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A REAL-TIME LOCATION-BASED CONSTRUCTION LABOR SAFETY MANAGEMENT SYSTEM

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Abstract. The construction industry continues to record a high number of accidents compared to other industries. Furthermore, the ramifications of construction accidents are growing in terms of both economic loss and loss of life with trends toward larger-scale, more complex projects. For this reason, there is an increasing awareness of the importance of safety management in the construction industry, and the need for more effective safety management techniques. This paper introduces a real-time location-based construction labor safety management system that tracks and visualizes workers' locations in real-time and sends early warnings to endangered workers. The system is developed by integrating: a real-time locating system (RTLS) for tracking of workers' location; a location monitoring system for mapping the workers location on a computerized building model; and alarm technology for sending early warnings. The developed system has been applied to an apartment project and an RTLS technology test center in Korea, and proved to be effective in tracking and monitoring workers in real-time and preventing construction accidents. It is envisioned that the developed system will enable proactive construction safety management in South Korea and the methodologies developed in this study will be applicable to other contexts with minimal customization.

Keywords: construction safety, real-time locating system (RTLS), radio frequency identification, alarm technology, tracking, risk assessment, South Korea.

Introduction

The construction industry continues to record a high incidence of accidents compared to other industries. Recent records indicate that on average, 1.24% of construction employees have faced a calamity or suffered an accident while working. This number is much higher than in other industries, including transportation and warehousing (0.86%), manufacturing (0.46%), and mining (0.19%) (US Bureau of Labor 2006). With trends toward larger-scale and more complex construction projects, the ramifications of construction accidents are growing in terms of both economic loss, loss of life as well as social impacts such as the incapacity to work due to an injury. This highlights the importance of safety management in construction industry and supports a need for a more effective construction safety management system (Hinze *et al.* 1998).

To find an effective method for the prevention of construction accidents, an understanding of the mechanism of accidents generation is required. According to Heinrich (1959), every accident has its causes and can be prevented by identifying and eliminating the causes. Heinrich (1959) also classified causes of an accident into direct and indirect causes of accidents, where indirect causes are 'deficiency in safety management' and direct causes include 'unsafe mechanical or physical conditions' and 'unsafe acts of a person'. This suggests that a lack of safety management effort can result in either unsafe working conditions or unsafe acts, or both of them. Some combinations of these direct causes eventually trigger accidents. This means that an accident can be prevented or at least reduced by removing either unsafe conditions or unsafe acts.

In an effort to reduce accidents, diverse safety management activities have been implemented across the construction industry, including the Construction Safety and Health Program (CSHP) and the Construction Accident Prevention Technique (CAPT) (Reese, Eidson 2006). These safety management efforts, however, have mainly focused on the indirect causes of construction accidents (i.e. deficiency in safety management) without due concentration on the direct causes, which can vary significantly for each construction site depending on its given circumstance (Navon, Kolton 2007). For this reason, current safety management efforts usually provide general suggestions for preventing accidents. Detailed information is scarcely provided regarding the specific accident types expected on a particular construction site, and actions that would be effective to prevent them.

For effective prevention of construction accidents, both direct and indirect causes of accidents should be analyzed simultaneously. As an effort to address this necessity, diverse research efforts have been conducted on visualization or location-based safety management (Teizer, Castro-Lacouture 2007; Chae, Yoshida 2010;

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Carbonari *et al.* 2011; Chi, Caldas 2012; Lee *et al.* 2012). For example, Carbonari *et al.* (2011) developed a prototype for proactive construction safety management and real-time signaling of potential overhead hazards. Also, Lee *et al.* (2012) developed radio frequency identification (RFID)-based real-time locating system (RTLS) for construction safety management. In addition, Chi and Caldas (2012) presented an automated image-based safety assessment method for earthmoving and surface mining activities.

Motivated by these research efforts, this paper aims to develop a construction safety management system by which rigor around monitoring of direct accident causes can be improved, particularly tracking and visualizing workers' location in a real-time and proactive manner. This paper achieves the research objective through integrating: real-time locating system (RTLS) for tracking of workers' locations; a location monitoring system using ArchiCAD 12 for mapping workers' movement on a computerized building model and processing workers' real-time location data; and alarming technology for sending early warnings including detailed information to endangered workers. Also, risk assessment is conducted to identity potential dangerous zones and their associated hazard types.

This paper is presented in the following order: an overview of related methodology and technologies is provided; risk assessment is conducted based on historical construction accident database in South Korea; system modules are discussed, including RTLS, location monitoring system, alarming technology, and data protocol. Then, two case studies are conducted to test the location tracking and mapping performance of the developed system. The final section provides the conclusions and future directions.

1. Preliminary study

Prior to development of the construction safety management system, this section briefly reviews relevant works, particularly those related to visualization and tracking technologies for construction performance monitoring purposes.

1.1. Visualization for monitoring

Visualization methods for monitoring are classified into two major categories: Virtual Reality (VR) and Augmented Reality (AR). VR aims to exactly reproduce real-world situations as a computer simulation, to predict how the project will progress. In this way, VR can identify potential problems during building construction. For example, Issa (2000) introduced VR as a platform to integrate various data and applications. Heesom *et al*. (2003) developed a dynamic VR system, making it possible to derive an effective layout for space usage on construction sites. Irizarry and Abraham (2005) presented a VR-based methodology to improve safety in steel erection. On the other hand, AR superimposes virtual images created by computing onto real images (e.g. a photo), and identifies differences between the two. Relating to this, Golparvar-Fard *et al.* (2009) introduces an advanced approach that uses photographs to generate point clouds which are compared to the BIM geometry model for progress monitoring, and progress discrepancies through color and pattern using this innovative simulation model. Behzadan and Kamat (2009) developed a methodology to generate smooth and continuous AR animations from the results of discrete event simulation models. Dai *et al.* (2011) suggested an analytical approach to incorporating computer-generated 3D graphic of invisible underground infrastructure into the construction site so as to present an integral view of the site situation in construction engineering application.

