Integrating real time positioning systems to improve blind lifting and loading crane operations

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ABSTRACT

Mobile/tower cranes are the most essential forms of construction plant in use in the construction industry but are also the subject of several safety issues. Of these, blind lifting has been found to be one of the most hazardous of crane operations. To improve the situation, a real-time monitoring system that integrates the use of a Global Positioning System (GPS) and Radio Frequency Identification (RFID) is developed. This system aims to identify unauthorised work or entrance of personnel within a pre-defined risk zone by obtaining positioning data of both site workers and the crane. The system alerts the presence of unauthorised workers within a risk zone – currently defined as three metres from the crane. When this happens, the system suspends the power of the crane and a warning signal is generated to the safety management team. In this way the system assists the safety management team to manage the safety of hundreds of workers simultaneously. An on-site trial with debriefing interviews is presented to illustrate and validate the system in use.

Keywords: Crane safety, blind lifting, positioning system

INTRODUCTION

Although mobile cranes are the most essential form of construction plant in North America, there has been a record increase in the use of tower cranes – the archetypal symbol of construction plant in developed countries today (Shapira and Glasscock 1996; Shapira *et al*. 2007). Tower crane operatives have the advantage of a wide field of vision when compared with that of mobile cranes (Shapiro *et al*. 2000), but it is impossible to avoid blind lifting, especially in the construction of skyscrapers. Shapira *et al*. (2008), for example, have identified four tower crane blind lifting scenarios for high-rise construction. Peurifoy *et al*. (2006), on the other hand, notes that blind lifting also happens in low rise construction. In fact, Cheng and Teizer's (2011) investigation of crane related accidents in the USA found the restricted visibility of ground operations to be one of the most common causes of crane accidents. Both Shapira and Simcha (2009) and Shapira and Lyachin (2009) rate blind lifting as one of the most influential factors affecting the safety of cranes on construction sites. Similarly, Sertyesilisik *et al*.'s 2010 UK study reported a veteran slinger-signaler admitting that blind lifting is the one of the most dangerous of crane operations.

As a means of overcoming the blind lifting problem, a new tower crane management approach is described that involves overseeing tower crane operations by a Global Positioning System (GPS) and Radio Frequency Identification (RFID). The system obtains and compares the real time position of tower cranes and construction workers and, if an unauthorized worker is detected in a pre-defined risk zone, cuts-off the power to the tower crane involved. The approach, therefore, actively prevents 'struck-

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by' accidents caused by tower cranes on construction sites. An illustration and validation of the system in use is provided by an on-site trial and debriefing interviews with those involved, where the trial demonstrates the accuracy of the system and the interviews indicate its ability to significantly improve the safety performance of crane operations without affecting productivity.

BACKGROUND

Safety

In 2011, Tam and Fung (2011) conducted an extensive survey of tower crane safety in the Hong Kong construction industry. This identified a major weakness of current practice to be the ineffectiveness of communications between crane operators and other personnel (such as slingers and signallers), with around 24% and 6% respectively of their respondents not being capable of directing the movement of cranes and loads for ensuring the safety of personnel and not fully understanding radio/tele-communication signals among crew members. As a result, accidents easily happen when the crane operators have a restricted view (blind lifting). The situation is even worse, as Hinze and Teizer (2011) report that 'struck-by' accidents are the most likely outcome when a restricted view operation is carried out, as construction workers can easily be struck by a load suspended from the crane's hook during blind lifting. In addition, Tam and Fung's (2011) finding, that around 8% of crane operators imbibe alcohol in advance of doing their work, is expected to greatly exacerbate the situation.

