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Proactive training system for safe and efficient precast installation

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Abstract

The construction industry is a crucial component of the Hong Kong economy, and the safety and efficiency of workers are two of its main concerns. The current approach to training workers relies primarily on instilling practice and experience in conventional teacher-apprentice settings on and off site. Both have their limitations however, on-site training is very inefficient and interferes with progress on site, while off-site training provides little opportunity to develop the practical skills and awareness needed through hands-on experience. A more effective way is to train workers in safety awareness and efficient working by current novel information technologies. This paper describes a new and innovative prototype system – the Proactive Construction Management System (PCMS) – to train precast installation workers to be highly productive while being fully aware of the hazards involved. PCMS uses Chirp-Spread-Spectrum-based (CSS) real-time location technology and Unity3D-based data visualisation technology to track construction resources (people, equipment, materials, etc.) and provide real-time feedback and post-event visualisation analysis in a training environment. A trial of a precast facade installation on a real site demonstrates the benefits gained by PCMS in comparison with equivalent training using conventional methods. It is concluded that, although the study is based on specific industrial conditions found in Hong Kong construction projects, PCMS may well attract wider interest and use in future.

Keywords: Construction training; Construction safety; Work efficiency; Building Information Models; Real-time location system.

1. Introduction

Supervising the safety of workers is one of today's most important challenges in the management and organisation of construction worldwide, as workers frequently face exposure to potentially hazardous situations such as falling from a height and striking against, or being struck by, moving objects. In the Hong Kong Special Administrative Region[1], for example, construction is ranked as the most dangerous industry, with 46 fatalities in 2011 – around 24% of the total

[1] Hong Kong's current formal name. However, we refer to simply *Hong Kong* here as an internationally recognised name.

fatalities in all industries [1]. With a fatality rate of 0.337‰ in 2012 – an increase of 2.2% on the average of the previous five years [1] – the situation is worsening. With the recent introduction by the Hong Kong Government of ten major construction projects, the industry has experienced a shortage of labour, resulting in companies having to employ people with little relevant working experience. Moreover, the industry's high turnover rate is resulting in more experienced and productive workers being replaced by fresh ones with only baseline performance levels. A major outcome of this is the need for new workers to become as proficient as their predecessors as quickly as possible, especially in terms of efficiency and safety – two key factors closely associated with cost-effective and time-saving of construction projects [2] – making the provision of training in these two areas of significant importance for the industry.

Modern information technologies, which include real-time location and data visualisation, play a key role in providing support for data and messages travelling between management and workers within an intelligent communications network [3]. Real-time location and visualisation technologies have the potential to improve control of the safety and efficiency of workers by monitoring construction resources (people, equipment, materials, etc.) and identifying the status of work tasks anywhere and at any time

This paper presents a new approach, termed here the *Proactive Construction Management System* (PCMS), to the accelerated acquisition of safety and efficiency skills and awareness. This integrates data from sensors in training based on real-time tracking in order to measure and quantify safety and efficiency. Currently limited to location-based training for prefabricated product rigging and installation (like precast facade installation), the location of workers is tracked during hands-on training sessions involving the installation of temporary inclined bracing, fixing fabric reinforcement, etc. Chirp-Spread-Spectrum (CSS) technology is used to measure the location of the trainer and trainees, materials and cranes during tasks such as rigging, hoisting and fixing. The location-based data collected in this way is used to analyse their safety and efficiency.

Efficiency during the training session is visualised using a virtual reality environment for real-time and post-event analysis. To evaluate worker performance in the whole process, the track points of construction resources are analysed to identify starting time points and accumulated durations of different construction tasks of each construction craft and the real-time feedback (instructions from trainers or real-time warnings) and post-event analysis can be provided to workers to help improve performance. Therefore the ability to convert data quickly into information about safety and productivity is crucial to construction training [4]. After sufficient training has taken place, baseline (pre-trained) and post-trained performance are loaded into comparison modules to identify improvements and calculate the estimated efficiency as a benchmark for further progress control decision making. The effectiveness of the system is then determined by an opinion-based investigation of trainers and trainees, with their feedback being used to identify the shortcomings and limitations of the technologies, so that the training plan can be updated and improved for future training.

This paper is organised as follows. Firstly, current construction training methods and potential state-of-the-art of real-time location and data visualisation technologies are reviewed in Section 2. This is followed by the description and implementation of the new system in Section 3 and

Section 4. Section 5 describes a real on-site trial for the further development and validation of the system, while Section 6 considers the benefits and limitations of PCMS training. Concluding remarks are provided in Section 7.

2. Background

2.1. Problems with current construction training

Construction work is sometimes very dangerous and physical components get damaged and workers injured if operations are not carried out correctly [5]. This problem is particularly acute in hoisting prefabricated components. In recent times, in order to improve both safety performance and the efficiency of workers on construction sites, more emphasis has been placed on providing adequate worker training [6]. Although requiring more initial investment, construction workforce training programs are considered to be a significant advancement on the traditional master-apprentice approach. For example, it has been shown that investing 1% of a project's labour budget in both union and non-union training can result in double-digit returns in productivity, and reduced absenteeism and need for rework [7].

An apprenticeship program in the US Department of Labour consists of 44 hours a year of related off-site instruction, and at least 3 years, or 6,000 hours, of on-the-job training (Bureau of Labour Statistics, U.S. Department of Labour). The typical *off-site* training process involves three phases based on equipment training websites, including West Coast Training Inc., The National Heavy Equipment Operator School, construction health and safety training classes and programs as follows:

- *Classroom lecture*: Typical classroom activities include pre-work inspections (daily, weekly, monthly), potential hazard awareness, functions and operations of equipment and applications, how to work safely, show concern for fellow workers and look after the equipment, different types of construction equipment maintenance and repair regimes, and familiarisation with mobile construction equipment. Some additional learning modules are available to help meet special requirements. For example, a two-hour elective course on dumper truck operations introduces the concept of safety and communication between the truck driver and workers loading the trucks.
- *Hands-on instruction*: Hands-on construction work requires a site with room for practice exercises such as excavating, soil placement, trench sloping, benching, trench box/shoring placement and use, rigging and lifting, loading of trucks and stockpile re-handling. Usually an apprentice must practice and demonstrate knowledge of safe construction. In practice, apprentices must also demonstrate their understanding of how to perform general tasks safely and how to use specific equipment to accomplish a variety of tasks.
- *Testing*: Examinations can be conducted in written, oral or practical format. The written/oral test generally covers working skills and safety points made during the course. The practical examination tests individual performances in various tasks that maybe encountered on site (e.g., demonstrate an ability to follow directions, work safely, and show concern for equipment and fellow workers).

- *Other off-site training*: Self-study and peer-to-peer study are also an important and low-cost approach for workers to educate themselves through books, videotapes and co-workers.

However, these off-site training programs provide trainees with limited hands-on experience of real working conditions and result in inefficient performance when apprentices first work on-site.

On-the-job training can be more effective but is time-intensive, expensive, and potentially hazardous, sometimes requiring specialised equipment. The time element is significant as a trainee needs considerable practice to develop the coordination necessary for the safe and efficient manoeuvring of materials. The expense results from the need for an on-the-job trainer and to effectively disable productive construction equipment so that a trainee can practice manipulating materials. Other additional costs incurred by training providers include buildings, maintenance, and machine operating costs, supervisors and external assessors. The sum of these costs can be considerable. This is exacerbated greatly by the need for apprentices to be continually supervised by more skilled and experienced colleagues for several months or even years [9].

An ideal training program should enable workers to enhance working efficiency, upgrade safety awareness and practices more quickly, and reduce machine operation and training costs [5]. Compensating for the inherent drawbacks involved in current apprenticeship programs, real-time data collection and visualisation technologies afford new opportunities for effectively training apprentices in achieving this, with lower costs, fewer hazards and increased efficiency.

2.2. State of the art

2.2.1. Background of real-time location technologies

To date, several real-time location technologies have been tested, the most promising of these being Radio Frequency Identification Devices (RFID) [10,11], Global Positioning Systems (GPS), Wireless Local Area Networks (WLAN), Ultra-Wide Band (UWB) and Indoor GPS, and hybrid systems comprising combinations of two or more technologies [12,13] to cover a wide range of accuracy values and yard areas [14,15]. Although all these technologies can be used to monitor the movement of construction resources, they need to satisfy the following criteria in construction work [16]:

- *Robust*. Working well in a variety of site layouts such as open or closed, cluttered, small or large, and open or indoor spaces
- *Operational range*. A sufficiently long range to guarantee good coverage of the entire site. This can vary between a few centimetres for RFID readers, over 100m for WLAN and UWB access points and receivers respectively, and virtually limitless for GPS
- *Accuracy*. Capable of accurately and precisely recording the positions associated with monitored work tasks. Accuracy ranges from 0.01m for indoor GPS, less than 0.5m for UWB, and up to several metres for standard GPS
- *Device form and size.* Small enough to fit on an object without interfering with the work
- *Data update rate*. High data frequency provided in real-time (at least 1 Hz)

- *Social impact*. Non-invasive technology, but providing adequate safety and health protection.

Global positioning systems (GPS) are outdoor locating systems involving satellites, ground control stations and end users. GPS is a readily available technology and now one of the general specifications of mobile cell phones. In general, the position obtained by commercially available GPS has an error of approximately 15 metres in non-open areas [17]. The use of GPS has proved to be effective in the construction industry for locating materials in large industrial projects, where accuracy is not a major concern [18]. Although the use of a Real Time Kinematic (RTK) GPS could provide more accurate results, RTK-GPS is expensive and the size of the equipment needed makes it impossible to obtain the position of construction workers without interfering with their work.

