Intrusion warning and assessment method for site safety enhancement

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Published in:
Safety Science

DOI:
10.1016/j.ssci.2015.12.004

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Abstract:

Intrusion (unauthorized stepping-into/staying-in a hazardous area), as a common type of near-miss, is the prime cause of many incidents on construction sites including those involving falling from a height and striking against or being struck by moving objects. Accidents often occur because workers take shortcuts in moving about the site without perceiving the potential dangers involved. A great deal of research has been devoted to developing methods for preventing such behavior, mainly based on the theory of Behavior-Based Safety (BBS), which aims to regulate the safety behavior of workers according to safety regulations. In current BBS practice, trained observers or safety supervisors are responsible for safety behavior inspections based on safety plans and operation regulations. This observation process is time-consuming and its effectiveness depends largely on the observer's safety knowledge and experience, which often results in omissions or bias. Combining computer-based automatic tracking techniques with BBS has the potential to overcome these limitations and greatly enhance the benefits of BBS.

This paper presents such an approach by integrating a location-based technology with BBS. A detailed background is provided, describing intrusion problems on site, the existing use of BBS for behavior improvement, difficulties in achieving widespread adoption and potential technologies for location tracking and in-time feedback. A conceptual framework of positioning technology-enhanced BBS is then developed, followed by details of an on-line supporting system, Real Time Location System (RTLS) and Virtual Construction System (VCS). The application of the system is then demonstrated and tested on a live construction site in Hong Kong. Final comments concern further research work needed and prospects for extension to other situations involving safety considerations.

***Key words*:** intrusion behavior; positioning technology; behavior-based safety; assessment.

1. Introduction

Construction is a pillar industry in Hong Kong. It is also recognized as one of the major high-risk industries worldwide (Jannadi and Bu-Khamsin, 2002). Near-miss intrusion (unauthorized stepping-into/staying-in a hazardous area) on construction sites can lead to process disturbance (Winsemius, 1965). This is closely connected with many critical issues of safety (Swuste et al., 2014), such as falling from a height (Zhou et al., 2012), striking against or being struck by moving objects (Shapira et al., 2012) like a moving vehicle (Hinze and Teizer, 2011). In part, the intrusion is evoked by the convenience of taking shortcuts in moving about the site and when workers do not appreciate the field-of-view of others (Teizer et al., 2013). In Hong Kong, this situation has become more serious as increased labor shortages in recent years (Hong Kong Census and Statistics Department, 2005-2014) have forced construction companies to employ elderly people or people with little relevant work experience (Hong Kong Census and Statistics Department, 2011).

In Hong Kong, to prevent intrusion and improve safety performance, researchers and safety managers have put their endeavor in the following two aspects: 1) enhancing safety management and enriching protective measures, and 2) providing more safety trainings. The prevailing Green Card Program is organized by the Occupational Safety & Health Training Center for mandatory safety training courses. Construction workers are obligated to take the courses and pass the written exams before they are qualified to work on construction sites. What's more, warning signs and posters have always been indispensable in safety management. As shown by statistics from Labor Department (2004-2013), the input in safety training has resulted in a sharp decrease of construction accidents during 2000 to 2004, which proves that safety training is an effective way for accident prevention (Dong et al., 2004). But after 2004, the consistent safety training expenditure failed to significantly lower the accident rate, which reveals the effectiveness of traditional safety training has reached a bottle neck.

Behavior-Based Safety (BBS) offers a potential means of improving the situation as it has impressed safety researchers with its efficiency in modifying personal safety behavior (Krause et al., 1999b) and has been successfully implemented in many fields (Depasquale and Geller, 1999). However, the method has several drawbacks for use in the construction industry: 1) it relies on well trained and highly experienced safety observers, 2) subjective observations or surveys are needed that result in omissions or biases, and 3) being an outcome-based group level assessment method delays feedback unduly.

Positioning technologies are recently receiving attention because they have the potential to foster better safety and productivity by tracking construction resources (labor, equipment, materials, etc.) anywhere and anytime (Torrent and Caldas, 2009, Ergen et al., 2007, Cheng et al., 2011). This paper is somewhat a development of Giretti et al. (2009), in which a real time location system for safety-related behavior monitoring and warning is presented. Giretti et al. proved the effectiveness of their tracking system in monitoring unsafe behaviors, but left questions like how workers respond to warnings and how to improve their behaviors to be answered. Combining BBS and positioning technologies may therefore provide the solution needed and hence the goal of this paper is to investigate the novel prospect of a positioning technology-enhanced BBS automatically assessing personal safety performance and providing feedback sufficiently and quickly to prevent accidents occurring. In doing this, the idea is developed in the context of intrusion on a worksite. The on-line system has the primary functions of tracking stationary or moving workers and danger sources, sending out warning signals and assessing intrusion behavior. The locations of several targeted workers and danger sources are tracked in real-time and intrusion warnings are triggered automatically when workers are too close to danger sources. The warnings and worker responses are recorded for use in analyzing individual worker safety and providing timely feedback. Intrusion behavior and responses are visualized using a virtual reality (VR) technology for real-time and post-event visualization.

The paper is organized as follows. First a detailed background is provided, describing intrusion problems on site, the existing use of BBS for behavior improvement, difficulties in achieving widespread adoption and potential technologies for location tracking and in-time feedback. A conceptual framework of a positioning technology-enhanced BBS is then developed, followed by details of the on-line supporting system, Real Time Location System (RTLS) and Virtual Construction System (VCS). The application of the system is then demonstrated and verified on a live construction site in Hong Kong. Final comments are provided concerning further research work needed and prospects for extension to other situations involving safety considerations.

2. Background

2.1 Intrusion Problems on Site

A near-miss, identified as a special kind of accident precursor, is defined as an event in which no damage or injury actually occurs but, under slightly different circumstances, could have resulted in harm (Phimister et al., 2004). It is widely accepted that reported accidents on construction sites are just the tip of the iceberg, with the very large number of near-misses that occur resembling the portion of under-water surface (Wu et al., 2010). This is also supported by the estimation that90.9% of all accidents produce no injuries, while 8.8% result in minor injuries and only 0.3% cause major injuries (Heinrich et al., 1950). The estimation remains accurate in the construction industry in recent times as Hubbard and Neil observed that major accidents comprise only 3% of the total, giving an accident ratio of 1 major to every 32 minor accidents (Hubbard and Neil, 1986). For construction work, an unauthorized presence in a hazardous area - termed an *intrusion* in this study - represents a very common near-miss. It is the major cause of process disturbance (Swuste et al., 2014) and leads to many critical safety issues such as falling from height (Zhou et al., 2012), electric shocks and being struck by working equipment (Wu et al., 2010). It not only causes the unauthorized intruder to suffer from an accident such as that of falling from height (Zhou et al., 2012), but also can interrupt or hurt workers in the danger zone.