1.2. Location tracking for monitoring

The discipline of construction progress monitoring has shifted from paper-based data collection and analysis, which is time-consuming and error-prone, to automated data collection. Initially, the bar code technique was used for automated data collection until its low level of recognition and insufficient storage capacity resulted in its replacement by the Radio Frequency Identification (RFID) technique (Ergen *e al*. 2007). RFID, however, is limited for portal based identification purposes: thus, the need for a more advanced type of RFID has arisen (Song *et al.* 2006). To address this need, there have been numerous research efforts for the advanced real-time locating system (RTLS) for diverse purposes in construction (e.g. safety management, productivity improvement and material tracking) (Fosbroke 2004; Teizer, Castro-Lacouture 2007; Wu *et al.* 2010; Chae, Yoshida 2010; Cheng, Teizer 2010). These studies can be largely categorized into: 1) the application of RFID to whole parts of the construction site and its procedures; and 2) developing an algorithm for improving feasibility of localization. As an effort to apply RFID to a whole construction site, Jaselskis and El-Misalami (2003) proposed the application of a material tracking system considering cost, schedule, quality and safety of the whole project process, and conducted a pilot test. Chin *et al.* (2008) suggested a management system that monitors progress on structural steel erection using RFID and 4D CAD. Also, for improving performance of localization, Song *et al.* (2006) proposed the proximity method that allows tracking of material effectively on a construction site. Dziadak *et al.* (2009) developed a model to manage the location of buried assets using RFID. Jing *et al.* (2008) suggested a method using RFID and two-dimensional code technology to manage people flow and logistics more effectively.

1.3. Tracking and visualization technologies for construction safety management

There have been significant research efforts applying location tracking or visualization technology for a systematic construction safety management (Teizer, Castro-Lacouture 2007; Fullerton *et al.* 2009; Hallowell *et al.* 2010; Chae, Yoshida 2010; Chi, Caldas 2011). These efforts focused on directly managing workers and objects to improve safety performance by proactively capturing site information (Lee *et al.* 2012). Fullerton *et al.* (2009)

developed pro-active-real-time safety technology using radio frequency wave spectrum to improve the safety of a work zone by alerting workers. Hallowell *et al.* (2010) identified the potential barriers and enablers associated with integrating sensing technologies within existing safety management strategies by interviewing safety managers. Chae and Yoshida (2010) applied Radio Frequency Identification (RFID) technology for prevention of collision accidents with heavy equipment. Teizer and Castro-Lacouture (2007) introduced an approach leveraging the advancements of wireless Ultra-Wideband (UWB) positioning and reflectorless Range Imaging (RIM) sensing technology in the construction productivity and safety monitoring. Chi and Caldas (2011) presented an automated object identification method using standard video cameras on construction sites.

2. Risk assessment by work type

In order to develop an effective real-time construction safety management system, construction safety risk needs to be assessed for identifying potential dangerous zones. Construction safety risk is used to measure the extent of risk in a given dangerous area. In order to assess the extent of risk for a specific work type, we utilize the Korea Occupational Safety and Health Agency (KOSHA)'s 2007 report, which is one of the most comprehensive risk assessment models in the Korean construction industry. KOSHA's 2007 report summarizes the analysis on about 18,000 accident cases which were occurred in 2006.

According to the KOSHA'S 2007 report, the risk assessment by work type consists of three steps: hazard identification, risk calculation, and risk assessment. Hazard identification is performed in two stages: 1) work type selection; and 2) hazard identification. In the work type selection stage, the work type to be assessed is selected and the scope of assessment is determined. The work type is composed by activities and the activities are analyzed using the previous accident cases for assessing the level of danger. Hazards are identified based on unsafe factors like unsafe behavior of worker, unsafe materials and substances, unsafe working method, and unsafe equipment. In the risk calculation step, the risk is calculated by multiplying degree of severity and frequency of a work type. The frequency is calculated based on total number of injured workers and the number of injured workers per work type. Also, the severity of risk is calculated based on the number of injured workers per work type and a conversion value from the loss of workdays by work type. The severity and frequency of risk is calculated according to the equations below:

$$\text{Frequency} = \frac{\text{Injured worker's number by work type}}{\text{Total number of injured worker}} \times 100\,;$$

$$\text{Severity} = \frac{\text{Conversion value from loss of workday by work type}}{\text{Injured worker's number of work type}}\,.$$

Table 1 shows an example of risk assessment by work type for apartment construction. According to the KOSHA's 2007 report, apartment construction is classified into 32 work types (e.g. foundation, excavation, blasting, retaining wall bearing, refilling, form work, and so on) and the risk of each work type is calculated. Using this data, we classified the work types to five grades from 1 (low risk) to 5 (high risk) depending on the degree of risk by work type. Then, the degree of risk is visualized by five colors (i.e. red = 5, orange = 4, yellow = 3, green = 2, and blue = 1).

Table 1. Risk Assessment by work type

Work type	Risk	Grade and color
Form work	24.259	5 grade represented by red color
Machinery	14.657	4 grade represented by orange color
Interior finishing	11.955	
Electric installation	10.780	
Plastering	9.414	
Panel	8.295	
Reinforced	6.665	3 grade represented by yellow color
Manhole	5.878	
Earth	5.270	
Steel-frame	4.848	
Watertight	4.756	
Painting	4.553	
Safety scaffolding	4.016	
Tile	3.541	2 grade represented by green color
Window & Door	3.437	
Concrete	3.265	
Metal	2.184	
Landscaping	2.142	
Retaining wall bearing	1.395	
E/V	0.630	1 grade represented by blue color
Excavation	0.573	
Gang-form work	0.482	
Working environement	0.411	
Tower crane	0.397	
Foundation	0.366	
Grouting	0.344	
Temporary road	0.321	
Refilling	0.273	
Blasting	0.153	
Shifting inconvenience	0.053	
Temporary electrictity	–	
Danger equipement	–	

Based on this, the safety manager can identify the dangerous zone and potential accident types according to construction schedule. Potential accidents types are classified based on the Hinze and Russell's classification, which consists of 14 different types of accident including falls, dropping, collapse, strangulation, electric shock, landslide, collision, suffocation, fire, overturning, destruction, explosion, and drowning. Particularly, in the South Korean construction industry, falls, electric shock, dropping, collision, and strangulation were identified as the major accident types. This analysis result is not very different from studies conducted in other countries which can expect the applicability of the developed system to other contexts.

3. System development

This section provides a system overview and a detailed explanation of the system modules and data transmission protocol among the modules. The modules include real-time locating system, location monitoring system and alarming technology.