Riaz et al. [19] have also developed a conceptual model that utilises a combination of GPS, smart sensors and wireless networks to produce an innovative and proactive health and safety management system, SightSafety, which can track workers and equipment, notify management and workers of near-misses and ultimately contribute to reducing accident rates and improved efficiency. However, SightSafety provides positional accuracy of a few metres range (0.5m to 5m) and consequently it is ineffective when the monitored objects are closer to each other than the accuracy range.

For indoor tracking, Khoury and Kamat [19a] investigate the effectiveness of three wireless technologies for dynamic indoor user position tracking, focusing on WLAN, UWB, and indoor GPS – their experimental results demonstrating a relatively high accuracy (1 to 2cm) in positioning a mobile user. A low-cost location sensing solution based on a set of passive RFID tags also can provide indoor construction and underground facilities locations, these being estimated and represented by zones and coordinates [20]. Experimental results indicate an average error rate of 0.17m for detecting the target's zone and an average of 1.3m accuracy in detecting the coordinates.

Rather than locating workers within a site, Lee et al. [21] suggest using ultra-sonic and infrared to prevent workers from entering prohibited areas. This consists of an MSD based on hybrid sensors used as a detector, a transmitter, repeaters and receiver connected to the main computer. The function of this proactive system is to send warning signals to workers at risk in order to lower the number of possible fall-related accidents and increase the efficiency of safety management.

Robust and accurate localisation performance and cost effectiveness are important for construction sites, particularly where safety management is involved, where a localisation error can lead to a fatality. Moreover, mobile workers need to be constantly tracked both outdoors and indoors due to the spatial expanse and dynamic nature of typical construction projects and that most construction sites are non-line-of-sight (NLOS), while some technologies are constrained by the complex site layout. For instance a GPS can be applied only outdoors while RFID-based approaches have also proved to be unsuitable for real-time monitoring due to their limited communication range and low accuracy.

One of the most promising technologies for real-time location in both outdoor and indoor settings is UWB, which has better signal penetration capability and high resistance to multi-paths and found to be a most reliable and accurate real-time position tracking technology. Consequently, UWB has been applied in various fields for localisation. However, UWB has limitations, such as a high initial cost (e.g., UWB tags cost $10–40 per tag) [22] and slow progress in the development of UWB standards. Furthermore UWB is not wireless and needs a power supply and communication cables. What is needed is an inexpensive tracking system that practicable for use in the harsh and dynamic construction environment.

2.2.2. Background of real-time data visualised technology

Data visualisation technologies have been successfully implemented in the construction industry in the form of Building Information Models (BIM), which has resulted in significant cost savings particularly when applied to complex projects. Virtual prototyping (VP) has been employed in a conceptual framework composed of three components: modelling and simulation, the identification of unsafe factors, and safety training [23]. In this application, managers can identify the potential hazard factors for themselves by walking through the virtual site and observing the simulated processes. Some unsafe factors based on integrated safety rules can also be automatically detected and displayed in the virtual environment. Moreover, VP can be used to instruct workers in carrying out real construction processes.

Li. et al [24] propose an integrated virtual reality (VR) system that generates a near to reality construction environment for construction planners to perform construction activities in a real world manner in order to plan, evaluate and validate the operations involved. Immersive VR systems also have wide applications in practice and the education of architects, engineers, and contractors who deal with the design and construction of buildings [25]. By immersing the user in a computer generated synthetic environment, VR learning and training offers an active learning experience where the user is in control and required to decide on suitable actions to take from a safe and secure observation point. As the use of VR can eliminate most hazards before workers arrive on site, it is useful to have as much information available on risks as possible. Data can be recorded and replayed at any time, which is especially useful in education and training settings. As a result, it has even been suggested that the use of VR technology may be "training's future" [26], with Sacks [27] for example recommending the incorporation of VR in construction safety training by using a 3D immersive VR power-wall.

Real-time data visualisation technology can therefore be highly suited to construction training as it provides realistic first-hand data to trainers and trainees. Real-time data visualisation also can help construction workers gain an intuitive understanding of equipment operation complexity including the potential hazards involved. Cheng and Teizer [25] presents a novel framework of streaming data from real-time positioning sensors to a real-time data visualisation platform that can be automatically monitored and visualised in real-time, thus offering benefits such as increased situational awareness to workers, equipment operators, or decision makers anywhere on a construction project or from a remote location. However, there is little research focusing on factors such as real-time proactive safety and activity monitoring.

In this paper, a new proactive construction management system (PCMS) is described for integrating real-time location and visualisation technologies to track the location of workers and equipment by using the CSS-based real-time location technology and Unity3D-based data visualisation technology. CSS is a wireless personal area network technology that adopts IEEE

802.15.4.a [28]. Unlike other spread spectrum methods, CSS uses its entire allocated band width to broadcast a signal, making CSS more robust to channel noise. In addition, CSS is resistant to multi-path fading even when operating at a very low power level. All these characteristics ensure that the location hardware can be a small size and with small long life batteries. Additionally, CSS is resistant to the Doppler Effect, which is typical in mobile radio applications, and allows 2Mb/s data transmission over an effective distance of 1km with relatively low power consumption, ranging from 1W to 100mW [29]. It is also safe for humans and highly compatible with other network technologies, minimising the chance of signal disturbance and thus improving the accuracy of its positioning [30]. These features are necessary for cheap and easy deployment of CSS based tags and anchors on construction sites. All the equipment used is readily available and many of the components have been tested and validated throughout the industry.

3. Description of the system

PCMS is a comprehensive and proactive system integrated with multiple information technologies so that safety and efficiency related information (positioning tracking, machine maintenance, health and safety investigation, safety training, site hazards and dangerous detection, etc.) is effectively communicated to management and workers. PCMS provides a 'third eye' to site workers to detect and avoid dangers. In addition, PCMS also records the activities of a construction project in the form of data visualisation of workers and equipment, which also serves as a 'black-box' in case an incident or accident occurs.

3.1. Architecture

PCMS comprises two sub-systems: a Real-Time Location System (RTLS) and a Virtual Construction Simulation system (VCS) (see Fig.1) divided into three tiers. Fig. 2 shows the deployment of PCMS in construction site.

3.1.1. Real-time location system (RTLS)

The RTLS involves 1) a real-time location network and 2) a real-time location engine as follow.

(1) Real-time location network

Adopting real-time location technology in a dense and cluttered construction site, by contrast, CSS, a wireless network technology can be a wise choice, which uses IEEE 802.15.4a in a wireless personal area network (WPAN) and time of arrive (TOA) as a location method [28, 29] and indicates an average error of one metre – a relatively accurate result in comparison with previous work.

A robust and accurate CSS-based real-time location network in Fig.3 involves five essential features:

- *Tags*. Multiple tags are used to locate workers, operators, equipment, vehicles and other moving objects, and integrated with timestamp devices, e-tagging devices, warning devices and SOS devices
- *Anchors* are also a kind of small hardware device designed to be fixed in some known static positions as reference points and used to convert an environment from NLOS into LOS to improve signal availability
- *Routers* are used to bridge the location engine and repeaters / tags
- *Repeaters* are used to repeat the communication signals between routers and tags