As illustrated in the theory of task dynamics (Winsemius, 1965), intrusion behavior is an individual's assessment of risk vs. time and/or convenience. If having a faster way of proceeding seems to be only slightly risker than following a safe path that is slightly longer, the extra risk is more likely to be accepted and the quicker route taken. The extra risk is also more likely to be underestimated. For example, in the virtual training system program conducted by Teizer et al. (2013), a rigger underestimated the risk and walked below the work space of a connector with a high risk of being struck by falling materials, demonstrating that workers often underestimate the dangers in working areas other than their own. This also leads to failing visibility and other misperceptions of dangers on site (Hinze and Teizer, 2011).

Intrusion is often neglected because current assessment is mainly focused on visible outcomes such as critical injuries and accidents, and it is hard to identify near-misses in time (SWA, 2013). Intrusion records are mainly kept by self-reporting, which is inhibited by a blame culture for error, time-consuming paperwork, and lack of feedback on how the information reported has been used (Van Der Schaaf and Kanse, 2004). To solve these problems, current activities mainly involve modifying behavior through safety regulations and training (Kaskutas et al., 2013) and improving safety attitude through better organizational safety culture (Fung et al., 2012). These methods are useful but do have disadvantageous such as:

1) being unable to remedy the limitations of human vision and ability to detect all surrounding danger sources;

2) largely relying on wandering inspection and lagged (outcome) measurement, which fails to provide feedback to change unsafe behaviors in time.

Undoubtedly, near misses provide insights into possible accidents and present a significant opportunity to further improve safety margins. Monitoring the factors involved and tracking their interactions based on real-time information on construction sites could be used to obtain near-miss data (Cambraia et al., 2010). It is possible to significantly improve safety by learning from previous near misses and tracking them in real time in order to take appropriate action prior to an accident (Wu et al., 2010). Grabowski et al. (2007) also confirm that recognizing alerts and signals before an accident clearly offers a potential for improving safety. However, little research has been done in both autonomous data requirement analysis of near misses on construction sites or technological solutions to track near misses based on real-time information.

2.2 Existing BBS and Behavior Improvement

BBS is an application of behavior analysis in safety management. This safety management method is distinguished from traditional ones in terms of the effectiveness of improving the safety behavior of workers (Zhang and Fang, 2012). BBS is an approach aimed at intervening and modifying human hazardous behavior (Geller, 1999) where primary attention is directed at specific safety-related behaviors that are, typically, performed by workers (Krause et al., 1984). It refers to the systematic application of psychological research into human behavior and an analytical or data-driven approach to identifying and changing critical behaviors (Choudhry et al., 2007). Usually the approach takes personal characteristics (Lai et al., 2011), compliance, participation (Dearmond et al., 2011), awareness (Arboleda and Abraham, 2004), ability (Han and Lee, 2013) and caring attitude (Siu et al., 2004) into consideration. BBS is a rigorous behavior focal system containing goal setting, training, observation, assessment and behavior modification, and effective safety performance measurement is of profound significance (Choudhry, 2014).

BBS was first used in 1978 for improving safety performance during the food manufacturing process in USA (Komaki et al., 1978). DePasquale and Geller (2000) report several successful applications of BBS in driving practice, such as in increasing safety-belt use (Kello et al., 1988, Geller, 1984, Geller and Hahn, 1984), turn-signal use, intersection stopping (Ludwig and Geller, 1991, Ludwig and Geller, 1997) and reducing driving speed (Houten and Nau, 1983). In addition to traffic management, BBS has been successfully implemented in various industries, such as the petroleum (Zohar and Luria, 2003), manufacturing (Ray et al., 1997) and nuclear power industries (Cox et al., 2004). Krause et al. (1999a) report an average of 20% to 25% year-on-year reduction in injuries and costs due to the implementation of BBS.

In the construction industry, multiple case studies have been conducted into the various functions of BBS in many countries (Table 1), such as in reducing incidents, enhancing safety commitment and improving personal behavior. In China, the adoption of BBS into one construction enterprise's safety practices produced a remarkable 15% improvement in overall safety performance (Chen and Tian, 2012), which clearly indicates the potential effectiveness and adaptability of the BBS approach to construction safety in China.

Table 1. BBS functions in the literature

	Incident Reduction	Personal Behavior at Work	Safety Commitment/ Responsibility	Safety Communication/ Feedback	Safety Participation / Attitudes	Safety Training/ Knowledge	Site Condition
(Lingard and Rowlinson, 1997)							*
(Lingard and Rowlinson, 1998b)							*
(Krause et al., 1999b)	*						
(Quintana, 1999)	*		*	*			
(Al-Hemoud and Al-Asfoor, 2006)	*					*	*
(Wiegand, 2007)	*	*			*		
(Vaughen et al., 2010)				*	*	*	
(Kaila, 2011)	*	*	*	*			
(Lees and Austin, 2011)	*	*				*	*
(Choudhry, 2012)			*		*		
(Galloway, 2013)	*	*			*	*	
(Zhang and Fang, 2013)	*	*	*			*	

2.3 Difficulties in Achieving Widespread Adoption

Despite many successful applications, BBS has always faced critical difficulties in the construction field. Many other researchers, such as Lingard and Rowlinson (1998a), have investigated the use of BBS in the Hong Kong construction industry. In their nine-month study, four different areas were investigated: housekeeping, access to height, bamboo scaffolding and personal protective equipment, finding that BBS was not universally effective, with only the 'housekeeping' category being effective while the other categories failed to show any significant improvement. Although many factors may affect the outcome of BBS, the difficulty is largely attributed to inaccurate assessment and inefficient inspection. Occupational health and safety (OHS) has traditionally been measured by outcomes such as accidents, injuries, illnesses and diseases (Arezes and Miguel, 2003). This lagged measurement still prevails in many industries since it is relatively easy to collect data, easily understood, objective and valid (Lingard et al., 2011). However, these "after the fact" indicators limit the opportunity for prevention and correction in time. As a result, these retrospective indicators are not an accurate representation of construction worker safety.

As human behavior is the key factor leading to accidents ((HSE), 2002), many researches treat safety issues in a more proactive way (Blewett, 1994, Council, 2005, Wales, 2001). These personal performance indicators are derived from hazardous behavior during work time and involve safety compliance as well as supporting participation. Safety compliance indicators refer to following the safety regulations and plans, which constitute a key part of the BBS methodology.

Safety performance in BBS is calculated by the percentage of safe behavior of all observed behavior (Choudhry, 2012). This percentage can provide a good reflection of safety at the group or project level, but conceals personal/individual safety. The lack of personal level assessment compromises BBS's ability to improve everyone's safety behavior. Furthermore, the observed behavior is judged by "all or nothing" normality (Wiegand, 2007) and cannot reveal the whole process involved in the behavior.

Another issue concerns the inefficiency of behavior inspection in safety management. With current practice, trained observers or safety supervisors are responsible for safety behavior inspection based on safety plans and operation regulations (Zhang and Fang, 2013). This time-consuming activity largely depends on the supervisor's safety knowledge and experience, which often results in omissions or biases.