3.1. System overview

The proposed construction safety management system tracks workers' location in a real-time manner by applying a Real-Time Locating System (RLTS), and visualizes workers' locations using a location monitoring system developed based on ArchiCAD 12 (GRAPHISOFT 2008). When a worker approaches a dangerous area, it automatically (or manually) sends warning signal to the worker through alarm technology (Fig. 1). By doing so, this system can assist to minimize unsafe conditions (i.e. direct cause of accidents), thereby preventing accidents in a construction site. In order to identify dangerous situations and hazard types for a given work type, risk assessment is conducted as described in the previous section.

3.2. Real time locating system (RTLS) based tracking

For the purpose of tracking the real-time location of workers, a RTLS system is developed. This section describes the RTLS hardware configuration and localization methods.

1) *Hardware configuration*

The RTLS hardware is composed of four main parts: tag, reader, base-station and engine. A tag is attached to each worker to be tracked. Each tag measures its distance from surrounding readers and then transmits this reader-to-tag distance data to the base-station. A reader is classified as either stationary or portable, both of which are used in this system. A stationary reader is utilized where power can be provided at its installation location, and a portable reader is utilized otherwise. The base-station receives the reader-to-tag distance data and then processes and sends the data to the engine for localization. Finally, the RTLS engine functions as the main server for the system, handles the data processing and storage for output, and filters the data it receives from the base station to maximize the tracking performance. Table 2 shows the functions and specifications of the RTLS hardware.

2) *Localization methods*

The RTLS localization methods consist of position determination method and wireless networking method. The position determination method is applied to identify a worker's location and the wireless networking method is utilized to support data communication between the hardware components. Several techniques are being utilized for the position determination including Received Signal Strength Indication (RSSI), Time Difference of Arrival (TDOA), Time of Flight (TOF), Angle of Arrival (AOA) and Time of Arrival (TOA). Table 3 summarizes the position determination methods.

While RSSI, TDOA, and TOF are being widely utilized for tracking purposes, they are not suitable in construction environments. RSSI, for example, can encounter a high level of localization error due to the multipath problem where obstacles are prevalent. TDOA can maintain high performance in location tracking in a clear Line Of Sight (LOS) environment which is unusual in construction. Also, TDOA and TOF require time synchronization (consistency of reader and tag time) which can make their application in construction difficult. The AOA technique requires an isotropic antenna which has limited communication range. TOA also requires time synchronization, but is more stable compared to TDOA or TOF method. Moreover, TOA is highly robust in tracking object positions and has a large coverage area without being largely affected by the multipath problem. TOA has therefore been chosen for this research.

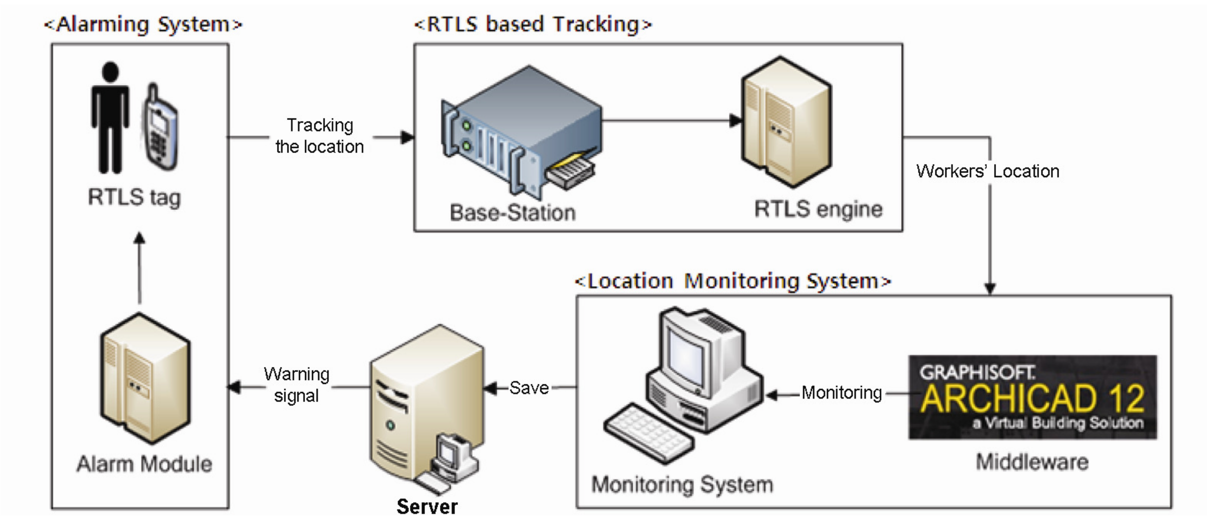


Fig. 1. System architecture

Table 2. RTLS hardware

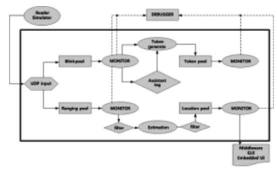
Classification	Function	Specifications	Figure
Tag	– Tracks a worker's location using receptions from reader	– Processor: TI MSP430 – RF Transceiver: NA5TR1 – Transmission distance: 450m	
Reader	– Works as a reference point to identify location of a tag	– ARM co.'s Cortex-M3 – 72 MHz Movement – 128 KB flash, 20 KB RAM	
Base-Station	– Receives distance data from the tag and passes it to the engine	– 400 MHZ Intel PXZ255 MCU – 10/100 Mbps TCP/IP compatible	
Engine	– Filters and processes distance data from the base station	– Multi-Lateration: Trilateration – Data filtering: Statistical method	

Table 3. Position determination method (based on Bahl and Padmanahan 2000)

Techniques	Position determination method	Merit	Demerit
Received Signal Strength Indication (RSSI)	– Calculates the location using signal strength from access point	– Hardware is realized relatively cheaply and easily	– Influenced severely by multipath – Accuracy is affected by distance
Time Difference of Arrival (TDOA)	– Similar to TOA but calculates using signaling intervals between readers	– Accepts TOA merits – Differs from TOA because TDOA is not depend on the clock bias of the transmission node – Performs well in a NLOS environment as well as outside	– Needs partial time synchronization
Time of Flight (TOF)	– Uses the time elapsed when the signal is transferred between the tag and reader, based on the transfer rate of the RF signal	– Can extract results relatively easily and quickly	– Needs time synchronization
Angle of Arrival (AOA)	– Location calculated using distance and position of RF sign signaling tag and receiving reader	– Accuracy is not affected by distance – Minimal influence due to multipath	– Needs an isotropic antenna and antenna array – Cannot extract exact location coordinates
Time of Arrival (TOA)	*– Estimates distance between reader and tag using RF signaling speed*	*– Its accuracy is not affected by distance* *– Minimal influence due to multipath*	*– Needs partial time synchronization*

The TOA technique uses a trilateration technique based on multilateration (Fig. 2). First, based on the reference coordinates (x, y) of the readers, the distance between the tag and each respective reader is calculated using the time of signal arrivals between the readers and the tag. Pending the availability of distance data from at least three readers per tag, the coordinate of the tag is derived through the trilateration technique.