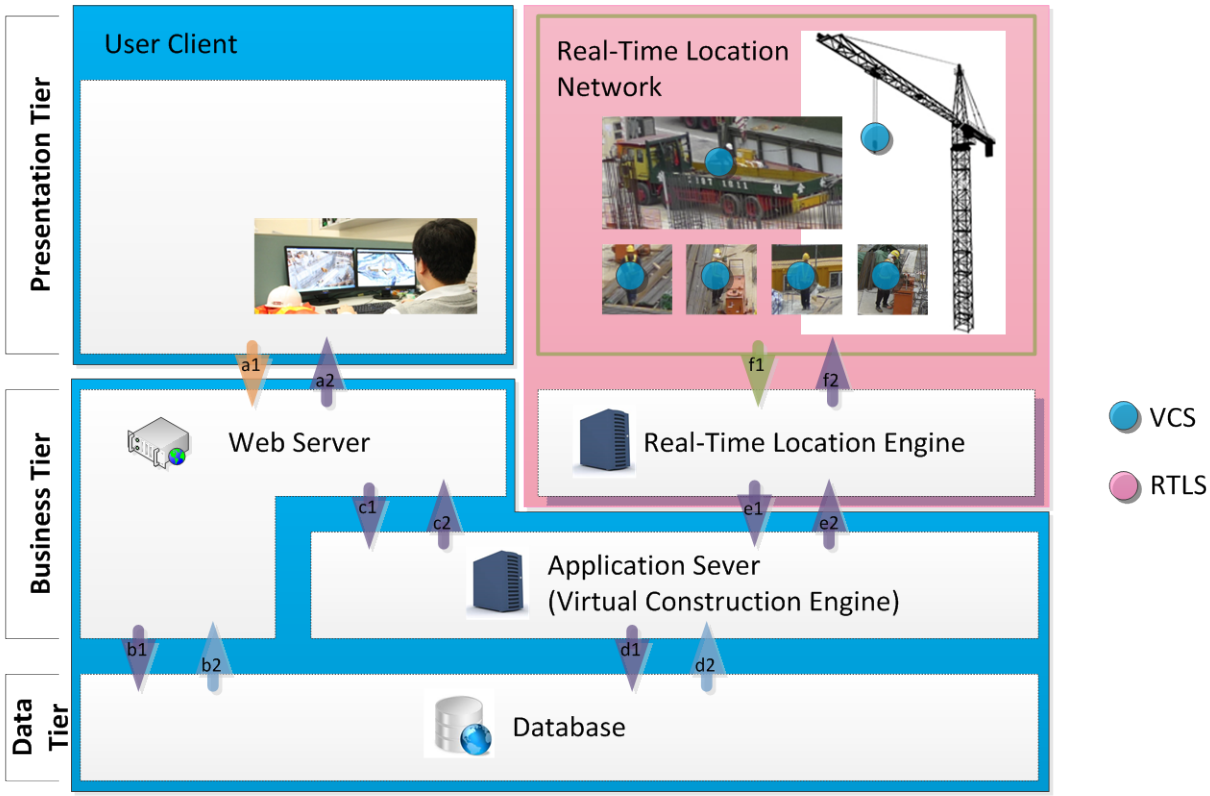

Fig.1. System architecture

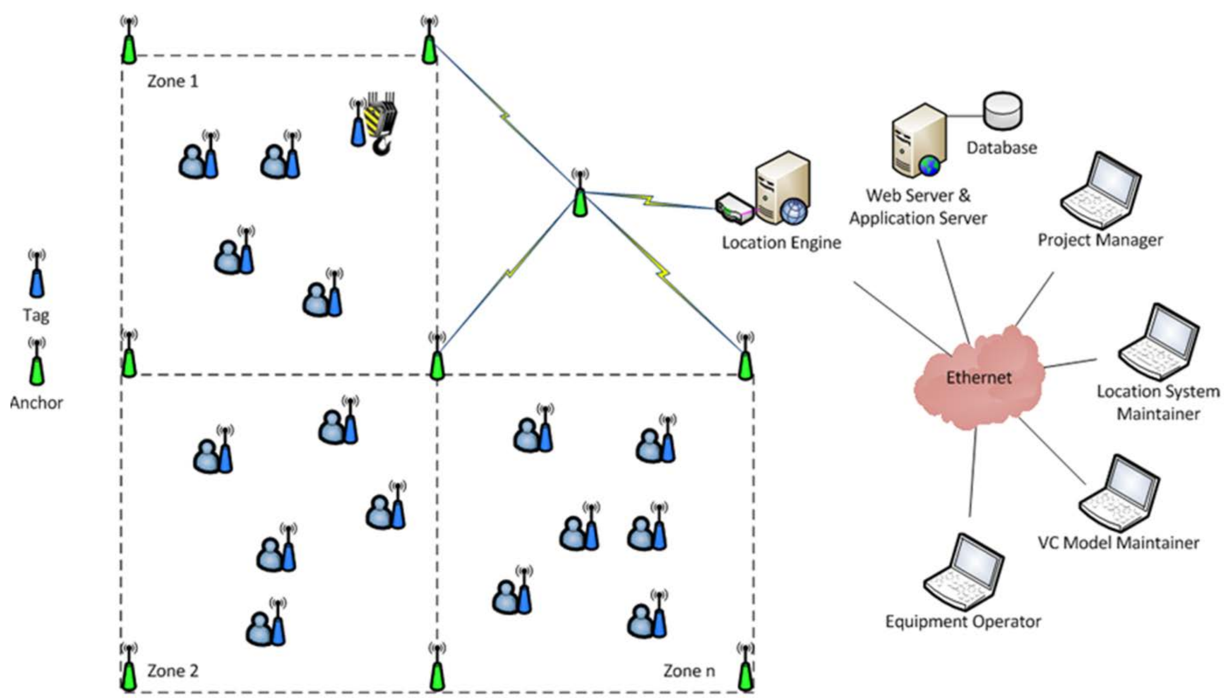

Fig.2. System deployment

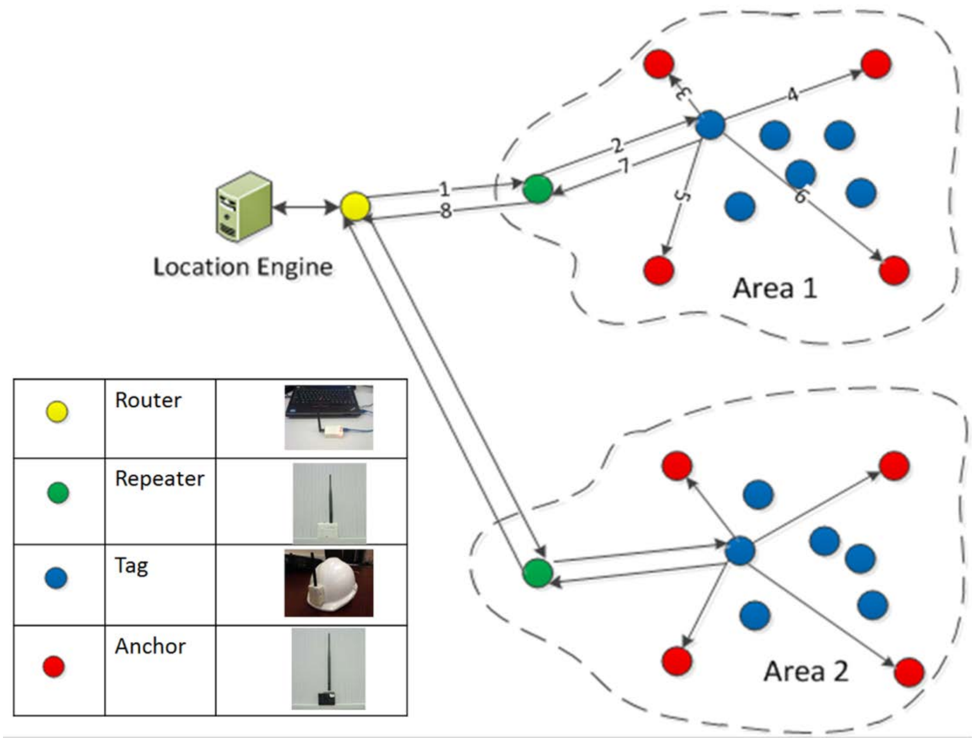

Fig.3. Real-time location network

- *CSS Wireless technology* sends ranging results to the location engine and warning signals are routed to specific tags in real-time.

(2) Real-time location engine
The location engine finds the coordinates of the tags using trilateration based on the three distance values while data is sent to the application server through the location network.

The RTLS has three functions: 1) managing the location network, 2) calculating the tag locations and 3) relay danger alarm signals to specific tags through the location network.

3.1.2. Virtual Construction Simulation system (VCS)

The VCS consists of an application server (i.e., the Virtual Construction Engine), user client, end user, web server and database server.

(1) User client
The user client is developed by using Unity3D and is a web-based application for visualising construction processes, tracking people and equipment and replaying construction processes.

(2) Application server, web server and database server

This serves as a bridge connecting the user client to the location engine. A three-dimensional model of the site, surrounding environments and position of pre-defined hazardous areas are stored here. The locations of the observed objects (workers, equipment and vehicles) are also translated and visualised in real-time. Once the detected distances between workers and their surrounding sources of danger are less than an allowable value, warning signals are triggered and sent to the real time location engine, which then relays the signal to activate the tag warning devices installed on the helmets. Finally, the tag positions are stored for later retrieval to replay the construction processes involved as first-hand training materials. The servers integrate all the positioning and alarm-situation data with a human-machine interface in a web centre, and can be used by an operator via an intuitive graphical user interface.

(3) End users equipped with e-tagging system

The end users comprise site managers, equipment operators, site workers and system maintainers and are enabled to communicate with the system through the user client interface. An e-tagging system (including data storage and retrieval) is used to enhance the PCMS function for the safety of the site end users [19]. This provides an internal linking with the safety database by wireless and offers numerous other benefits, including encoding employee e-tags with personal information (e.g. user profile, role, task and existing project conditions) and training information (e.g. work permit and training grade). Moreover, vehicle e-tags can be encoded with maintenance information for equipment health monitoring, thus generating automatic updates of vehicle maintenance schedules and inspections. The technologies that can potentially be used for e-tagging purposes include RFID e-tags, MEMS devices or even a combination of both, with all the real-time information concerning construction processes being shown on a graphical user interface (GUI) screen in a remote web centre [19]. Fig.4 shows the GUI interface in PCMS training.

The default data output stream provided by the PCMS consists of two types of tag data according to the objects being tracked: person tags (including workers, operators and managers) and non-person tags (including vehicles, equipment and other moving objects such as crane hooks). A classification of tags is needed in order to overcome the interference between the signals of different tags located within the same area.

The data packet associated with tag position data is of the form:

<TagID>; <X>; <Y>; <Z>; <Battery Power>; <Timestamp>; <DQI>

where the timestamp is the UNIX timestamp format. Combining automated work sampling with the timestamp enables the efficiency analysis.

In addition to the TagID and time-stamped spatial data (x, y, z, t) for the tag, the PCMS collects additional state information regarding the tag such as battery power and a data quality indicator (DQI) [31].