The use of a video communication system, as suggested by Everett and Slocum (1993), provided an early innovative idea for improving communications between crews and hence improved safety. However, there is as yet no evidence of any such system being used in practice. Numerous studies have also been carried out of lift planning, including: visualisation (Dharwadkar *et al.* 1994); heavy lift optimization and multiple lifts planning (Varghese *et al.* 1997; Dharwadkar *et al.* 1994; Lin and Haas 1996); and lifting time estimation (Leung and Tam 1999). This work is focused on improving lifting efficiency, however, rather than being concerned with safety during the lifting process. Another area of study that has been carried out by numerous researchers is path planning (Ajmal Deen Ali *et al.*, 2005; Lozano-Perez and Wesley, 1979; Sivakumar *et al.*, 2003). As with lift planning, however, research in path planning is only concerned with efficiency. These studies do not address safety problems that occur during the lifting process. Instead, the intention is to identify the shortest path for lifting in order to reduce the duration of the operation.

The development of robotic or automatic cranes has also attracted considerable attention (Kang and Miranda, 2006; Rosenfeld and Shapira, 1998; Yu *et al.*, 2005; Kim and Song, 1997; Lee *et al.*, 2002). This aims to optimize the use of cranes while preventing human errors occurring during the process. It can be argued that the use of robotic or automatic cranes may also be able to improve safety, as they may reduce the chance of unwanted movement due to human error. There are some problems in implementing this in practice however. For example, a robotic crane will change entire working practices and have huge implications in terms of cost and time. Also questionable is the ability of robotic cranes to deal with different situations, such as overweight lifting.

Crane monitoring systems have also been developed by Bernold *et al*. (1997) and Lee *et al*. (2006). These systems were motivated first by safety concerns and so safety is one of the areas monitored by the systems. However, there is no evidence to suggest that either of the two developed systems have been implemented in practice. In a similar manner to the proposed system, Lee *et al*. (2009) investigate the use of laser-technology to track the lifting path of a robotic tower crane. Three experiments involving the prototype system established its accuracy to be 10cm or less with 95% confidence. Once again, however, the system has not been implemented on a construction site or trialled under different weather conditions.

The literature review indicates, therefore, the existence of only a very limited amount of research into crane safety. There is also no available tool for managing the safety of tower crane operations and hence little to prevent or reduce the occurrence of struck-by crane accidents.

Positioning systems

Positioning systems are widely used in different industries for obtaining the position of an object and have been used in the construction industry since the early 2000s. In 2002, Lee *et al*. (2002) investigated the possibility of improving crane operations by using a Global Positioning System (GPS). Although the result of the research was

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positive, GPS was not taken up by the construction industry at the time due to the insufficient level of accuracy involved.

With the general enhancement of computer technologies since that time, the accuracy of positioning systems has improved. By 2004, Kwon *et al*. (2004), in investigating the use of GPS for construction safety management, found that it could improve the safety performance of a construction project – a result confirmed later by Kim *et al*. (2006). Within a short space of time, GPS had been adopted in the construction industry for different purposes, such as in locating materials (Caldas *et al*. 2006), tracking construction materials on site (Song *et al* 2006), resource management (Gong and Caldas 2008) and site safety management (Teizer *et al*. 2007). A similar approach is the use of Ultra Wide Band (UWB) technology to track the position of workmen inside underground construction sites (Mok *et al* 2010). Similarly, Giretti *et al*. (2009) developed an automatic UWB alert system to manage construction workers and monitor the position of workers within a building under construction. Cheng *et al*. (2011) evaluated the use of UWB for tracking the location of construction resources in harsh environment and established the potential of UWB for real-time localization and tracking. Cheng *et al*. (2012) further studied the use of UWB for trajectory and path planning analysis and developed a system that could gather useful information for the management team to improve safety and efficiency.

Today, many different positioning systems are used in many ways (see Woo *et al*., 2011, for a full review) and some systems are accurate to within a few centimetres (Siwiak *et al*. 2001). From this, it is easy to see that positioning systems have now become sufficiently powerful and accurate to enable the position of objects to be adequately monitored in a variety of situations.