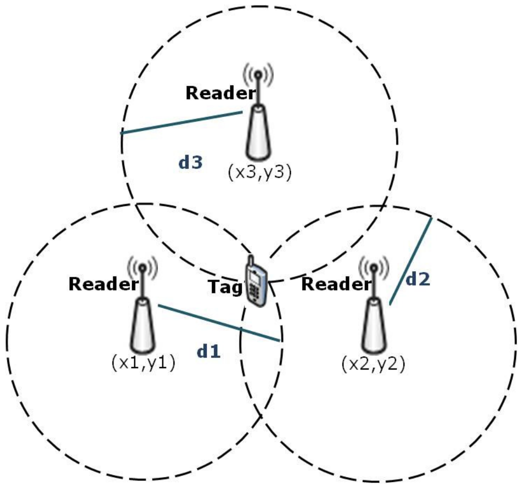


Fig. 2. Multi-lateration (TOA)

The wireless networking technique is required to send the distance data to a base station or engine. There are several networking techniques, as shown in Table 4. The Chirp Spread Spectrum (CSS) technique has been adopted in this research. The CSS works well to mitigate multipath fading and channel noise, and enables precision ranging with a long range of measurement by comparison to other techniques (Son *et al.* 2009). In CSS, fast data transmission is available on 2.45 GHz and its speed can reach 2 Mb/s. The signal transmission distance is 1 km, which is enough to cover a large-scale building project. The CSS method has an expanded range of data communication and a high level of tolerance for both multiplicity and complexity that can result from the overloading and overlapping of passages and portals. In addition, the CSS is compatible with other networking methods, which reduces the chance of a signal disturbance and minimizes the potential error in location coordinate determination. Using TOA and CSS, information concerning the tag's position is derived and transferred to the RTLS engine in the format of x and y coordinates and floor information (i.e. z coordinate).

3.3. Location monitoring system

In order to visualize the movement of workers transmitted by RTLS, a location monitoring system was developed based on ArchiCAD 12 environments (Fig. 3). The monitoring system should seamlessly receive the real-time location data, and process the data within the monitoring process for the purpose of increasing the scalability of system. For this, the monitoring system allows the system users to identify the location of workers and designate the dangerous zone in the building. The monitoring system has four main functions: 1) registering the building; 2) designation of dangerous zones; 3) establishing reader reference points; and 4) establishing reader locations.

The building registration function enables the users to represent the outline of a building in the monitoring system. To register the building, it is important to set up a reference point for the building in the location monitoring system. Once the user designates the global reference point of the building in the system, the building is set to measure its coordinates from the reference point. After this, the user chooses the polyline element and draws the outline of building, which is extracted by floors and is stored on the RTLS server.

Designation of dangerous zone function allows the user to specify the dangerous zones within the building by using the fill element provided in ArchiCAD 12 library. The dangerous zone is set by the construction safety manager and the alarm for the potential accident types in a given zone is sent to the worker in real-time manner. In addition, the safety manager can set a threshold value for sending the early alarming to the worker by considering

Table 4. Comparison of wireless networking methods

	RF range	Transmission velocity	Transmission distance	Electric power	Net organization	Standard association
Wireless Local Area Network (Wireless LAN)	2.4/5 GHz	11~54 Mbp/s	50 m	800~1,600 mW	P2P, Star	IEEE 802.11 WiFi Alliance
Bluetooth	2.4 GHz	1 Mbp/s	10 m	50/80 mW	P2P, Star, Ad-hoc	IEEE 802.15.1 Bluetooth SIG
ZigBee	868/915 MHz 2.4 GHz	250 Kbp/s	10~75 m	1/75 mW	P2P, Star, Mesh	IEEE 802.15.4 Zigbee Alliance
Ultra-Wide Bandwidth (UWB)	3.1~10.6 GHz	480 Mbp/s	20 m	~200 mw	P2P, Mesh	IEEE 802.15.3a WiMedia Alliance
Chirp Spread Spectrum (CSS)	*2.45 GHz*	*2 Mbp/s*	*1 km*	*100 mw-1 W*	*Star, Peer-to-peer*	*IEEE 802. 15. 4a*