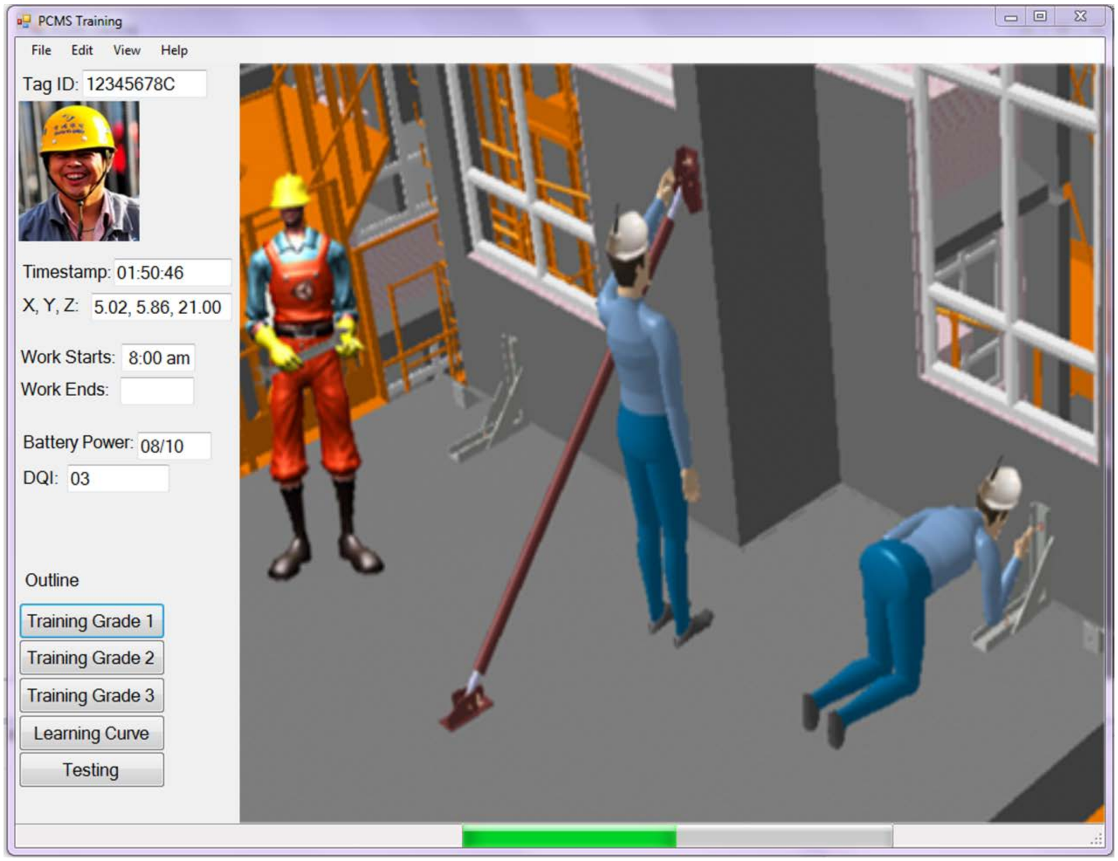

Fig.4. GUI interface

3.2. Hardware

(1) Compulsory safety helmet

The compulsory safety helmet required for all construction site workers is used as the base to accommodate the miniature positioning and communication instruments. The position of each worker is sampled periodically and sent via wireless to a monitoring station to detect near misses and provide workers with timely warnings or alerts [32].

(2) SOS device

A worker falling into a deep hole where wireless communication signalling is not possible can launch an SOS device with a loud alarm to attract the attention of other workers and help reduce construction casualties.

3.3. Safety database

The database is composed of four modules: Input, training, admin and help (see Fig.5). *Input* module refers to inputting 3D construction layout, hazard coordinates, worker and vehicle ID and personal emergency treatment. The physical coordinates of hazardous areas (such as falling edges) are imported into the database and the selected area are automatically highlighted and stored as danger zones. The graphical information can be renewed according to the progress of construction. *Training* modules provides the safety training functions including efficiency training, safety training, performance testing and goals and plans updating. *Admin* module involves the necessary administrative activities for PCMS training such as tag position, workers alerting and safety information records. Different categories of safety information corresponding to each activity, such as near misses in falling from a height and collisions between workers and vehicles are maintained in separate files [16]. Safety relevant data are recorded objectively and at any time. Analysis of safety data and generation of information leads to new safety knowledge and more advanced and better safety training and education, and can also improve the health of equipment and vehicles [32]. Besides *Admin* module enables the system administrator to assign the access rights to different types of users (such as client, safety managers and workers). *Help* module enables users to change or reset password, view and download user manual and check the FAQ. The information in the database is updated over time to prevent repeating near misses and is accessible via the Internet to query vehicle / pedestrian locations, safety reports, on-site health and safety practices [19].

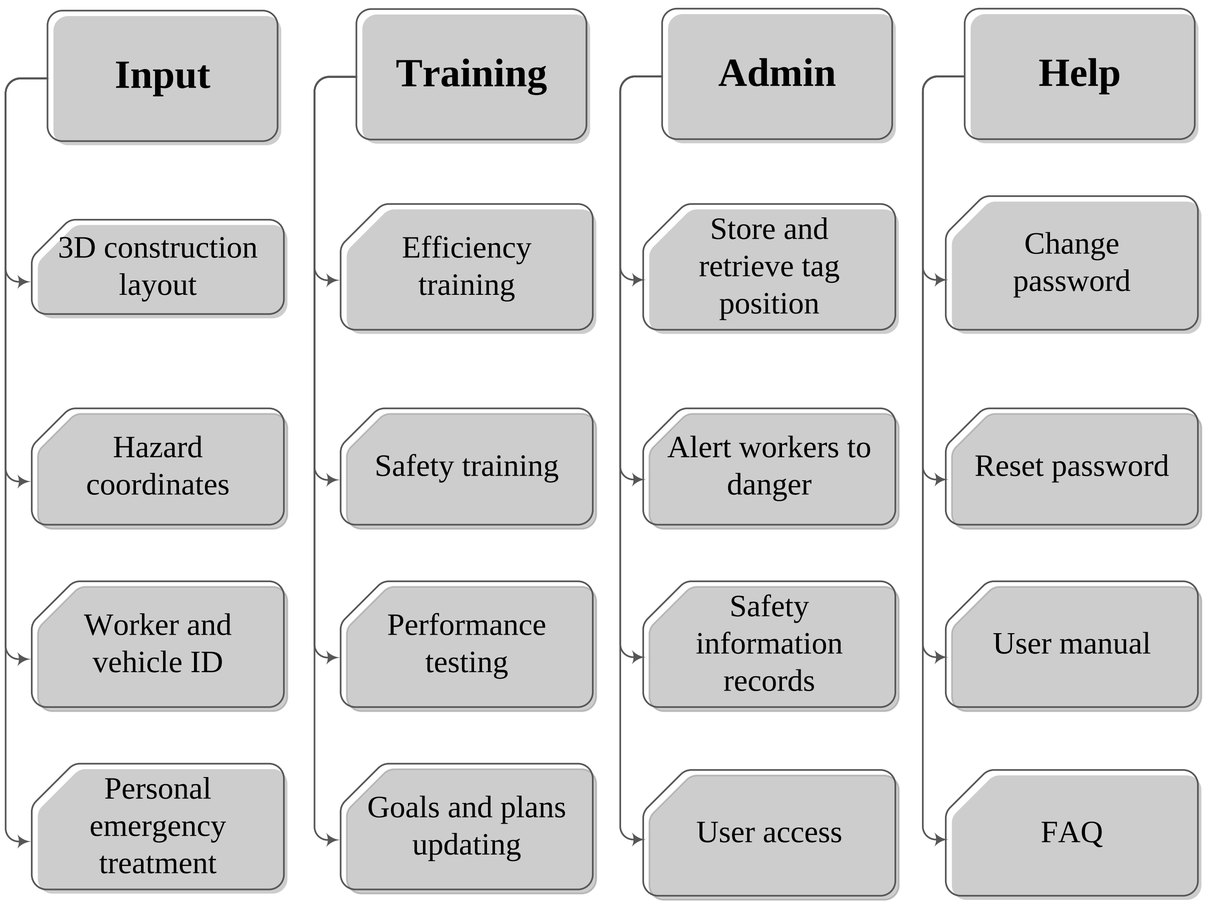

Fig.5. Safety database composition

4. Using the system

4.1. Hazard detection

Hazards such as falling from height and being struck by moving vehicles are detected using the algorithm in Fig.6. The user client first inputs the physical coordinates of hazardous areas. The dynamic danger zone forms a cylindrical work space around danger objects (such as vehicles and crane hook), with the radius from the circle's centre to the perimeter depending on warning distance in Fig.7, which is programmed into the system according to human reaction times, driving speed and braking distances of the vehicles, etc. The statistic danger zone is a rectangular area related to an opening of slab or wall opening. There are three kinds of warning distance. The warning distance of falling hazards (like floor with opening and unprotected side) are two meters; the warning distance of moving objects (like crane hook with weight) are eight to ten meters according to the height of weight; the warning distance of moving vehicles (like excavators and bull dozers) are eight meters. For the purpose of tracking and collision detection of equipment and workers, the system accurately detects their trajectory and positioning, computes their speed and direction of motion, and determines if any e-tagged object (vehicle or pedestrian) is near or approaching the danger zone. Early warnings or alerts received by workers based on the distance from the risk (see Fig.7) can enhance workers' capacity to detect the sources of near misses. To avoid interruption of normal construction activities, the helmet warning devices sound only three times when a worker enters a danger zone and one time when leaving. In cases of high risks signalled by alerts, any vehicles involved are immediately immobilised to prevent the occurrence of an accident. Moreover, the management are automatically notified so any corrective action can be taken [19].