Teizer *et al*. (2010) developed an autonomous pro-active real-time safety alert system which could alert devices when two or more construction resources are in too close proximity by using Radio Frequency. A series of experiments were carried out which demonstrates the effectiveness of the system in blind spot scenario situations. Motivated by Teizer *et al*.'s (2010) success, here we use another position technology (GPS) to track the movement of the tower crane hook and adjacent workers.

SYSTEM ARCHITECTURE

It is difficult to manage the safety of blind lifting and landing operations. In order to improve the situation, a Real Time Positioning System (RTPS) system is proposed. This involves the combination of GPS and RFID and aims to monitor cranes and workers simultaneously within the lifting and landing areas of crane operations. The crane hook and its surrounding area is defined as a restricted zone, within which only authorized workers are allowed to enter. The RTPS detects any unauthorized entry and alerts the user. In this way, unauthorized work that is too close to the blind lifting can be avoided. This approach prevents unwanted interactions between workers and cranes and therefore minimises the risk of struck-by accidents.

The system architecture is shown in Figure 1. The RTPS comprises of three tiers and six functioning units in three tiers: 1) presentation tier; 2) business tier; and 3) data tier. The presentation tier is formed by the Graphical User Interface (GUI) which integrates all information into a graphical format. The second tier consists of the four major functioning units of the system: 1) web server; 2) virtual construction engine; 3) real-time location engine; and 4) real-time location network. The real-time location network comprises two positioning systems: 1) GPS; and 2) Radio Frequency Identification (RFID). The GPS system directly obtains the positioning data of the tower crane hook (external area) while the RFID system obtains the position of both construction workers and the hook (both external and internal area). Due to the different formats of the two positioning systems, a real-time location engine is used to convert the data of both systems for importing to the virtual construction engine. The virtual construction engine then integrates the 3D positioning data imported by the location engine into the BIM environment. The BIM data is stored in the third tier (database). The GUI then imports the data from the virtual construction engine by means of the web server. The GUI provides a clear picture to the user of the actual situation involved in the construction site by showing the position of workers in BIM format. The system user can easily identify the location of any incident where unauthorised work occurs.

<Take in Figure 1>

Positioning equipment

To obtain the position of the targets (crane hook and workers), both GPS and RFID technologies are adopted. An active RFID tag is a piece of equipment that continuously transmits signals, while the RFID receiver receives the signal

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transmitted by the RFID tag. The active RFID tag allows the user to store different data for reading by the RFID receiver. The role of the construction workers and crane hooks are stored in the active tag so that the receiver can read the identity of the workers and hooks. The GPS is responsible for obtaining the position of the crane hooks when they are not covered by the RFID network. The GPS receivers are attached to the hooks to obtain their position in different situations.

Details of the use of the tag, receiver and other units are shown in Figure 2. A GPS receiver and RFID tag are attached to the crane hook and active RFID tags are attached to the safety helmets of the construction workers. During the lifting and landing process, the location of the workers and crane hooks are thus read by the RFID readers installed as shown in Figure 2 and imported to the BIM environment. The area surrounding a hook denotes a hazardous area. If any worker ventures within the hazardous area without authorisation, the RTPS automatically obtains the location of the identified RFID tag and reports it to the system user through the GUI. In this way, the system can easily track the origin of the signal as every tag contains a unique identity number. The system user can thus identify the identity of any unauthorised entrants into the hazardous zone. The use of an active RFID tag instead of a passive RFID tag creates a potential problem of size and weight as an active RFID tag requires electric power and a battery to generate a signal. However, the weight and size of the active RFID tag used is sufficiently small (less than 200g) to be attached inside the safety helmet and not cause any inconvenience to the user. Only an active RFID tag enables user to store data (i.e. the identity of construction workers) within the tag.