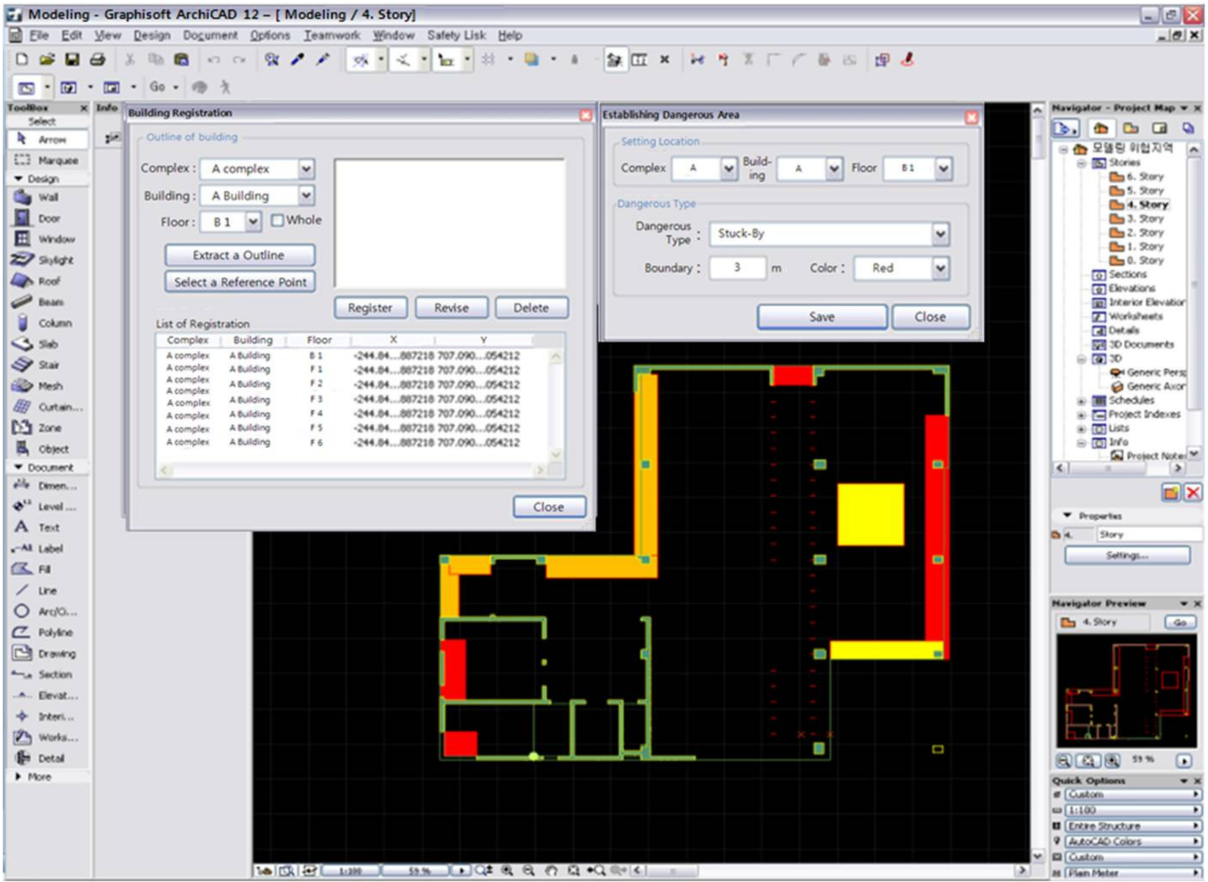


Fig. 3. Location monitoring system

the performance of tracking when the worker is in the vicinity of the dangerous zone. In this research, the threshold was set to be 1.5 m/s considering the average movement speed of an adult male (Tarawneh 2001). Further research effort on the optimal size of the threshold is required by carefully analyzing the moving velocity of a worker or object in construction sites and the reaction time of the worker.

The establishment of readers' reference point function sets a reference point for setting the coordinates of the readers. Using this function, the user can set the reference point of readers in the location monitoring system and store the coordinate in the RTLS server. Lastly, reader's locations input function is used to determine the location of readers. Using this function, the user sets the location of the reader and inputs the specification of reader, building, and floor.

3.4. Alarming system

Alarm technology is applied to send warning signals to alert a worker when he or she approaches a dangerous area (i.e. unsafe condition). The alarming system is composed of an alarm transmitter and a receiver. The transmitter receives alarm signals from the RTLS engine and delivers it to the alarm receiver, which then sends it to the worker on site. The alarm transmitter and the receiver are attached to the RTLS engine and each tag respectively, as these attachments are highly suitable for use on work sites. Once a worker's location coordinates are sent to the RTLS engine, the engine compares the coordinates of dangerous areas (specified in the location monitoring system) with the worker location coordinates (transferred from the RTLS).

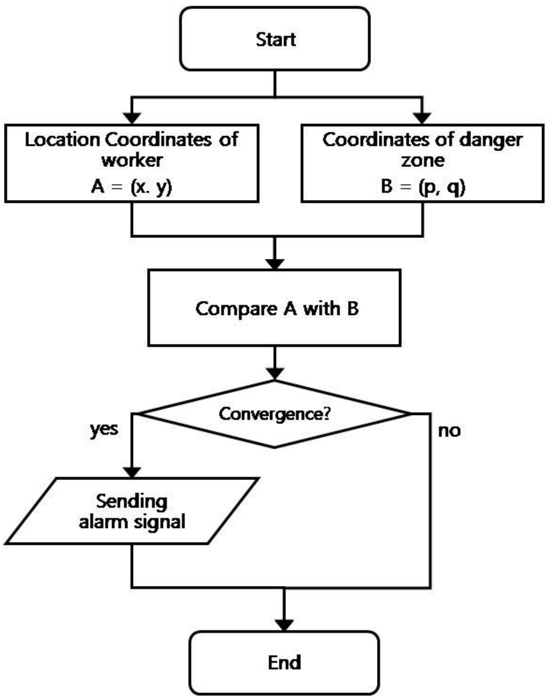


Fig. 4. Alarm signal transmission algorithm

Figure 4 shows the alarm signal transmission algorithm. The principle of this algorithm is to confirm whether there is an overlap between the coordinates of a worker location and those of dangerous areas. The location coordinate of a worker is compared with the polygon coordinates of the dangerous area, and if the location of the worker is inside the range of the dangerous area polygon, an alarm signal is sent to the worker. This alarm signal is expected to provide workers with detailed information about the expected accidents types. To this end, 14 different alarm signals are provided to represent different types of hazards including falls, dropping, collapse, strangulation, electric shock, landslide, collision, suffocation, fire, overturning, destruction, explosion, and drowning.

3.5. Data transmission protocol

Data protocol must be defined for data transmission between each module. In this context, protocol is a standard data format that each module uses to communicate. To establish a protocol, the type of information and the requirement for data processing must be determined. There are two data streams: tag-to-engine; and engine-to-tag. For data transfer from tag to engine, the data protocol includes project ID, tag ID, worker coordinates (i.e. x-y coordinates and floor information) and time of data transmission. On the other hand, for data transfer from engine to tag, the data protocol contains project ID, tag ID, alarm code, alarm number, and interval of alarm output.