In general, therefore, mass application of existing BBS is not possible for construction work as it mainly applies post-mortem analysis at the group or project level due to the lack of a means of quickly and objectively collecting real-life behavioral data from sites.

2.4 Positional Technologies for Location Tracking and In-time Feedback

Following their successful application in manufacturing (Brewer et al., 1999) and traffic management (Wang et al., 2004), a wide range of positioning technologies have become available with the potential for improving on-site management (Carbonari et al., 2011). Of these are Radio Frequency Identification Devices (RFID), Laser Detection and Ranging (LADAR), Vision Cameras (VC), Audio Technology, Radio Detection and Ranging (RADAR), Global Positioning Systems (GPS), Ultra Wide Band (UWB), and infrared heat and magnetic sensors (Teizer et al., 2008). Many popular technologies are able to solve problems in material flows, equipment usage and movement. For example, Grau et al. (2009) compare the automated identification and localization of engineered components with traditional manual methods on industrial sites and demonstrate significant productivity gains. Yang et al. (2012) also illustrate the use of surveillance cameras and discrete-state inference algorithms for assessing tower crane activities during the course of a workday.

In terms of safety management, the identification of accident precursors, training and inspection are three main aspects involved in improving safety behavior. For instance, Teizer et al. (2008) record the movement of workers by UWB and use a combination of convex hull and shortest path algorithms to identify obstacles and dangers according to the frequency with which workers cross their path. They then use emerging radio frequency (RF) remote sensing and actuating technology to improve construction safety by pro-active real-time warning workers-on-foot and plant operatives when they become too close to each other (Teizer et al., 2010). Carbonari et al. (2011) have also established a new advanced hardware/software system to perform real time tracking of workers' routes and prevent workers being in hazardous situations by a virtual fencing tool. For education and training, Teizer et al. (2013) integrate real-time location tracking and three-dimensional immersive data visualization technologies to train and assess the operations of steel-erection tasks.

However, the success of these methods is often comprised by poor accuracy, high cost, complex deployment and lacking validation by on site case studies. For example, the commonly used wireless devices for obstacle avoidance require tags (small hardware devices designed to be mounted on helmets and moving objects) on every individual resource on a site (human, material, and equipment), which is vulnerable to unforeseen events involving mistakenly untagged resources (Teizer et al., 2007). Failures also derive from limited signal strength through obstructions, the unavailability of GPS satellites or losing contact with a base station to determine precise locations, the high cost of tags, etc (Teizer et al., 2010). At the same time, the dynamic and evolving environments of construction projects require further amendments to the technologies trialed in the laboratory (Carbonari et al., 2011). Moreover, although monitoring materials is largely considered to be adequate, continuously monitoring labor is less so (Navon and Sacks, 2007) and more effective approaches are urgently needed (Teizer et al., 2008).

3. The Proactive Intrusion Management Method

3.1 Positioning Technology-enhanced BBS methodology

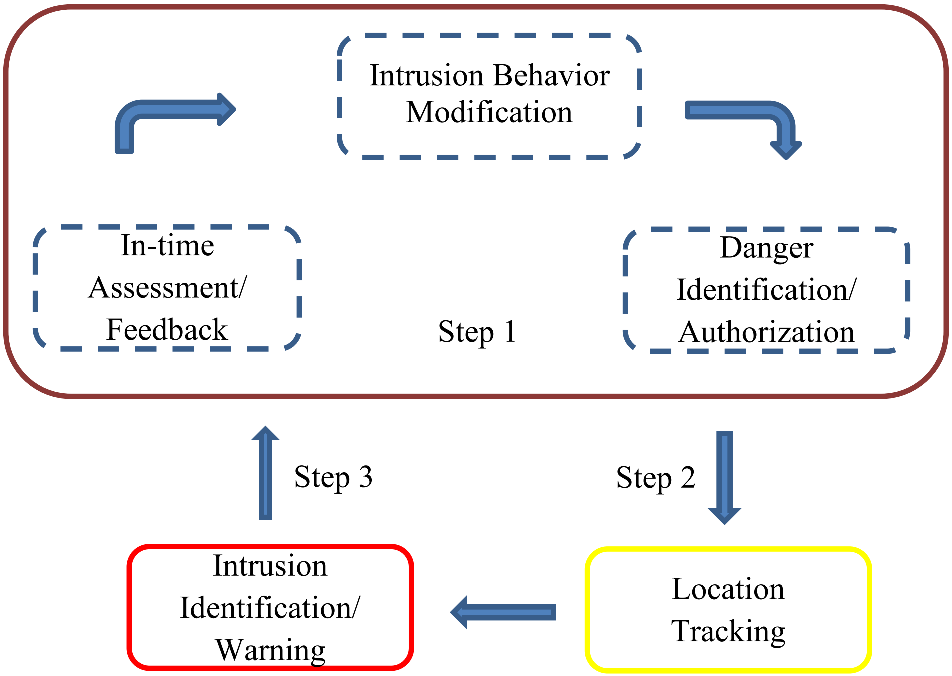


Fig. 1. The conceptual framework of positioning technology-enhanced BBS

Figure 1 contains the conceptual framework of a positioning technology-enhanced BBS developed according to the classic four-phase BBS implementation process (Cox and Vassie, 1999) and Supervisory-Based Intervention Cycle (Zhang and Fang, 2013), This enhanced BBS follows a top-down mechanism, which needs the project manager or safety officer to lead the cycle. At the beginning of the cycle, both danger zones and working zones are identified based on a full discussion with experienced project managers and safety officers such that:

$$F \triangleq \{(x_1, x_2, x_3) \in R^3 | \cap_{i=1}^{m} N_i X \leq n_i\}; \qquad X = (x_1, x_2, x_3),\ i = 1,2, \dots, m \quad (1)$$

$$W \triangleq \{(x'_1, x'_2, x'_3) \in R^3 \big| \cap_{j=1}^{n} N'_j \leq j\} \qquad (x'_1, x'_2, x'_3),\ j = 1,2, \dots, n \quad (2)$$

$$\varphi(X) = \begin{cases} 1; & X' \in F \\ 0; & else \end{cases} \quad (3)$$

where (x_1, x_2, x_3) are the coordinates of points in the danger zone, while (x'_1, x'_2, x'_3) are the coordinates of points in the working zone. Whether or not the worker is permitted to stay in danger zone is judged by comparing X with X' shown in $\varphi(X)$. In function (1) and function (2), both danger and working zones can be designed as a space, a plane, a line or a dot.

The common danger zones can be divided into two categories: 1) static zones related to, but not limited to, floor holes, unprotected sides, and wall openings; 2) dynamic zones are primarily related to on-site heavy plant, including tower cranes, moving cranes, excavators, bull dozers, etc. Workers are informed through training of both the danger zones and authorized working zones. This training can be used to improve safety by directing attention to intrusion prevention.

