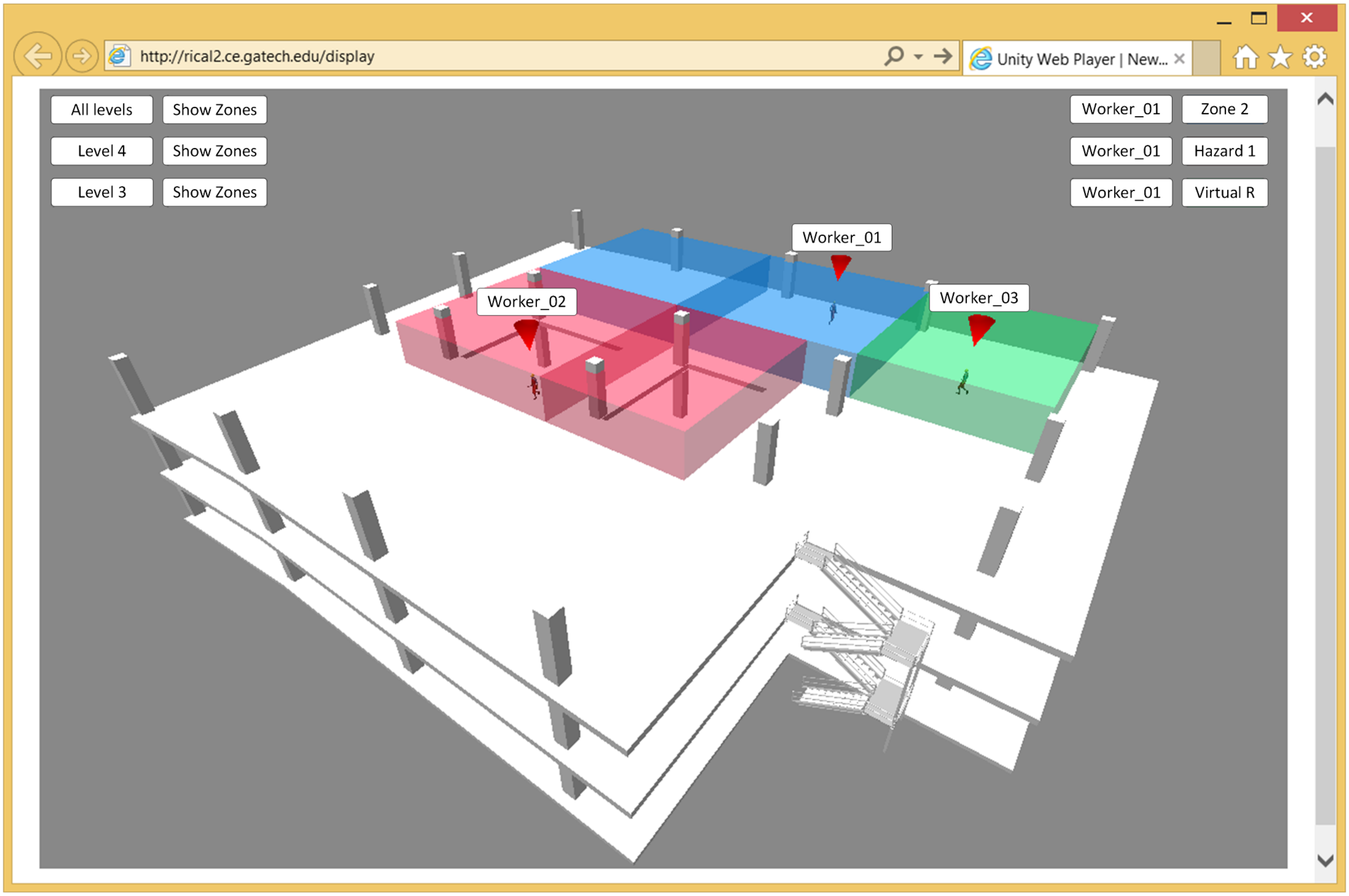

Fig. 12. Cloud-enabled remote monitoring user interface

- The virtual room (95.6%) has a higher accuracy compared to other zones (87.2%). In the virtual room, a RFID gate is assembled to detect both entering and exiting of the room. Two Astra-NA antennas were mounted on the top of the gate facing downward. This setup can detect RFID tags more effectively without the influence of obstruction and tag orientation; and
- The system accuracy in Zones 1, 2, 3, and 4 on the fourth floor are lower than the accuracy of other zones on the third floor. Since the router/hotspot that connected all the RFID readers was installed on the third floor, some delay and signal loss can be expected from the readers on the fourth floor.

Overall, the results indicate that the tracking network was able to cover the designed areas on the construction site, and within the areas, the system was able to locate workers in various moving patterns.