The data shown in Tables 5 is formatted as follows. The project ID is used to define each project and is composed in 2 byte form. The tag ID is used to uniquely identify a tag, and hence the worker to whom it is attached, and is composed in 4 byte form. The worker's location is transmitted in the format of two coordinates (x and y). These coordinates are defined with respect to a building plan datum, and are formatted in "mm" units. Floor information is composed in signature 1 bit, and the floor numbering in 7 bits, where 0 marks the ground level and signature 1 marks the basement. Time is composed of 7 bytes, marking year/month/day/hour/minute/second in 2/1/1/1/1/1 byte form. The alarm code expresses warning messages according to warning codes composed in 1 byte form. The alarm number indicates the alarm type and is composed in 1 byte form. Finally, the interval indicates the alarm output frequency (in seconds) and is composed in 1 byte form.

4. System performance test

Two case studies were conducted to test the tracking and monitoring performance of the developed systems: 1) an apartment construction site in Yong-In, Korea; and 2) RTLS technology test center at Pusan National University in Korea. The performance of tracking can vary subject to the testing environment. For this reason the first case study was conducted to test efficiency and applicability of the system under two different environments: a line of sight (LOS) environment and a non-line of sight (NLOS) environment. An LOS environment is where there are no obstacles like walls, materials, equipment and workers between a tag and a reader. In this environment, signals are well transmitted without any disturbance, so the result is expected to be quite robust of localization performance. On the other hand, in an NLOS environment there are obstacles between a tag and a reader, which can disturb the propagation of the signal by reflection, diffraction, and refraction of the radio waves. This can result in the creation of multipaths, whereby the distance of frequency movement becomes longer than the linear distance. For this reason, in an NLOS environment, tracking performance may be significantly reduced. The basement parking lot was selected for testing an LOS environment and the first three floors of the apartment project were selected for the NLOS environment where walls, columns, and construction equipment act as obstacles in the construction area.

4.1. Testing under a line of sight environment

The RTLS hardware (engine, base station, reader, and tag) was installed in the case study apartment site. The personal computer (PC) that hosts the RTLS engine and base stations was installed using a power supply and land-line Local Area Network (LAN). Readers were located in each floor and their coordinates were configured in the engine and a tag was attached to each worker. When workers moved around the site, the deployed RTLS captured their real-time location and represented the information on the 2D site map (displaying each workers' x and y coordinates) as shown in Figure 5.

After this, the safety manager sets up the location monitoring system. In ArchiCAD 12, the building should be modeled based on existing architectural drawings. The complex, building, and floor were set using building registration function. Building coordinates were created by fixing the referencing point and applying the polyline element. In dangerous zone function, dangerous zone were designated by applying fill element, and the grade of dangerous area is determined according to the risk of work type. Finally, the reference points of equipment and readers' locations are set, and IDs of readers, complex, building, and floor of each reader are set.

Figures 5 and 6 show the monitoring and tracking performance of the developed system under a LOS environment (underground parking lot). As shown in Figure 5, the system could successfully update the location coordinate of a worker obtained through the RTLS in the

Table 5. Protocol for data transter

Data transfer from tag to engine	Data	Project ID	Tag ID	X Coordinate	Y Coordinate	Floor Information	Time
	Bytes	2	4	4	4	1	7
Data transfer from engine to tag	Data	Project ID	Tag ID	Alarm Code	Alarm Number	Interval	
	Bytes	2	4	1	1	1	

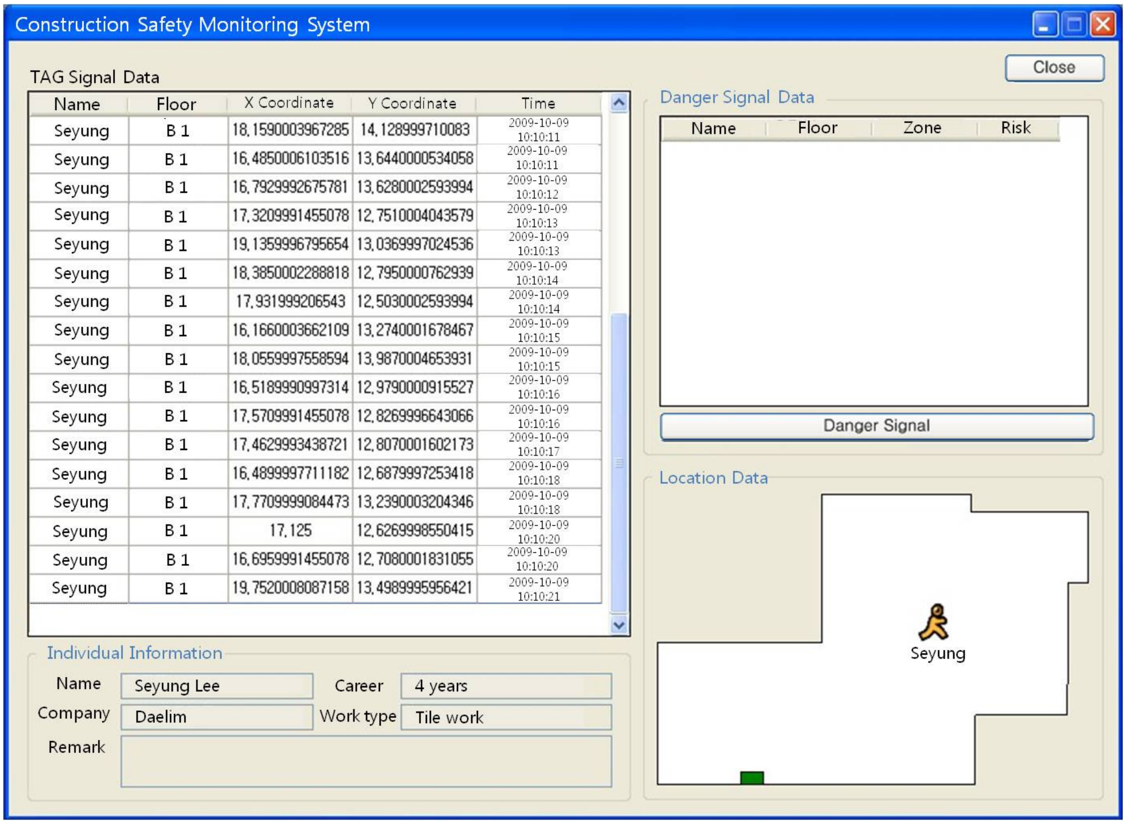


Fig. 5. Monitoring performance under a LOS environment

LOS environment. The 'Danger Signal Data' section represents the entry status for the dangerous areas. Figure 5 indicates that the worker is not in a dangerous area (denoted by green color). The location data is also converted to a visual representation of the building outline, the dangerous areas of the floor and workers' locations. Workers' individual information (e.g. name, career, company, work type, or remark) can also be identified.