In the inspection and assessment phase, traditional manual observations and subjective judgments are substituted by automated intrusion warning and response assessment:

$$g(Y, t) = \begin{cases} 1; & Y \in F, \varphi(\mathrm{Y}) = 0 \\ 0; & else \end{cases} \quad (4)$$

where the worker's real-time location Y is tracked by positioning technology and recorded in a database. If an unauthorized worker ($\varphi(\mathrm{Y}) = 0$) enters a danger zone ($Y \in F$), an intrusion warning rings out as in-time feedback to workers. After the intrusion warning, the unqualified behavior is identified by:

$$g(Z, t + \Delta t) = \begin{cases} 1; & Z \in F, G(Y, t) = 1 \\ 0; & else \end{cases} \quad (5)$$

where Δt denotes the response time after the warning. In this phase, there are two kinds of corresponding activities: a) if the worker leaves the danger zone ($Z \notin F$), this behavior is recognized as a safe response; but b) if the worker is still located in the danger zone ($Z \in F$), the unsafe response is regarded as a regulation violation.

The warnings, time and coordinates are collected and recorded for further statistical analysis including intrusions at different times, intrusions by different workers, and intrusions into different danger zones. Formal feedback and interventions regarding these outcomes are provided to workers to modify their intrusion behaviors, and are also provided to safety managers as a reference to goal setting in the next round. The safety performance measured in different rounds can be compared both at the individual and group level to judge whether the intrusion behaviors have been effectively modified.

3.2 On-line Supporting System

This multi-user on-line supporting system, which is named the Proactive Safety Management System (PSMS), comprises two parts: a Real Time Location System (RTLS) and Virtual Construction System (VCS). The RTLS applies tags and reference anchors (receivers fixed at static positions as reference points) in detecting and sending information through wireless signals. The VCS, on the other hand, is responsible for measuring the relative 3D positions of workers and their surrounding danger sources/zones, and recording the real-time 3D movements of workers and moving plant. If deemed necessary by the PSMS, warnings are sent to alert workers through tags installed on their helmets. In order to access the latest virtual construction models in a convenient and timely manner, the PSMS adopts the typical three-tier web-based application structure illustrated in Figure 2 composed of a presentation layer, business layer and data layer.

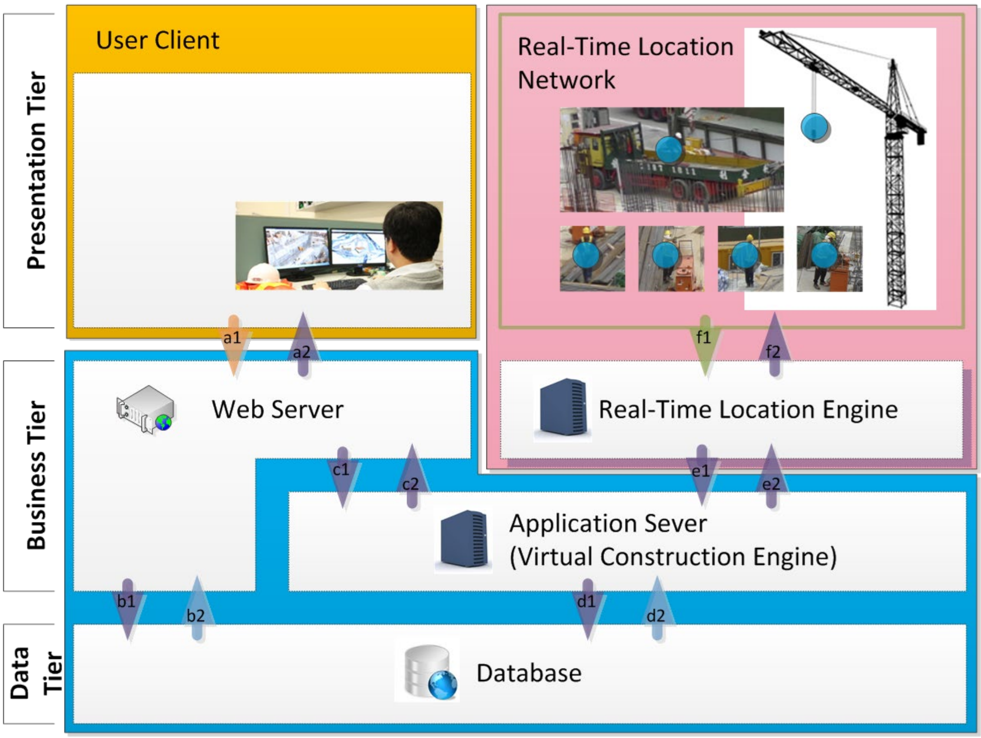


Fig. 2. Three-layer system architecture

The real time location network is the most important part of the RTLS, involving a ranging and real time location engine for recording and calculations involving the associated tags and anchors. In order to be applied in construction work, the tracking technology should meet criteria in terms of cost and maintenance, device form factors, scalability, data update rates, and social impact (Cheng et al., 2011). As a result, many positioning technologies have been investigated and Chirp Spread Spectrum (CSS) technology is employed for ranging, which estimates the physical distance between two devices by the Time of Flight (TOF) of radio frequency signals. CSS is a spread spectrum technique defined in the standard IEEE 802. 15. 4a (Cho and Kim, 2010) and uses wideband linear frequency modulated chirp pulses to encode information which is relatively less time-consuming, robust against disturbances and multipath fading, uses low power consumption and is easy to implement in silicon (Nanotron Technologies, 2014).

To enable site managers to monitor intrusion behavior comprehensively and timely, virtual construction technology is integrated with RTLS as a location-based virtual construction system that allows immediate synchronization between virtual building models and realistic construction situations. This location-based virtual construction system is realized with the help of a location engine, SmartFoxServer and Unity as shown in Figure 3.

The location engine is named the PSMS Site and programmed to calculate the position of the tags and then send the position information to the application server. It is also responsible for relaying danger-warning signals to the location network as a sound or vibration trigger. The danger is identified by comparing the coordinates of the tags with those in the danger zones marked in the 3D model – a process programed according to the Java.awt.geom and Polygon2D algorithms. The danger zones are marked in a virtual model and the coordinates are called by the application server from the database.