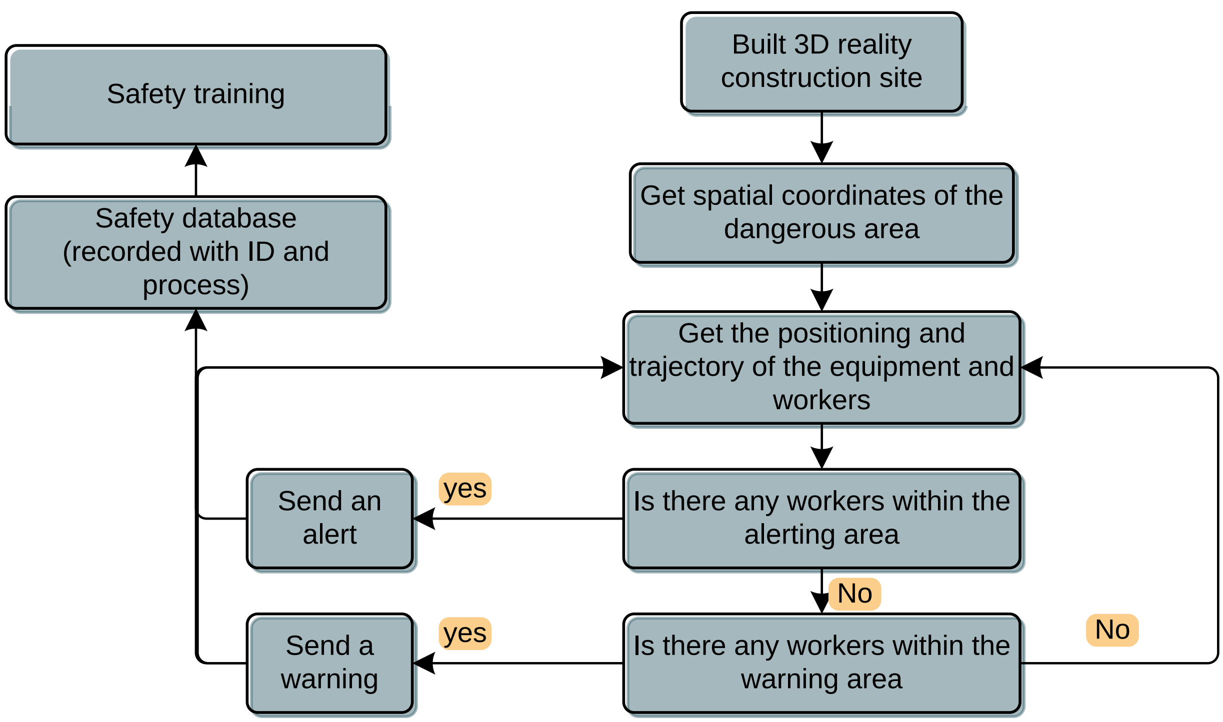

Fig.6. Algorithm for hazard detection

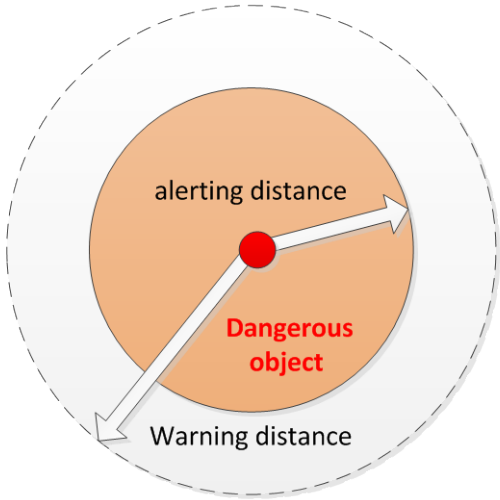

Fig.7. 2D proximity warning and alerting envelope

In addition, due to the high noise levels experienced on many construction sites, accompanying visual signals are provided to operators or workers, via vehicle on-board screens, PDAs.

4.2. Construction training

PCMS is an integrated training system that amends hazardous practices and raises working efficiency. The training procedures which worker received are in the form of:

- *Real-time feedback.* At the task level, the training system helps each trainee to identify high risk activities. Real-time proactive safety warning increases the situational awareness of trainees and real-time instructions from trainers provide a timely rectification of the trainees' incorrect operations.
- *Post real-time analysis.* During instructional sessions, the training system provides worker-centric feedback, in the form of working visualisation video or instructions from trainers, on both safety and efficiency performance without the pressure of costs and the influence of inclement weather.

In brief, the workflows of the PCMS training framework in Fig.8 are as follows:

(1) Before the workers receive construction training, they learn how to use the PCMS devices, so they can easily understand and pay attention to unsafe behaviours when using the devices.

(2) Typical classroom activities are provided for trainees including pre-work inspection, potential hazard awareness, abstract functions of equipment and other instructional information.

(3) The traditional training program ends with some hands-on practice when basic safety and efficient working practices have been communicated, and the trainees then start on-the-job training during real-site construction. Instead, PCMS uses real-time location tracking and data visualisation technology to provide objective data collection and analysis in practical exercises.

(4) The PCMS training system provides real-time feedback in the form of warning or alerts to both trainers and trainees so they can immediately correct the performance on the training site.
(5) Real-time visualisation engages all the training participants in enhanced memory retention and increased learning effectiveness.
(6) Post real-time data analysis is composed of training data analysis and comparison of historical information. Potential off-site/post-event data processing can be conducted to compute the effectiveness of trainees as well as the frequency of any breaches of existing safety standards. By examining historical data, the performance trends of the entire gang can be reported to the training administration.
(7) Individualised training programs can be generated for the purpose of improving the training effectiveness of individuals and to meet specific training objectives for those who need it or those who may want to further increase their skill level through additional or specialised training. The targeted efficiency of a modified training plan can then be set, adjusted, monitored and evaluated.
(8) Finally, proactive feedback from trainers and trainees are collected, from which the PCMS training plan can be updated with new training goals.

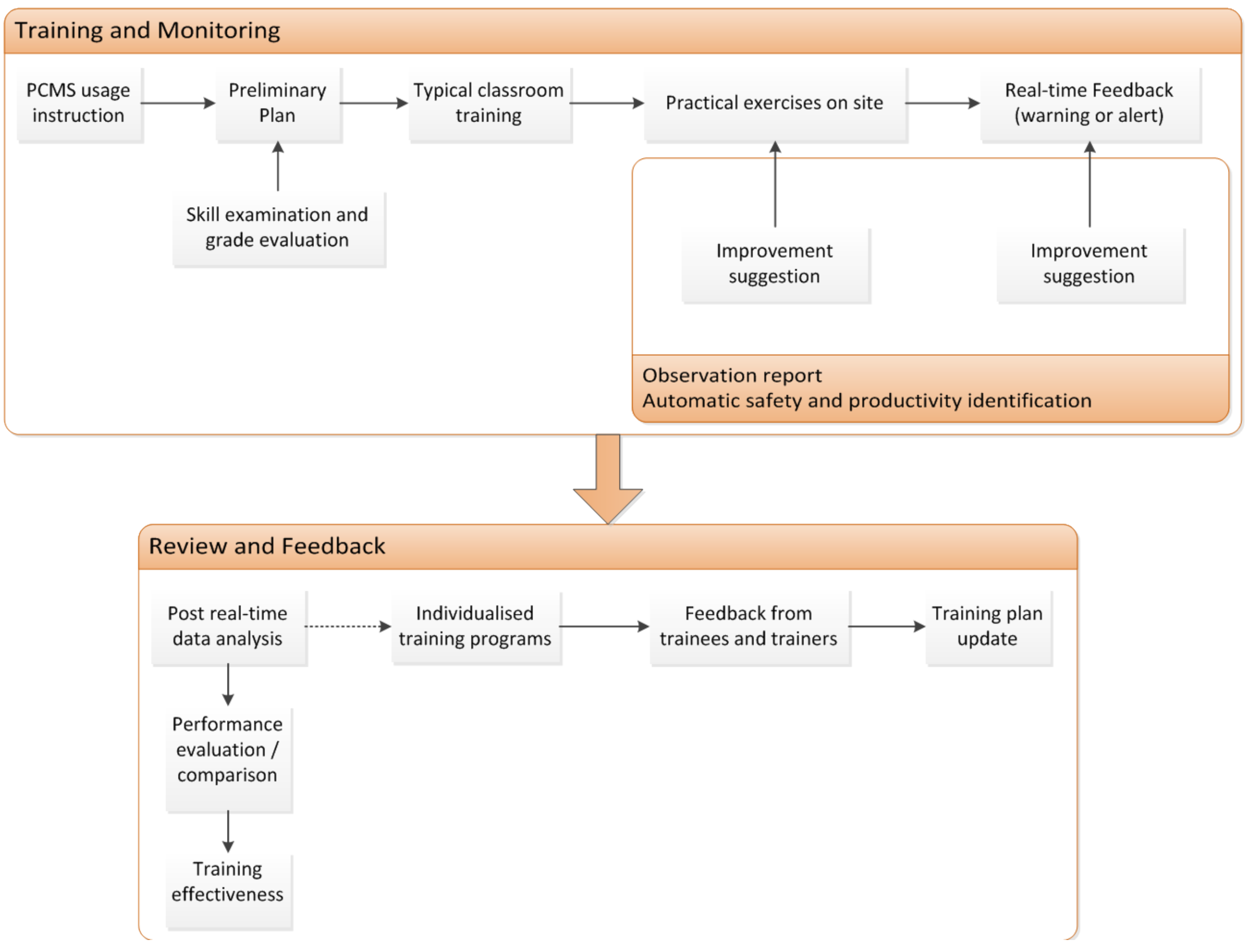

Fig.8. Workflow of training processes

In short, the PCMS training system provides an opportunity to identify and communicate the risks of individuals/crews during and after training, to enable modification of the work environment and worker behaviour before the trainees enter a real construction site.

5. Construction site trial

The site of the trial involved the construction of four 40-storey public housing blocks, the client of which is the Housing Authority of Hong Kong. The Housing Authority is required by the government to achieve large production, high quality, low construction cost and fast construction through standardisation of housing block design, mechanisation of construction methods, use of prefabricated building components, fast track construction resources and monitor construction progress in real-time. Several trials have been conducted on this construction site to test the use of PCMS in live construction training. The focus of this scenario was the integrated training of precast facade installation.