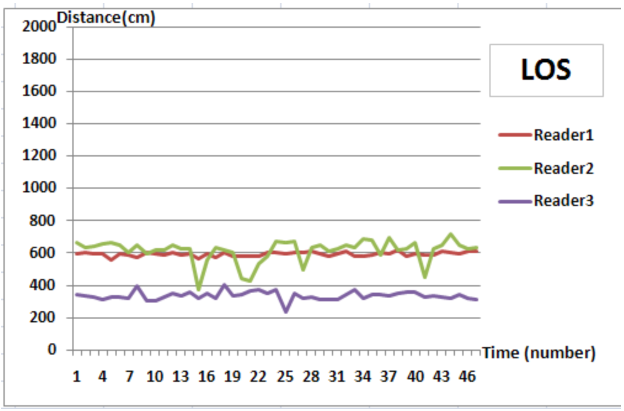


Fig. 6. Tracking performance under a LOS environment

The developed system should be able to measure the tag-to-reader distance for its effective application for the purpose of construction labor safety management. Figure 6 shows the tracking performance of the developed system. Distances between the tag and three readers (Y-axis) are plotted based on each time interval (X-axis). As shown in Figure 6, the distances between the tag and three readers are relatively consistent in the LOS environment. The average distance between the tag and readers 1 and 2 is about 593 cm with 12.6 cm of standard deviation while the average distance between the tag and reader 3 is approximately 336 cm with 27.4 cm of standard deviation. Overall, under the LOS environment, the developed system showed an acceptable level of tracking performance, which is attributed to the smooth radio frequency transfer in this environment.

4.2. Testing under a non-line of sight environment

The monitoring and tracking performance of the developed system was also tested under an NLOS environment (the first floor). Figure 7 shows the monitoring performance of the developed system in the NLOS environment. In the monitoring system, location data is converted to a visual representation of the location of workers so that the safety manager can identify workers who are in or near the dangerous area and the worker's detailed information. As shown in Figure 7, 'Danger Signal Data' section shows that a worker is approaching a dangerous area. Based on this information, the safety manager can automatically (or manually) send a warning signal to the worker with the detailed information regarding the identified dangerous situation (i.e. dangerous area, worker name, x-y coordinate and floor information, type of danger, and the level of danger).