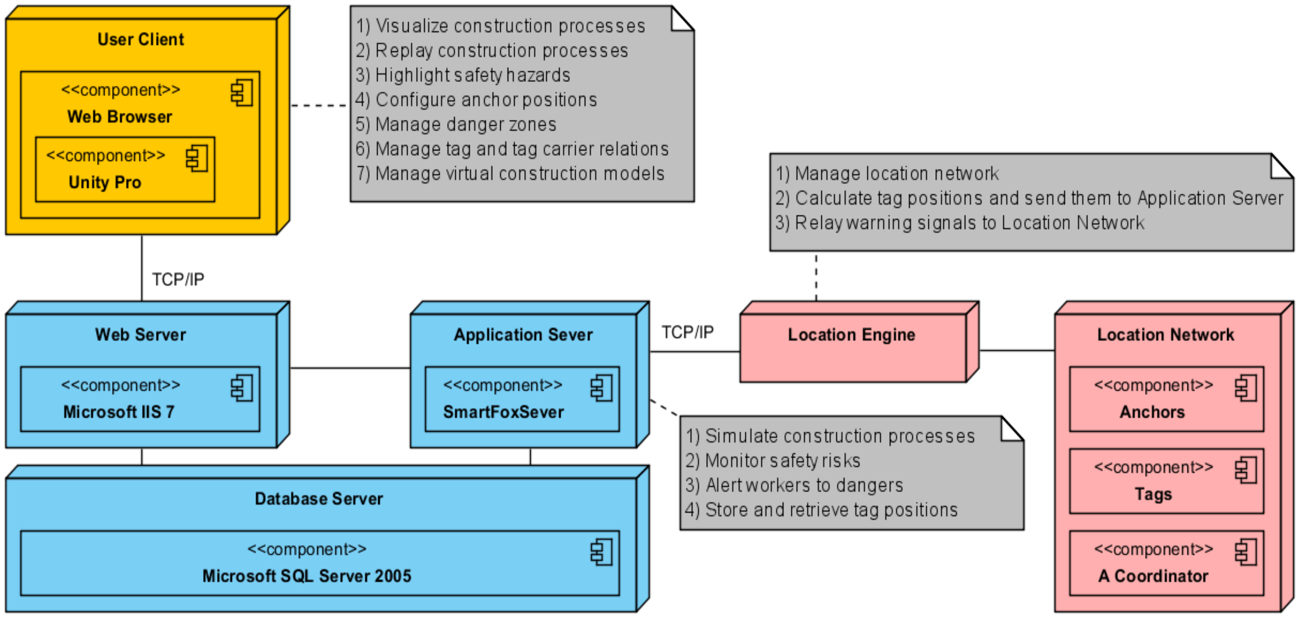


Fig. 3. System deployment

All the programs are developed on a SmartFoxServer, which is a massive multiplayer game server providing a comprehensive platform for the rapid development of multi-user applications and games with mainstream programming technologies. To be a multi-user system, a Server Object Extension is also developed in an application server to drive and synchronize all the User Clients in terms of real construction situations. The User Client is built by Unity for visualizing construction progress, defining static and dynamic dangers, as an integrated authoring tool for creating 3D video games or other interactive content such as architectural visualizations or real-time 3D animations.

The connection and information transfers between the network and location engine on the computer are carried out by a NanoLOC TRX transceiver, which is based on CSS and is the only wireless device using CSS with real time location and RFID abilities (Nanotron Technologies, 2014).

4. Site Trial and Analysis of Results

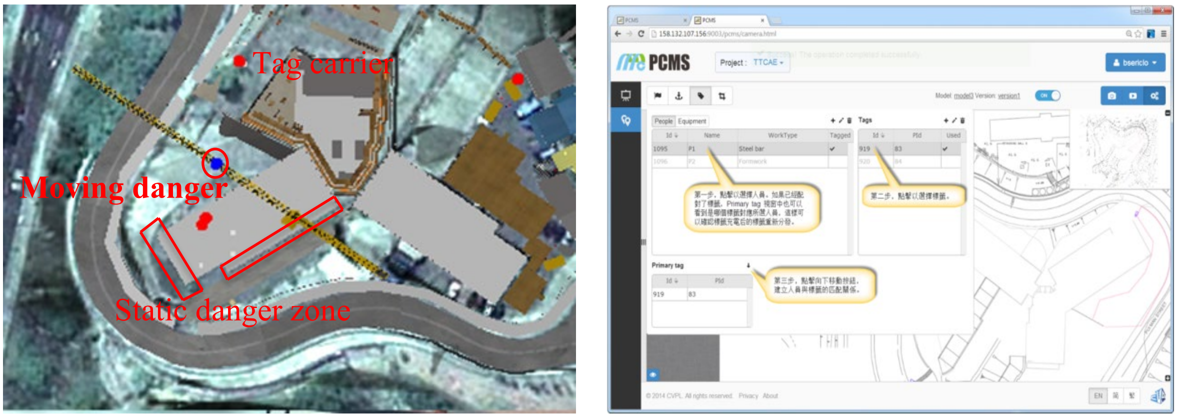
Intrusion behaviors involve multiple scenarios and complicated operations. In order to demonstrate the feasibility and validity of positioning technology-enhanced BBS, it is necessary to test the on-line supporting system in a real world environment. This also shows how the system works. A sloping construction site with many tower cranes is selected as this kind of project is very common and accident-prone in mountainous Hong Kong.

4.1 Experiment deployment

Three construction workers were selected randomly as the tracking objectives, and were required to act normally as any other working day. Three workers are all male, married and in the age group of 40 to 45. Tag carrier 1 (TAG 1) and TAG 2 graduated primary school while TAG 3 finished high school. The trial lasted from 10 AM to 4 PM during the main working time and formal feedback and interventions were given at the end of the 3rd hour.

The experiment was deployed as shown in Figure 4. Three danger sources for unauthorized workers were identified on the construction site by experienced safety managers and related safety officers. These include two static danger zones close to edges and one dynamic danger source beneath a moving tower crane arm. The scope of the dynamic danger zone centered the vertical projection of materials being lifted, with an added safety radius. The parameters of the danger sources were recorded on a map or virtual model such as in Figure 4 (a), including the danger type and the shape, radius and location of the danger zone. To calculate the distance between workers and moving danger sources, another tag was attached to the arm of the crane.

For real time tracking, tags fixed on helmets were utilized to track the location of workers. The tags were then matched with the personal information of the workers, such as name and work type as shown in Figure 4 (b). In this case, none of the three tag carriers was authorized to work in the danger zones. Through careful calculation and prolonged discussion among those involved, the response time to the warning signal was set as 5 seconds.



(a) (b)

Fig. 4. The experiment deployment and authorization

4.2 Data analysis

After deploying the hardware on the work site and inputting information into the system, the real time location of the work site was calculated and synchronized on the virtual map as shown in Figure 5, where the red spots indicate the movement of tag carriers, and the blue spot indicates the movement of the dynamic danger zone beneath the crane arm. The synchronized 3D model visualizes the movement, and the real-time coordinates of both the tag carriers and dynamic danger zone were recorded as (X, Y, Z) in the database. Since the signals can be distorted by occasional outliers, a Robust Kalman Filter (Durovic and Kovacevic, 1999) was applied to reject outlier measurements shown as the black line in Figure 6.