System Latency

False positive and false negative cases were attributable to rapidly changing positions and the latency of the RFID localization system. The RFID readers have a maximum refresh rate for receiving data from antennas and sending the data to the server. The default maximum refresh rate is 10 Hz. The latency of the RFID localization system was observed to be 0.8 s, which is consistent throughout the experiment. The latency on the RFID localization system also contributes to the overall delay on the cloud-based visualization program. The delay on the cloud-based visualization program will be further discussed in the following section.

Real-Time Remote Monitoring through a Cloud Server

A hotspot using wireless data service was used for pushing location data to a cloud server established on a Georgia Tech domain. During the test, live location data pushed to the cloud server were processed by a program on the cloud server. Once the location data were processed by the program and linked to the predefined worker database, the worker location and other relevant information were ready to be accessed from client devices. During this test, a laptop and a tablet at remote locations (i.e., site office) were able to access the live visualization interface through a web browser. The worker location data visualized in the web browser have a minor delay of around 2 s compared to the actual worker location. This delay is caused by the cumulative delay in data transmission from the RFID localization system to the hotspot and from the hotspot to the cloud server. Fig. 12 shows the real-time cloud-enabled remote monitoring interface in a web browser.

Different zones are indicated in 3D BIM model, and the real-time locations of workers are visualized by the arrows. This interactive user interface enables the users to change the view perspectives and toggle the display settings such as select the level they want to view, show or hide zones, and follow a particular worker.

Discussion

To test the performance of the developed system, the research team deployed the system at a building construction site featuring a total area of 804 m^2 over two floors. The system was tested in three scenarios to test the positioning accuracy, sensing coverage, latency and overall system reliability. The test process and results were recorded in video clips and screen recordings of the user interface. The test results indicate the developed system was able to locate test subjects in the deployed areas in real time with high recognition rates (recall = 89.6%, precision = 84.7%, and accuracy = 88.1%).

From the field test, system limitations were identified as follows: (1) coverage of the RFID network is subject to the range of individual antennas and their layout, (2) system latency depends on the refresh rate of the RFID readers and the location and signal strength of the router/hotspot, (3) RFID antennas should ideally be mounted on higher positions such as ceilings or top of columns to eliminate trip hazard and promote a less-constrained workspace. In addition, the research team did not use the up-to-date versions of RFID systems; thus it is highly likely that the newer RFID systems with faster refresh rates would provide better localization performance. Although it was not demonstrated in this field test, wireless speakers (Wi-Fi or Bluetooth) can be easily embedded in the proposed local network system to provide audible alerts to workers when they approach the safety hazard zones. In addition, light infrastructure and BIM-enabled system configuration update featured in the proposed RFID system makes it possible to quickly reconfigure zones as the site condition changes.

As a major contribution in this research, the integration of localization system and cloud computing and sharing technology greatly expands the functionality and flexibility of traditional real-time location systems (RTLS). First, the computation burden of processing real-time sensor data on the local system can be shifted to a cloud server. Thus, the system requirement for local processing capability is minimized. Therefore, the initial cost for hardware and lifecycle maintenance efforts for the onsite system can be minimized. Second, the location data pushed to the cloud server are backed up automatically so that the risk of losing data is greatly reduced. Third, sharing data through the cloud server enables real-time remote monitoring and collaboration among different stakeholders.

Conclusion

This study introduces the design, development, and performance test of a real-time indoor localization solution for construction site monitoring purposes. Taking advantage of building information modeling and cloud computing, the proposed RFID localization solution is able to localize construction workers and provide real-time visualization on various devices through a cloud server for remote monitoring. The system is designed and developed to maximize its accuracy, reliability, and scalability when applied in an indoor construction environment. By establishing an ad hoc local network for data transmission, the RFID localization system is able to cover multiple floors and areas of diverse geometry. A program on the cloud server processes the worker location data obtained from the RFID localization system and provides users with contextual knowledge about worker locations by interactively visualizing the location of construction workers on a BIM model. The cloud computing system allows users to access the location data in real-time on various remote platforms (e.g., laptop, tablet, or smartphone). The proposed system makes it possible to provide decision-makers with a timely warning if a worker is in proximity to hazardous areas or tagged construction materials are in the wrong place. The developed system was tested in a full-scale implementation on an actual building construction site. A comprehensive analysis was conducted on localization accuracy and latency. The system performance in cloud-based visualization was discussed based on the test results. Other practical issues such as ease of use, scalability, and current limitations were also discussed. The field test results and the discussion with site engineers and managers indicate that the proposed RFID indoor localization system has a great potential in practical applications such as site security control, safety management, and first responder rescue. Furthermore, the findings in this study expanded the application of localization technology in the cloud computing area for information visualization and data sharing.

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References

Akinci, B., Fischer, M., and Kunz, J. (2002). “Automated generation of work spaces required by construction activities.” *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2002)128:4(306), 306–315.

Armbrust, M., et al. (2010). “A view of cloud computing.” *Commun. ACM*, 53(4), 50.