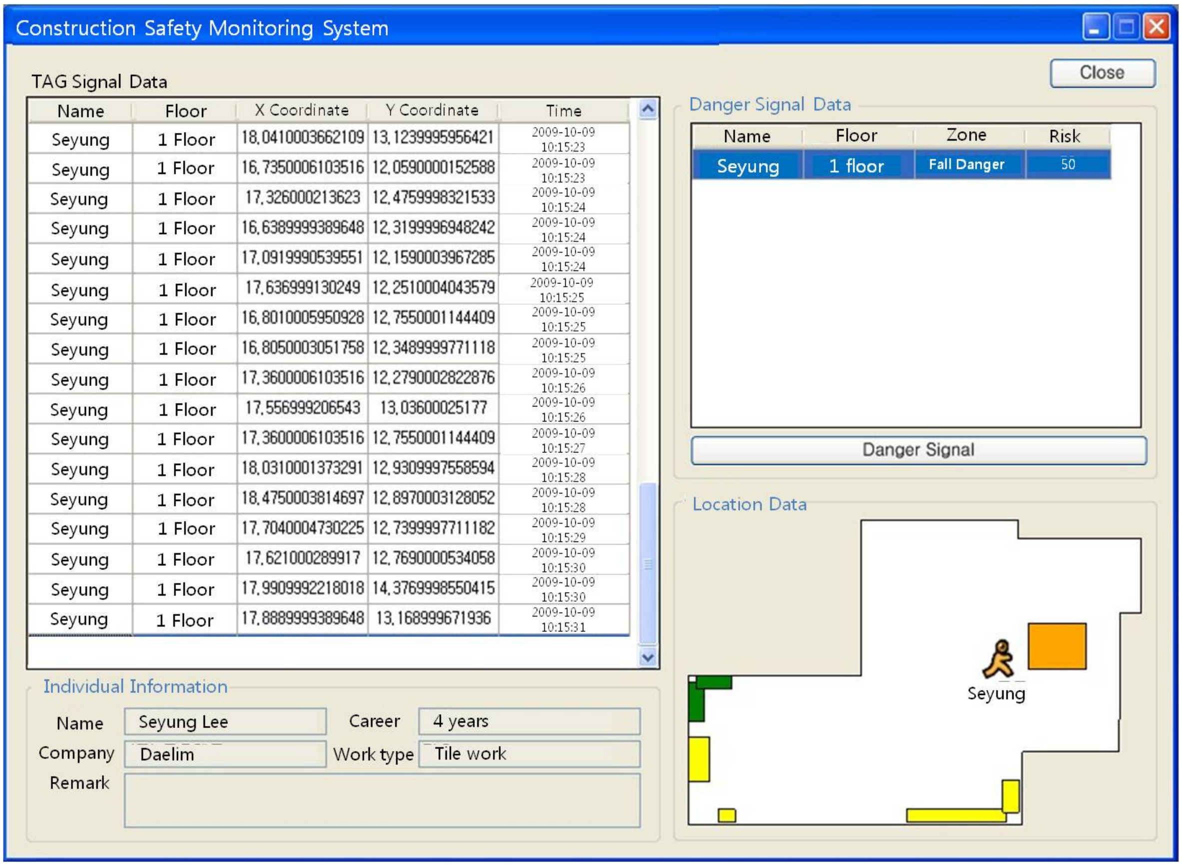


Fig. 7. Monitoring performance under a NLOS environment

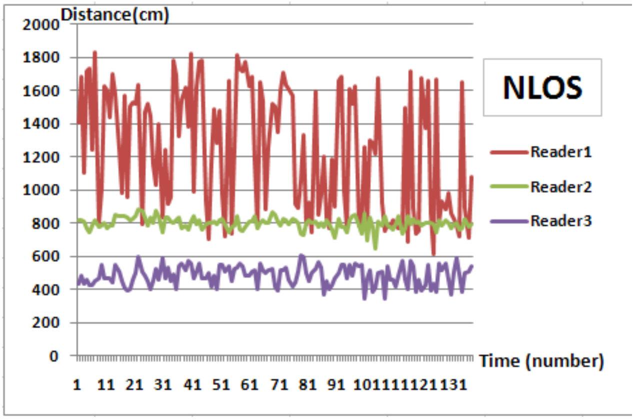


Fig. 8. Tracking performance under a NLOS environment

Figure 8 shows the tracking performance of the developed system in the NLOS environment. As shown in Figure 8, the readers 2 and 3 showed relatively consistent tag-to-reader distance in the NLOS environment. The average distances are 800 cm and 484 cm with the 36 cm and 59 cm of standard deviation. While these standard deviations are a bit greater than those in the LOS environment, these deviations are acceptable considering the pre-defined threshold to send the early warning signal. However, the distances between the reader 1 and the tag significantly fluctuated widely between 600 cm and 1,800 cm with the 371 cm of standard deviation. This is because there was an obstacle (i.e. structural wall) between the reader 1 and the tag. This testing result confirms that the tracking performance of the developed system can be significantly reduced in an NLOS environment due to signal reflection, refraction, and diffraction and suggests needs for an enhanced tracking performance in an NLOS environment.

4.3. Application of assistant tag

The previous test results showed that significant localization errors can exist in the NLOS environment. Construction sites are typically NLOS environments and thus, the localization errors need to be reduced for the developed system to be effectively applied. A time of arrival (TOA)-based tracking system requires information concerning the distance between the tag and at least three readers as shown in Figure 2. If the number of readers in a position measures their distance from a given tag is less than three, it is impossible to derive the exact location of the tag using the trilateration method. To address this issue, an assistant tag was applied to increase the tracking performance of the developed system in an NLOS environment. The assistant tag is an additional tag the user can access its location coordinates and this can work as a virtual reader when there is a shortage of readers with line of sight to a particular tag (Cho *et al*. 2008).

In order to measure the impact of the assistant tag under various obstacles in a safer testing environment, the second case study was conducted in the RTLS technology

Table 6. Reduction of localization error in an NLOS environment with assistant tag

Type of obstacle	Actural location (x, y)	Tracked location		Localization Error		
		w/o assis. Tag (x, y)	w/ assis. Tag (x, y)	w/o assis. Tag (cm)	w/ assis. Tag (cm)	Reduction (%)
Concrete	(1735, 1517)	(2403, 972)	(1961, 1240)	862	357	59
Steel	(2167, 289)	(2308, 126)	(1816, 196)	215	123	43
Wood	(3777, 1211)	(3504, 975)	(3627, 1081)	361	198	45

test center at Pusan National University in Korea, which is very similar to a typical construction site that have many steel obstacles and columns. The test was conducted as follows: first, the global reference point was designated and the readers were located according to the relative distance to the reference point. The location of tags could then be derived based on the location of the readers. In addition, the assistant tags were located nearby the tags which were to be tracked and location coordinates of the assistant tag was stored in the RTLS engine. In order to measure the tracking performance of the developed system, localization error was calculated by comparing the location of the tag obtained from the RTLS and the actual location of the tags, which had previously been measured manually.

$$\text{Localization Error (cm)} = \sqrt{(\text{Actual } x \text{ coordinate} - \text{Tracked } x \text{ coordinate})^2 + (\text{Actual } y \text{ coordinate} - \text{Tracked } y \text{ coordinate})^2}\,.$$

Table 6 shows localization error under three different obstacle types frequently utilized in construction environments including concrete, steel and wood. Also, Table 6 shows that utilization of assistant tag can significantly decrease localization error. For example, when concrete wall served as an obstacle, the localization error without using an assistant tag was 862 cm. However, application of an assistant tag reduced the localization error to 357 cm, which is 59% of localization error reduction (i.e. (862–357)/862). The test results indicate that the application of an assistant tag has a great potential to minimize the localization error in NLOS environments. However, these test results also show that further research effort on assistant tag is required to enhance the tracking performance. For example, one research effort required is to optimize the location of assistant tag, which can virtually convert an NLOS environment into an LOS environment. Thus, the authors' subsequent research effort is devoted to the development of an optimization algorithm to improve localization performance. Interested readers can find more details regarding the use of assistant tag from Lee *et al.* (2012).

Conclusions

Every accident has its causes and can be prevented by identifying and eliminating the causes. According to Heinrich (1959), the causes of an accident can be classified into indirect accident causes (i.e. deficiencies in safety management) and direct causes of accidents (e.g. unsafe mechanical or physical conditions and unsafe acts). Direct causes of accidents are unique in each individual construction site. Based on this recognition, this study introduced a real-time location-based construction labor safety management system. For this purpose, a real-time locating system (RTLS) was applied to track location of workers on a real-time basis, and a location monitoring system was developed where workers' locations and potential dangerous areas are visualized. Finally, an alarming technology was utilized to warn endangered workers. Integrating these technologies, the developed system can assist the management and control of direct causes of accidents in real-time. Two case studies were conducted in order to test the tracking and monitoring performance of the developed system. The case studies confirmed that the developed system can show an acceptable tracking and monitoring performance in a LOS environment; however, exhibit a significant localization error which should be overcame in order for the system to be utilized for the purpose of construction safety management. To address this issue, this paper adopted assistant tags and the case study confirmed that application of an assistant tag has a great potential to decrease the localization error in an NLOS environment and increase the applicability of the developed construction labor safety system.

While the developed system was proved to be effective to prevent construction accident, it also has several limitations that should be overcome in the following studies. First, the threshold value of dangerous zones need to be further investigated by considering the moving velocity of a worker or an object and the required time for a worker to respond to the identified danger after receiving warning signals. Also, the developed system needs to be tested under large number of workers. Lastly, identification and registration of accident risk needs to be automated. Overcoming these limitations would enhance the performance and applicability of the construction labor safety management system and ultimately minimize construction accidents and hazards.

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