For the developed system, there are two types of errors: alarm absence and false alarm. To differentiate the two, alarm absence denotes that the system fail to send an alarm when an alarm is due, while false alarm means that the system gives an alarm at a wrong time such as when a worker is not in a danger zone or when an authorized worker is in the danger zone. To investigate the system accuracy, three observers were arranged on work site for error detection. Three errors were identified and recorded during the experiment: a) Tag Carrier 2 (TAG 2) was not in the two danger zones when he received an alarm, b) alarm was not sent to TAG 3 when he was in Danger Zone 2 (DZ 2), and c) TAG 3 got an alarm when the hook moved far away from him. These three records were rectified before statistical.

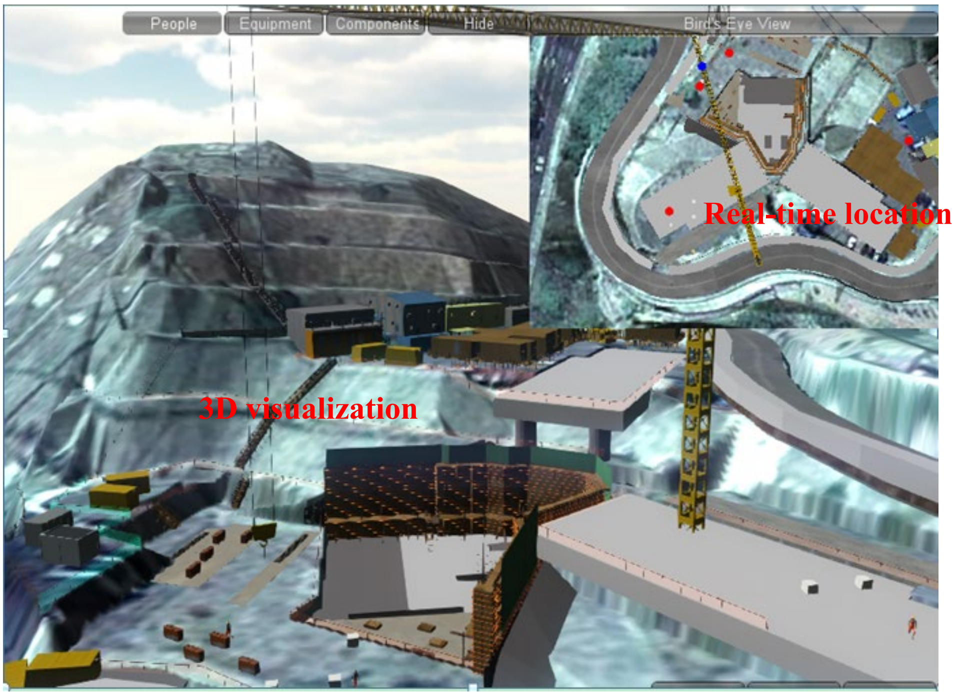


Fig. 5. The synchronization and visualization of workers' locations

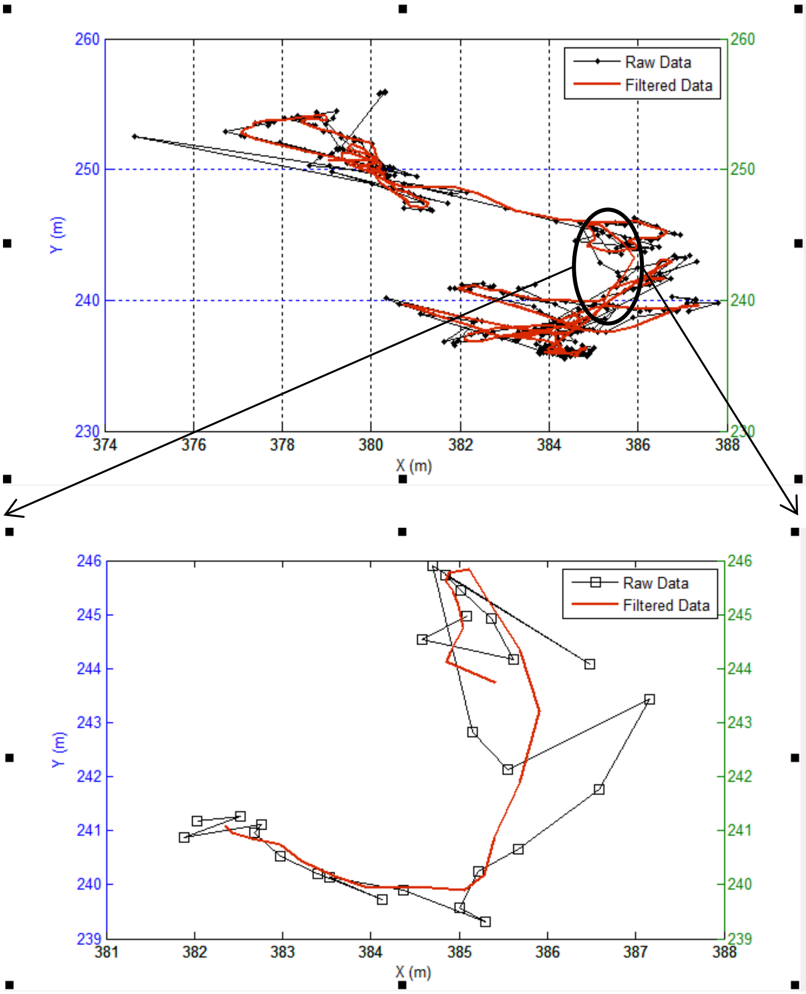
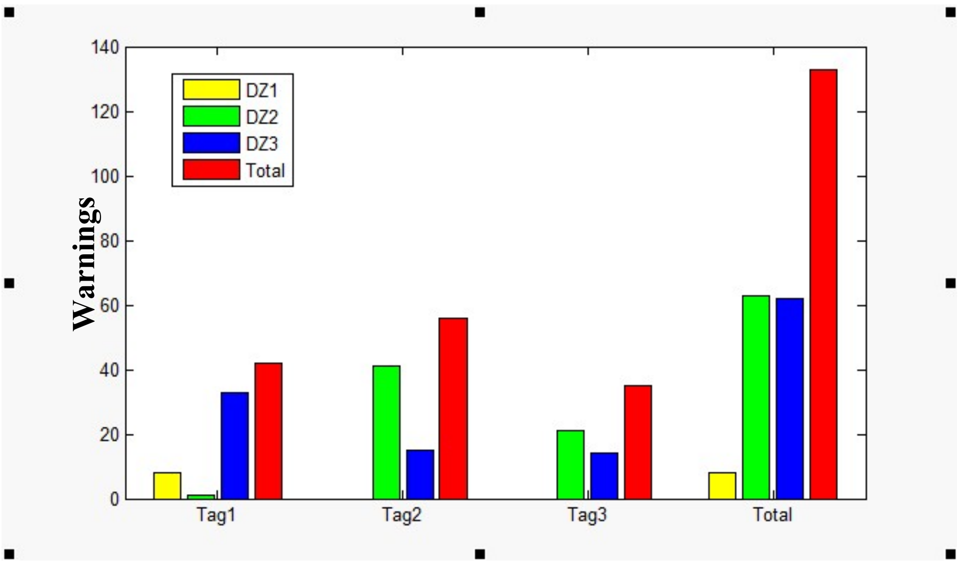