Behzadan, A. H., Aziz, Z., Anumba, C. J., and Kamat, V. R. (2008). “Ubiquitous location tracking for context-specific information delivery on construction sites.” *Autom. Constr.*, 17(6), 737–748.

Chae, S., and Yoshida, T. (2010). “Application of RFID technology to prevention of collision accident with heavy equipment.” *Autom. Constr.*, 19(3), 368–374.

Chin, S., Yoon, S., Choi, C., and Cho, C. (2008). “CAD for progress management of structural steel works in high-rise buildings.” *J. Comput. Civ. Eng.*, 10.1061/(ASCE)0887-3801(2008)22:2(74), 74–89.

Cho, Y. K., Youn, J. H., and Martinez, D. (2010). “Error modeling for an untethered ultra-wideband system for construction indoor asset tracking.” *Autom. Constr.*, 19(1), 43–54.

Cho, Y. K., and Youn, J.-H. (2006). “Wireless sensor-driven intelligent navigation robots for indoor construction site security and safety.” *Proc., 23rd Int. Symp. on Automation and Robotics in Construction*, ISARC, Washington, DC, 493–498.

Costin, A., Pradhananga, N., and Teizer, J. (2012). “Leveraging passive RFID technology for construction resource field mobility and status monitoring in a high-rise renovation project.” *Autom. Constr.*, 24, 1–15.

Domdouzis, K., Kumar, B., and Anumba, C. (2007). “Radio-frequency identification (RFID) applications: A brief introduction.” *Adv. Eng. Inform.*, 21(4), 350–355.

Eastman, C., Lee, J. M., Jeong, Y. S., and Lee, J. K. (2009). “Automatic rule-based checking of building designs.” *Autom. Constr.*, 18(8), 1011–1033.

Ergen, E., Akinci, B., East, B., and Kirby, J. (2007). “Tracking components and maintenance history within a facility utilizing radio frequency identification technology.” *J. Comput. Civ. Eng.*, 10.1061/(ASCE)0887-3801(2007)21:1(11), 11–20.

Guerrieri, J. R., et al. (2006). “RFID-assisted indoor localization and communication for first responders.” European Space Agency, Piscataway, NJ, 1–6.

Jaselskis, E. J., Anderson, M. R., Jahren, C. T., Rodriguez, Y., and Njos, S. (1995). “Radio-frequency identification applications in construction industry.” *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(1995)121:2(189), 189–196.

Jaselskis, E. J., and El-Misalami, T. (2003). “Implementing radio frequency identification in the construction process.” *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2003)129:6(680), 680–688.

Jiménez, A. R., Seco, F., Prieto, C., and Guevara, J. (2009). “A comparison of pedestrian dead-reckoning algorithms using a low-cost MEMS IMU.” *Proc., WISP 2009—6th IEEE Int. Symp. on Intelligent Signal Processing*, Piscataway, NJ, 37–42.

Kim, K., and Cho, Y. K. (2015). "BIM-based planning of temporary structures for construction safety (ASCE)." *Int. Workshop on Computing in Civil Engineering*, ASCE, Reston, VA, 436–444.

Kumar, B., Cheng, J. C. P., and McGibbney, L. (2010). "Cloud computing and its implications for construction IT." *Proc., Int. Conf. on Computing in Civil and Building Engineering (ICCCBE 2010)*, Nottingham University Press, Nottingham, U.K., 315.

Lee, H.-S., Lee, K.-P., Park, M., Baek, Y., and Lee, S. (2012). "RFID-based real-time locating system for construction safety management." *J. Comput. Civ. Eng.*, 10.1061/(ASCE)CP.1943-5487.0000144, 366–377.

Li, N., and Becerik-Gerber, B. (2011). "Performance-based evaluation of RFID-based indoor location sensing solutions for the built environment." *Adv. Eng. Inform.*, 25(3), 535–546.

Liu, H., Darabi, H., Banerjee, P., and Liu, J. (2007). "Survey of wireless indoor positioning techniques and systems." *IEEE Trans. Syst. Man Cyber. Part C: Appl. Rev.*, 37(6), 1067–1080.

Lu, W., Huang, G. Q., and Li, H. (2011). "Scenarios for applying RFID technology in construction project management." *Autom. Constr.*, 20(2), 101–106.

Mell, P., and Grance, T. (2011). "The NIST definition of cloud computing." National Institute of Standards and Technology, Information Technology Laboratory, Gaithersburg, MD.

Wang, L.-C. (2008). "Enhancing construction quality inspection and management using RFID technology." *Autom. Constr.*, 17(4), 467–479.

Zhang, C., Hammad, A., Chen, J., and Yang, Y. (2013). "Experimental investigation of using RFID integrated BIM model for safety and facility management." *Proc., 13th Int. Conf. on Construction Applications of Virtual Reality*, London.

Zhang, S., Teizer, J., Lee, J. K., Eastman, C. M., and Venugopal, M. (2013). "Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules." *Autom. Constr.*, 29, 183–195.