5.1. Visualisation of recorded training for precast facade installation

The purpose of the trial was to visualise both the safety performance and efficiency of workers in training.

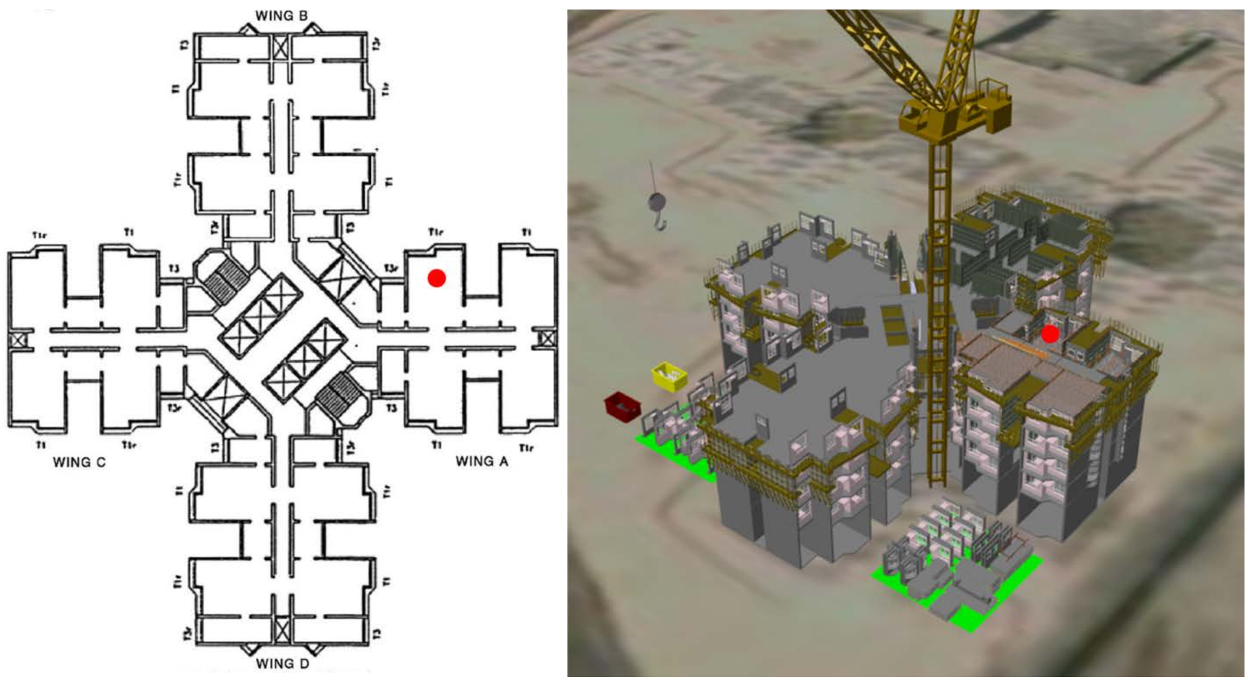

Fig.9. 2D and 3D Construction layout (the red point represents the training area)

Fig.9 shows one of the 2D and 3D field trail in construction site. The trial was conducted in a training area of the 4th floor of Wing A represented as a red point in Fig.9. The training area included a tower crane spanning the entire length of the building, precast facades, wall reinforcements, reinforcement colligation machines, screws, and some auxiliary structures such as inclined temporary bracings, toe brackets, and workers (trainers, trainees and crane operator). The objective was to test the applicability of the system in a compact environment with the goal of providing real-time feedback and visualisation training material to trainers and trainees. After the real-time environment was modelled in Unity3D, spatial-temporal information of the trainees, crane and materials was collected.

Two trainees participated in a training session to place a precast facade and fix the wall reinforcement. The trainees, trainer and a crane hook were all were fitted with tags. Each part of the work zone was covered by at least three anchors during the training period, with the variance in height of at least one anchor ensuring that the 3D trajectory data of the tagged resources (e.g., workers, equipment and materials) could be collected. The precast facade installation sequences were as follows (see Fig.10):

1. A tower crane transported a precast facade from the ground floor to the 4th floor for installation. The system then started timing and real-time tracking the tagged objects.
2. The trainees provided signals for aligning the precast facade to the desired position.
3. One trainee installed the inclined temporary bracing.
4. Another trainee screwed the toe brackets and the inclined temporary bracing.
5. After fixing the precast facade, one trainee released the lifting anchors.
6. Finally, the two trainees collaborated on fixing the wall reinforcement. Data were collected for the entire time of the training session.

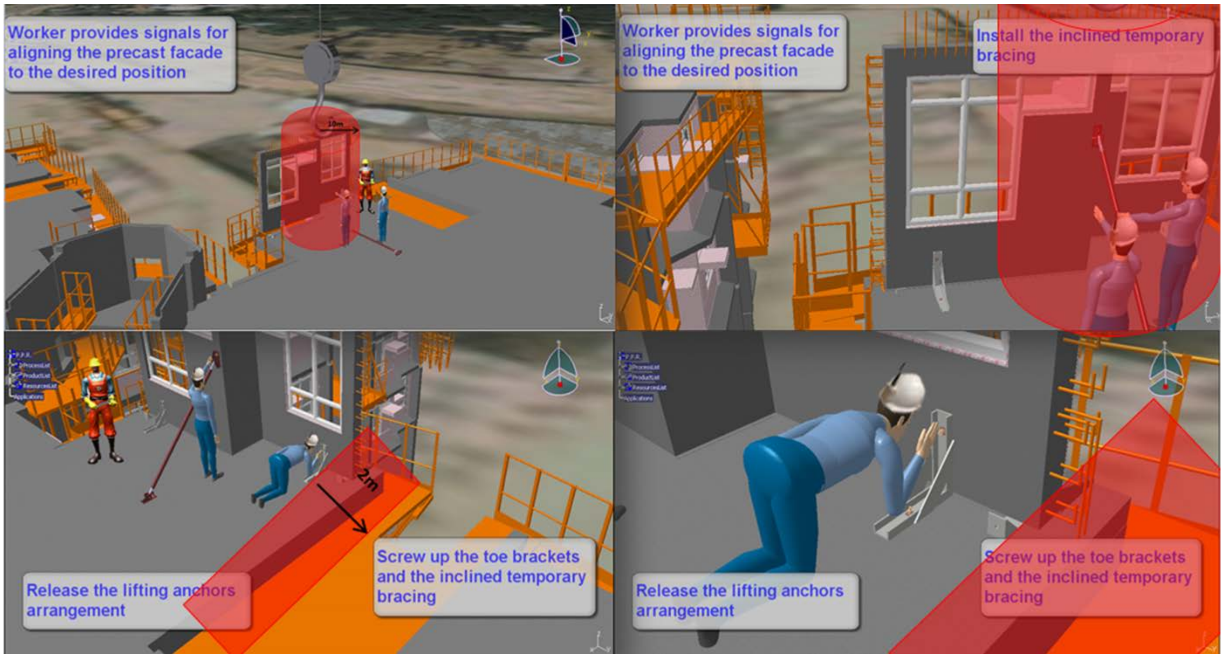

Fig.10. Workflow of precast facade installation

5.1.1. Data visualisation and safety analysis

The potential hazards involved in the training tasks were striking hazards and fall-related hazards. For example, personnel on the ground were passing through the work envelope of a tower crane working at height. The likelihood of being injured or killed by falling objects such as rebar and precast facades.

In this trial, the "safety work envelope" of the tower crane was defined as an 10m radius cylinder and the paths of the two installation worker trainees and crane operator were recorded. If any workers entered the safety work envelope, depending on the distance between the worker and crane hook, they would be warned or alerted three times. The collected data was then analysed to provide the following outputs:

- *The travel speed of the trainees* – for the analysis of work efficiency.
- *The travel path of precast facades* – in posterior-analysis allows a better resource allocation next time a lift conducted.
- *Replay of data* for the trainees instantly or in a later training session to draw trainee's attention to near-misses.
- *Visualisation of hazards or incidents* – allowing workers to be sensitive to hazard locations, type, and time. Also beneficial for pre-planning work tasks during on-site training meetings.
- *Multiple views* – generated to understand the field-of-view of others and gain situational awareness.

Visual training materials related to similar installation tasks were also prepared and provided for the site workers every day to help them understand the potential safety problems involved and practise their skills.

5.1.2. Data visualisation and efficiency analysis

The training task involved activities (non-work and work) of the trainees, materials (transportation of precast facades and wall reinforcement), and trainers (instruction). Assuming a worker's travel velocity is similar to the walking speed of pedestrians at about 1m/s [33], similar or greater speeds (at least 0.6m/s) can account for states of non-work travel time, while a slower speed, in combination with absolute location position over time, implies a constant work position. Fig.11 shows the algorithm of work status identification. If a worker had a speed of less than 0.6 m/s and was also in a work zone, this was defined as a work condition. The work zone was represented as a cluster of more than 30 location points, and about 2m radius around the workers centre location. The short feedback and instruction sessions between trainees and trainer were included in the non-work time. Any idle/waiting time (velocity less than 0.6m/s) in the work zone was ignored to the high intensity of work during training.

In this way, location-based monitoring of construction work efficiency was computed from the amount of time spent in a work zone and workload statistics. Additional inspection, such as by video camera and manual inspection, was used to estimate working completion and validate the work status identification algorithm.

In the trial, ten trainees spent one day placing precast facades and fixing wall reinforcement at the Wing A site, with safety and efficiency performance improving as the day progressed. To illustrate the improvement in working efficiency, a "learning curve" of two trainees was drawn in the safety database in comparison with an accepted equivalent "learning curve" for conventional training (Fig 12). The working time for the precast installation is shown on the vertical axis, with the amount of practicing time on the horizontal axis. As is indicated, working efficiency increased by 34% and 18% for PCMS and traditional training respectively for the same amount of practicing time.