Fig. 6. The Robust Kalman filter example

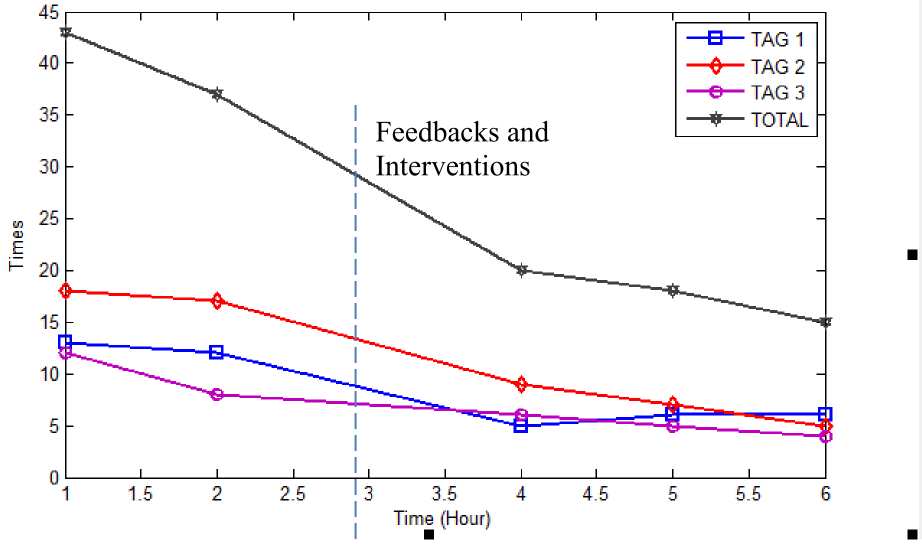
After error elimination, a total of 133 warnings were identified to be effective during the trial time. These are shown in Figure 7 in terms of the warning times of each tag carrier in different danger zones during various working times.

Firstly, a two-way ANOVA analysis is conducted to clear the performance variance in different times and at different danger zones. As shown in Table 2, both time and danger zone have significant effects on safety performance (Sig. =0.004<0.05, Sig. =0.000<0.05). Then the multi-comparison (Table 3) shows that DZ1 was associated with much less warnings than DZ2 and DZ3. (Sig. =0.000<0.05, Sig. =0.000<0.05, Sig. =0.693>0.05). This is because DZ1 is a moving danger zone caused by a crane, and workers are naturally more cautious of visible and moving dangers.

Although TAG 2 seemly got more warnings than the other two workers (56>42>35), but analysis results in Table 4 shows no significant performance difference in three workers (Sig. =0.364>0.05, Sig. =0.649>0.05, Sig. =0.176>0.05). Combining danger zone and tag carrier information shows that TAG1, the only worker to have intruded DZ1, also had the highest intrusions in DZ3. His less warning in DZ2 was because he worked elsewhere but needed to pass by for tools or rest occasionally. TAG2, on the other hand, frequently invaded DZ2.



(a)



(b)

Fig.7. Statistical analysis results

Table 2. Significance Test of Time and Danger Zone Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	606.667[a]	6	101.111	18.782	.000
Intercept	1179.267	1	1179.267	219.059	.000
Time	209.733	4	52.433	9.740	**.004**
Danger Zone	396.933	2	198.467	36.867	**.000**
Error	43.067	8	5.383		
Total	1829.000	15			
Corrected Total	649.733	14			

a. R Squared = .934 (Adjusted R Squared = .884)

Table 3. Performance Difference in Three Danger Zones

	(I) Danger Zone	(J) Danger Zone	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
LSD	1.00	2.00	**-10.6000***	1.46742	**.000**	-13.9839	-7.2161
		3.00	**-11.2000***	1.46742	**.000**	-14.5839	-7.8161
	2.00	1.00	**10.6000***	1.46742	.000	7.2161	13.9839
		3.00	-.6000	1.46742	**.693**	-3.9839	2.7839

3.00	1.00	**11.2000***	1.46742	**.000**	7.8161	14.5839
	2.00	.6000	1.46742	.693	-2.7839	3.9839

Based on observed means.
The error term is Mean Square (Error) = 5.383.
*. The mean difference is significant at the 0.05 level.

Table 4. Performance Difference of Three Workers

	(I) Name	(J) Name	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
LSD	1.00	2.00	-.9333	1.01711	**.364**	-2.9890	1.1223
		3.00	.4667	1.01711	**.649**	-1.5890	2.5223
	2.00	1.00	.9333	1.01711	.364	-1.1223	2.9890
		3.00	1.4000	1.01711	**.176**	-.6557	3.4557
	3.00	1.00	-.4667	1.01711	.649	-2.5223	1.5890
		2.00	-1.4000	1.01711	.176	-3.4557	.6557

Based on observed means.
The error term is Mean Square (Error) = 7.759.

To investigate the effects of in-time feedback and interventions on safety performance, the safety manager showed the warning records to the three tag carriers and helped them to identify the danger zones during the 3rd hour. The results are shown in Figure 7 (b), where it is clear that the intrusion behaviors of all three workers sharply decreased over the day (although TAG2 still received the most warnings). Furthermore, a one-way ANOVA shows that, in this case study, time is statistically significant (Sig. =0.006<0.01 in Table 5). Then an orthogonal analysis is done to compare the performance in hour 1 and 2 with 4, 5 and 6. The results indicate the performances in hour 1 and 2 have no significant difference (Sig. =0.389>0.05), and the same applies to hour 4, 5 and 6 (Sig. =0.77>0.05, Sig. =0.47>0.05, Sig. =0.662>0.05 in Table 6). However, the performances in hour 1 and 2 are significantly different from those in hour 4, 5 and 6 (Sig. =0.006<0.05, Sig. =0.004<0.05, Sig. =0.002<0.005, Sig. =0.29<0.05, Sig. =0.17<0.05, Sig. =0.08<0.05), which proves that safety behavior improved notably with reminders and instructions.

Table 5. Significance Test of Time Effects

	Sum of Squares	df	Mean Square	F	Sig.