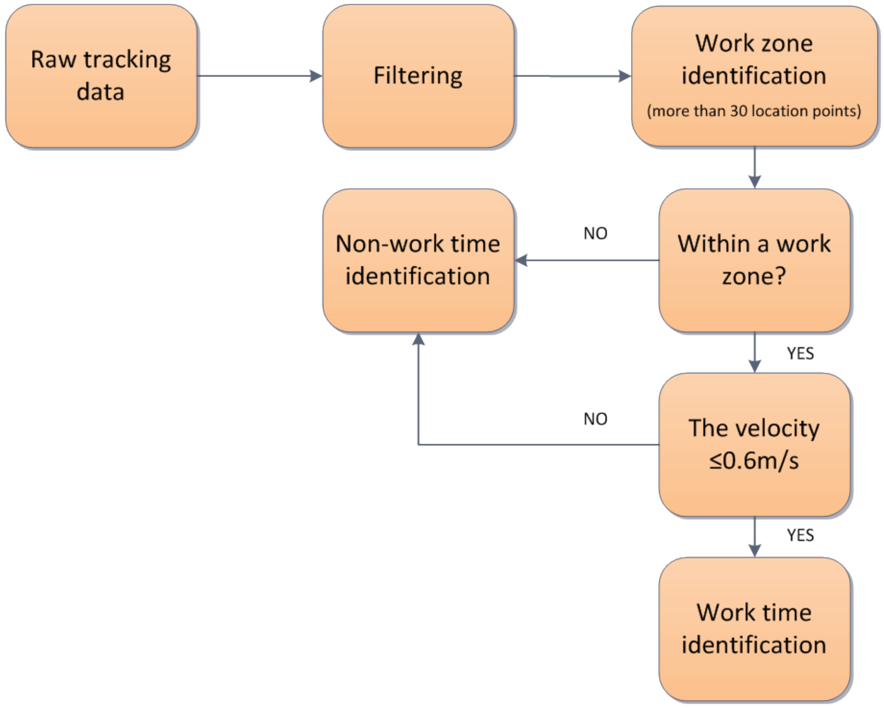

Fig.11. Work status identification algorithm

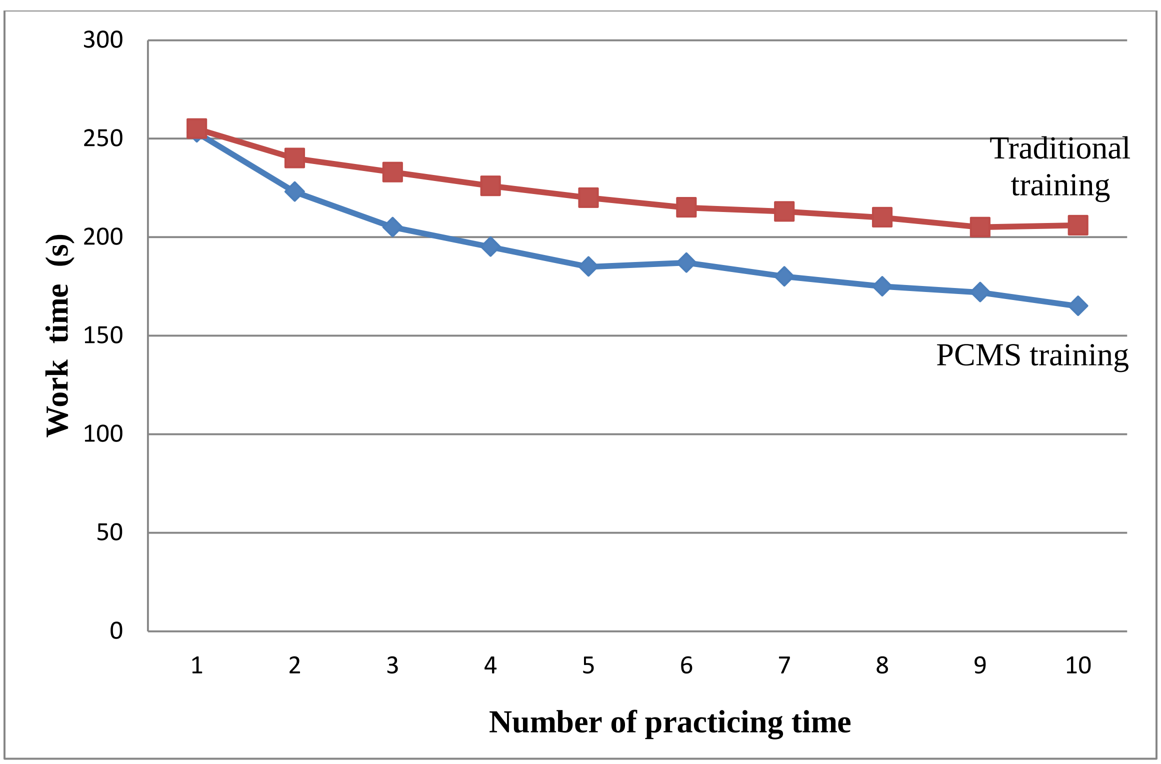

Fig.12. Practicing learning curve

5.1.3 Analysis of feedback from participants

A short questionnaire survey was conducted of the participants using PCMS, with the questions:

- What have been the most hazardous tasks on your jobs so far?
- What has been done before implementation of PCMS to boost construction site safety practices?
- Do you think PCMS can be effectively implemented in practice for safety and efficiency? If not, why?
- Did you feel safer when wearing PCMS tags?
- Did the PCMS devices interfere with your ongoing training activities?
- Would you like to continue to use the PCMS training program in the future?
- What improvements do you think can be made in training for safety and efficiency?

Although the pool of workers was limited, the opinion based feedback on the use of the PCMS training technology was collected and analysed in comparison with traditional training with the following results:

- 75% of participants considered that the real-time warnings or alerts can assist in eliminating risks, especially in hoisting and rigging heavy precast facades.
- 80% of participants thought the PCMS training was more useful than traditional training since it provides a measure of training effectiveness and increases objectivity in assessment and learning competency.
- 20% of participants questioned whether radio frequency (RF) harms their health.
- Some participants felt the tags stuck out too far from their helmets making it easy for the tags to be knocked off. Some also suggested the antenna of anchors and repeaters should be shortened.
- 70% of participants thought PCMS training could help them maintain a high level of engagement as they quickly became familiar with the actual job site layout and work skills needed.
- Some workers (trainees and trainers) believed that safety always clashes with efficiency.

6. Discussion

The benefits of PCMS in construction training for safety and efficiency can be summarised as follows (see Fig.13):

- Faster tracking, through e-tagging of equipment, vehicles and individuals working or visiting the construction site.
- Accurate and up to date position information (one worker five times per second or five workers one time per second) allowing “proactive” warning signals to be sent automatically when the workers or trainees might not be aware of the safety issues in their work or training environment.
- Tamper proof real-time accident and near miss accident reporting and equipment maintenance information – enabling managers to learn how to effectively allocate resources and improve efficiency and safety.

- PCMS's real-time data visualisation can be subsequently used as visualisation training material or act as a quantified benchmark for comparing construction safety and efficiency between different sites.

PCMS limitations are:

- Not all safety hazards relate to just location, thus many unsafe conditions or hazardous behaviours of workers cannot be identified.
- Due to privacy concerns, many workers do not like to be tracked for efficiency.
- The construction environment can affect the CSS signal propagation due to obstacles on site, steel-structures, reaction of workers, etc.
- Real-time data visualisation provides only a limited degree of realism. Augmented reality currently represents the most advanced virtual technology available for construction training in future.

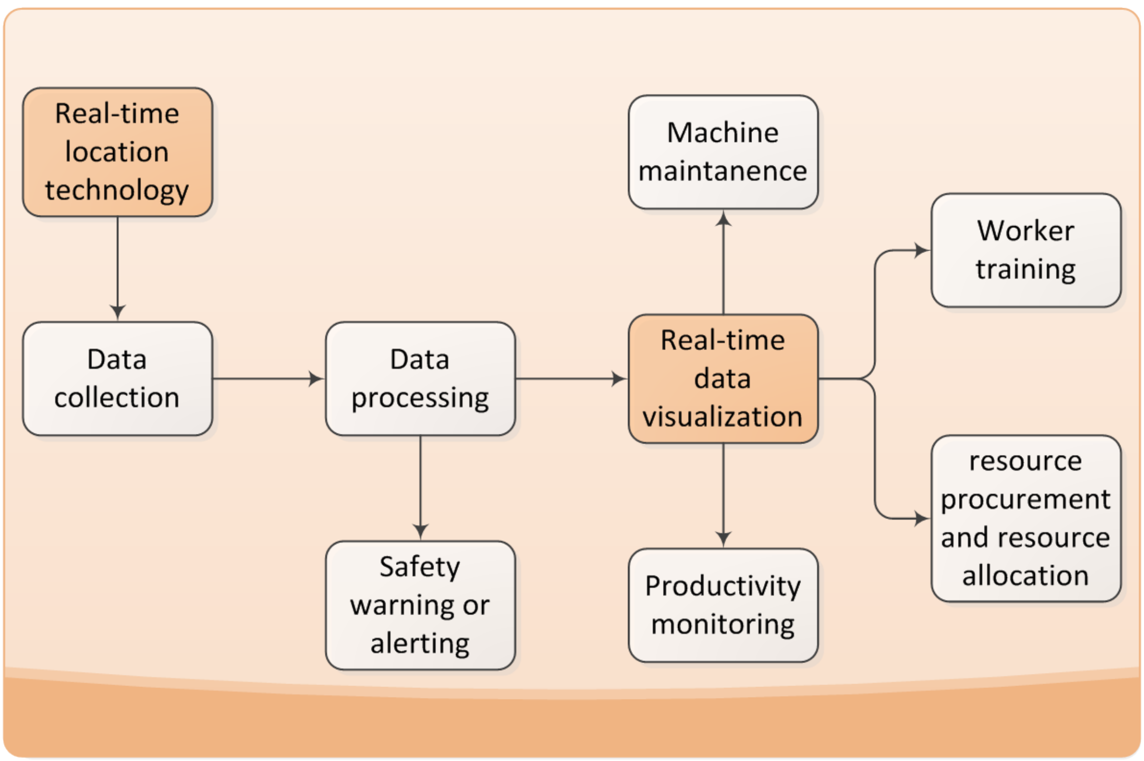

Fig.13. PCMS benefits

7. Conclusion

Current construction worker training practice does not take advantage of the potential of current information technologies to improve safety and efficiency performance, and depends mostly on the expertise and motivation of the trainer. This study proposed an innovative system based on real-time location and data visualisation technologies to effectively train novices with minimised hazards and high efficiency. Its effectiveness has been shown in several ways: hazards were detected and timely proactive warnings provided to avoid accidents; training was visualised vividly and assessed quantitatively; real-time or post-event feedback helped workers change their risky behaviours and improve the training program; the data from the construction training environment can be streamed and visualised at any time, which can be used to resolve the same or similar tasks later in the live construction environment and give the trainees immersive experience; and flexibility to provide training minimizing interfering with work on-site.

Although the system has been developed for the specific industrial conditions found on the Hong Kong construction sector, it has the potential for wider use in rest of the world, since many of the issued faced are similar in other countries. For example, many countries have a workforce shortage and new recruits with poor techniques and little working qualifications – making properly trained and skilled construction workers in big demand.

Because of the limitations of the construction site involved in the trial, only a relatively short and small-scale application was tested. Future larger scale trials with a longer application period would help provide a more realistic verification of the capacity of the system. Also needed is further research concerning: the return on investment for PCMS training, deployment of reliable and cost-effective real-time location technology, long-time testing of recurring safety and efficiency issues on different construction sites and reward systems for safe and efficient performance.

References

[1] Hong Kong Special Administrative Region, Labour Department, Occupational safety and health statistics 2011, www. labour. gov. hk/eng/osh/pdf/OSH_Statistic2011. pdf. (2012).

[2] J. Tuchman, Owners join effort to improve industry productivity, Engineering News Record. (2009) http://enr.construction.com/policy/associations/2009/1202-ownersproductivity.asp.

[3] S.P. Mead, Developing benchmarks for construction information flows, Journal of Construction Education. 6 (2001) 155-166.

[4] S. Bowden, A. Thorpe, Mobile communications for on-site collaboration, Proceedings of the ICE – Civil Engineering. 150 (2002) 38-44.

[5] X. Wang, P.S. Dunston, Design, strategies, and issues towards an augmented reality-based construction training platform, ITcon. 12 (2007) 363-380.

[6] J. Teizer, T. Cheng, Y. Fang, Location tracking and data visualization technology to advance construction ironworkers' education and training in safety and productivity, Automation in Construction. 35 (2013) 53-68. DOI: 10.1016/j.autcon.2013.03.004.

[7] D.K. Rubin, CII study shows craft training can generate big cost impact, Engineering News Record. (2007) http://enr.construction.com/news/finance/archives/070815b.asp.

[8] I.M. Srour, C.T. Haas, J.D. Borcherding, What does the construction industry value in its workers? Journal of Construction Engineering and Management. 132 (10) (2006) 1053-1058.

[9] C.J. Clements, B.M. Josiam, Training: quantifying the financial benefits, International Journal of Contemporary Hospitality Management. 7 (1995) 10-15.

[10] E. Ergen, B. Akinci, R. Sacks, Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS, Automation in Construction. 16 (3) (2007) 354-367. DOI: 10.1016/j.autcon.2006.07.004.

[11] J. Song, C.T. Haas, C.H. Caldas, Tracking the location of materials on construction job sites, Journal of Construction Engineering and Management. 132 (9) (2006) 911-918.

[12] M. Cheng, J. Chen, Integrating barcode and GIS for monitoring construction progress, Automation in Construction. 11 (1) (2002) 23-33. DOI: 10.1016/S0926-5805(01)00043-7.

[13] M. Cheng, C. Ko, C. Chang, Computer-aided DSS for safety monitoring of geotechnical construction, Automation in Construction. 11 (4) (2002) 375-390. DOI: 10.1016/S0926-5805(01)00059-0.

[14] R.J. Fontana, S.J. Gunderson, Ultra-wideband precision asset location system, Ultra Wideband Systems and Technologies, 2002 IEEE Conference on. (2002) 147-150. DOI: 10.1109/UWBST.2002.1006336

[15] H.M. Khoury, V.R. Kamat, Evaluation of position tracking technologies for user localization in indoor construction environments, Automation in Construction. 18 (4) (2009) 444-457. DOI: 10.1016/j.autcon.2008.10.011.

[16] A. Carbonari, A. Giretti, B. Naticchia, A proactive system for real-time safety management in construction sites, Automation in Construction. 20 (6) (2011) 686-698. DOI: 10.1016/j.autcon.2011.04.019.

[17] M. Modsching, R. Kramer, K. ten Hagen, Field trial on GPS Accuracy in a medium size city: The influence of built-up, 3rd Workshop on Positioning, Navigation and Communication 2006 (WPNC'06), Hannover. (2006) 209-218.

[18] C.H. Caldas, D.G. Torrent, C.T. Haas, Using global positioning system to improve materials-locating processes on industrial projects, Journal of Construction Engineering and Management. 132 (7) (2006) 741-749.

[19] Z. Riaz, D. Edwards, A. Thorpe, SightSafety: a hybrid information and communication technology system for reducing vehicle/pedestrian collisions, Automation in Construction. 15 (6) (2006) 719-728. DOI: 10.1016/j.autcon.2005.09.004.

[19a] H.M. Khoury, V.R. Kamat, Evaluation of position tracking technologies for user localization in indoor construction environments, Automation in Construction. 18 (4) (2009) 444-457. DOI: 10.1016/j.autcon.2008.10.011.

[20] S.N. Razavi, O. Moselhi, GPS-less indoor construction location sensing, Automation in Construction. 28 (2012) 128-136. DOI: 10.1016/j.autcon.2012.05.015.

[21] U. Lee, J. Kim, H. Cho, K. Kang, Development of a mobile safety monitoring system for construction sites, Automation in Construction. 18 (3) (2009) 258-264. DOI: 10.1016/j.autcon.2008.08.002.

[22] M.R. Hallowell, J. Teizer, W. Blaney, Application of Sensing Technology to Safety Management, Construction Research Congress. (2010) 31-40. DOI: 10.1061/41109(373)4.

[23] H.L. Guo, H. Li, V. Li, VP-based safety management in large-scale construction projects: A conceptual framework, Automation in Construction. 34 (2013) 16-24. DOI: 10.1016/j.autcon.2012.10.013.

[24] H. Li, Z. Ma, Q. Shen, S. Kong, Virtual experiment of innovative construction operations, Automation in Construction. 12 (5) (2003) 561-575. DOI: 10.1016/S0926-5805(03)00019-0.

[25] T. Cheng, J. Teizer, Real-time resource location data collection and visualization technology for construction safety and activity monitoring applications, Automation in Construction. 34 (2013) 3-15. DOI: 10.1016/j.autcon.2012.10.017.

[26] R.J. Seidel, P.R. Chatelier, Virtual Reality, Training's Future?: Perspectives on Virtual Reality and Related Emerging Technologies, Springer. 1997.

[27] R. Sacks, A. Perlman, R. Barak, Construction safety training using immersive virtual reality, Construction Management and Economics. 31 (9) (2013) 1005-1017. DOI: 10.1080/01446193.2013.828844

[28] J. Kim, J. Kang, D. Kim, Y. Ko, J. Kim, IEEE 802.15. 4a CSS-based localization system for wireless sensor networks, 2007 IEEE International Conference on Mobile Adhoc and Sensor Systems, MASS. 8 (2007) 1-3.

[29] H. Lee, K. Lee, M. Park, Y. Baek, S. Lee, RFID-Based Real-Time Locating System for Construction Safety Management, Journal of Computing in Civil Engineering. 26 (3) (2011) 366-377.

[30] Y.K. Cho, J.H. Youn, D. Martinez, Error modeling for an untethered ultra-wideband system for construction indoor asset tracking, Automation in Construction. 19 (1) (2010) 43-54. DOI: 10.1016/j.autcon.2009.08.001.

[31] T. Cheng, M. Venugopal, J. Teizer, P. Vela, Performance evaluation of ultra wideband technology for construction resource location tracking in harsh environments, Automation in Construction. 20 (8) (2011) 1173-1184. DOI: 10.1016/j.autcon.2011.05.001.

[32] A.H. Behzadan, Z. Aziz, C.J. Anumba, V.R. Kamat, Ubiquitous location tracking for context-specific information delivery on construction sites, Automation in Construction. 17 (6) (2008) 737-748. DOI: 10.1016/j.autcon.2008.02.002.

[33] R.L. Knoblauch, M.T. Pietrucha, M. Nitzburg, Field studies of pedestrian walking speed and start-up time, Transportation Research Record: Journal of the Transportation Research Board. 1538 (1996) 27-38.