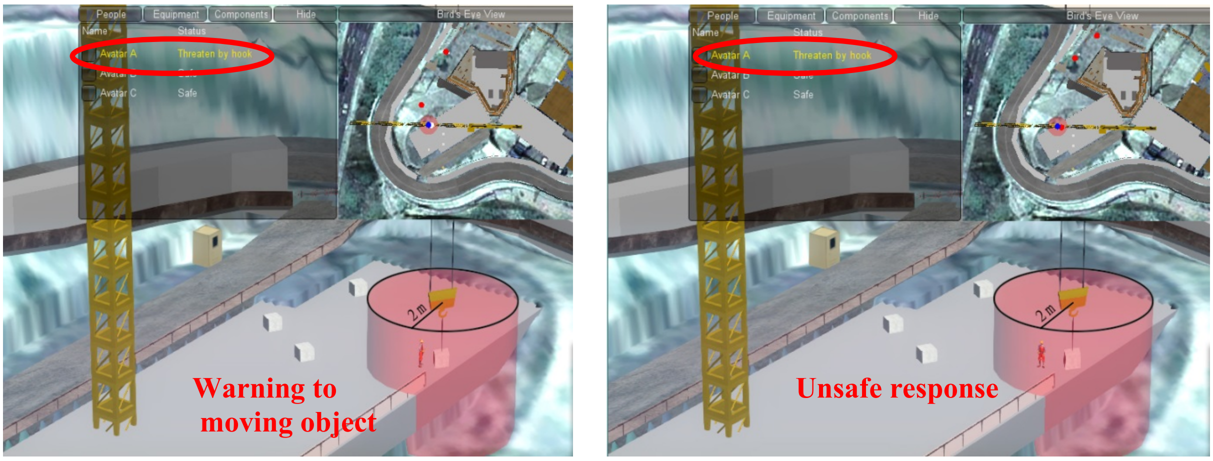
Between Groups	209.733	4	52.433	7.086	**.006**
Within Groups	74.000	10	7.400		
Total	283.733	14			

Table 6. Performance Differences in Different Time

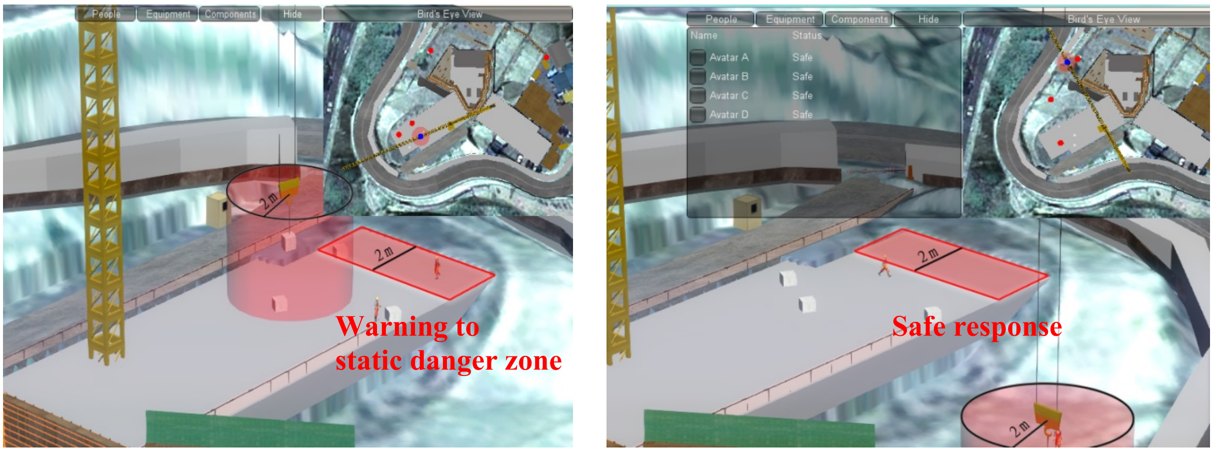
	(I) Time	(J) Time	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
LSD	1.00	2.00	2.00000	2.22111	**.389**	-2.9489	6.9489
		4.00	**7.66667***	2.22111	**.006**	2.7177	12.6156
		5.00	**8.33333***	2.22111	**.004**	3.3844	13.2823
		6.00	**9.33333***	2.22111	**.002**	4.3844	14.2823
	2.00	1.00	-2.00000	2.22111	.389	-6.9489	2.9489
		4.00	5.66667*	2.22111	**.029**	.7177	10.6156
		5.00	6.33333*	2.22111	**.017**	1.3844	11.2823
		6.00	7.33333*	2.22111	**.008**	2.3844	12.2823
	4.00	1.00	-7.66667*	2.22111	.006	-12.6156	-2.7177
		2.00	-5.66667*	2.22111	.029	-10.6156	-.7177
		5.00	.66667	2.22111	**.770**	-4.2823	5.6156
		6.00	1.66667	2.22111	**.470**	-3.2823	6.6156

*. The mean difference is significant at the 0.05 level.

Since there had been no similar cases previously, two representative scenarios were chosen as examples for the response analysis. As indicated by the results shown in Figure 8, the first intrusion warning was triggered by being too close to lifting materials and the worker ignored the danger warning. This was identified by the system and recorded as unsafe behavior. In another case, the worker was warned because he entered the danger zone which was near a slope edge. This time, the worker left the danger zone within 5 seconds of the warning and this it was therefore not recorded as an intrusion behavior.



(a)



(b)

Fig. 8. Intrusion behavior assessment

The case study therefore verifies the feasibility of high technology supported unsafe behavior assessment. By applying PSMS in data collection and location-oriented behavior analysis, unsafe behaviors can be identified and assessed accurately and objectively, while the automatic warnings and in-time feedback appear to be effective methods in reducing intrusion behavior.

4.3 Experiment Limitations and Future Research Directions

It is unfortunate but inevitable that the experiment has a few limitations concerning the experiment. Constrained by practical issues, the study subject sample size is relatively small, and the experiment could not be conducted in a longer period of time. Even though these impediments do not compromise the credibility of our study, the study will benefit from a larger sample size and a longer study period. We hope to overcome these shortcomings in our future study. Having said that, as this study is exploratory in nature, we wish this paper could inspire further research in safety behavior study. After all, intrusion is only one of the many unsafe behaviors, which could be monitored and altered through BBS

5. Conclusions and Future Work

BBS has been shown to be an effective methodology for improving safety behavior in construction work, but has failed to be widely adopted because it is dependent on a manual and experienced inspection process, and lacks accurate assessment and timely feedback. This paper solves this problem by providing an effective approach to automatically identifying intrusion behaviors with positioning technology and assesses the personal safety performance of workers according their response to danger warnings. This involved the development of a supporting multi-user platform to obtain the real-time position of workers in relation to virtual hazardous zones. An on-site case study was conducted of workers on a sloping construction site that verified its ability to identify incursions into the hazardous zones, issue timely warnings and capture worker responses. The warning and response data were then analyzed to assess individual safety performance and locations over time for effective BBS feedback and improved safety behavior.

Acknowledgements

The work was supported by the Innovation and Technology Commission (ITC), Hong Kong Special Administrative Region, under the project "Location-based Technologies for Asset Tracking and Risk Management" (ITP/036/12LP), a General Research Grant titled “Proactively Monitoring Construction Progress by Integrating 3D Laser-scanning and BIM” from the Research Grants Council of Hong Kong (Reference No. PolyU 152093/14E), and the National Natural Science Foundation of China (Grant No. 71390523). The authors gratefully acknowledge the Department of Building and Real Estate at Hong Kong Polytechnic University and the Research Institute of Complex Engineering & Management at Tongji University for providing supports to conduct this research.

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