<Take in Figure 2>

Positioning method of the RFID system

Different methods are available for calculating the position of the RFID system. Following Bouet and dos Santos (2008), as range-free RFID method is used. RFID readers are installed at both ceiling and floor level in order to obtain the 3D positioning data needed. As this method applies inclusive and exclusive constraints to identify the location of a specific tag within a specific zone, the system can read the position data precisely within the area covered. As this constraints method compares the position data of the tag obtained from the eight receivers (both at floor level and ceiling level), the height of the tag can thus be obtained. As a result, the system does not need to further define ground truth. The accuracy of the system is in the range of 0.2 to 1.2 metres under different settings and conditions. Details of the design of the RFID system are not provided here. Wang *et al*. (2007) have also developed another positioning method involving a RFID and which provides more accurate results. However the use of a reader instead of the tag as the reading target significantly increases the size and weight of the tag, making it impracticable to implememt in practice.

Signal strength

As lifting and landing operations are located on the roof of the building or open area, the signal does not travel beyond the surface of the roof. This prevents the signal being reduced by the building structure. On the other hand, RFID receivers are installed at both floor and ceiling level to obtain the position of the workers. The signal strength depends on the distance between receivers and is discussed in the on-site trial section later.

Mechanism to improve blind lifting

To improve the safety performance of the blind lifting process, the RTPS is defaulted to detect unauthorized workers within three metres of the crane's area of operation (although this distance can be adjusted to suit the needs of different purposes). The circular zone of three metres radius is centred by the crane hook. This zone is defined as a hazardous area in which only authorised workers (such as riggers) are allowed to enter. Information stored in the tags allows the system to verify the trade of the workers involved. Any unauthorized construction workers staying within the danger zone for over a one minute of time is pinpointed by the software engine and a warning signal is generated. The unauthorized entrance is identified by comparing the position of the workers with that of the danger zone. The setting of one minute is only a default measure and may be adjusted by the user. However, it is felt that, in general, a shorter duration may result in an unduly frequent misidentification of workers, resulting in a negative effect on the productivity of the crane. The default setting of one minute is intended to prevent the system from misidentifying a passerby as involved in an unauthorized working activity. The setting also prevents the system from misidentifying any unauthorized activity while the tower crane arm is swinging.

The tool therefore allows the user to actively prevent construction operatives working too close to the operation of the tower crane without authorisation. As a result, any unauthorized working activity or entrance to the roof during tower crane operations is easily and automatically identified by the tool. This is dramatically different to the traditional practice of crane management, which can only prevent operatives working next to the crane by giving instructions in advance and providing on-site supervision in several locations. An on-site trial follows to demonstrate the system in use and for comparison with traditional practice. The comments from users are also summarised and presented.

ON-SITE TRIAL

An on-site trial was carried out on an unnamed public housing construction project in Hong Kong. To verify the effectiveness of the proposed system, three different approaches were adopted. The first was to conduct an on-site trial, which aimed to verify the accuracy of the system on a construction site. During the on-site trial, the accuracy of the proposed system was estimated by comparing the coordinates obtained by the proposed system to that of several precise survey points on the roof of a specific building. After obtaining the accuracy of the system, the second approach was to demonstrate the use of the proposed tool. This approach aimed to prove that the concept could actually be adopted in real construction project. The third approach aimed to collect opinion on the use of the proposed system on a construction site by interviews. The interviews were conducted to collect the opinions of different members of the construction team including managers, engineers and labourers. The aim of the interviews was to verify the effectiveness of the tools from comments made by the users. The validation of the RTPS is presented in the following sections.

Validation of the accuracy of the RTPS

The accuracy of the RTPS is important as it is the core part of the system. The accuracy of each of the two adopted positioning systems was verified separately. The accuracy of the GPS, which is used to measure the accuracy of the position of the crane hook, was measured by an on-site experiment. A common personal GPS receiver was used for reasons of economy. Both the GPS receiver and the RFID tag, neither of which have a brand name, were purchased from a local technology store. There are two reasons for selecting this GPS receiver: 1) the selection of an economic receiver could reduce the development and application cost of the tool; 2) the use of a GPS receiver with unproved quality would demonstrate the minimum accuracy of the system.

The GPS receiver was placed in different locations on the construction site so as to read the positional data of ten different reference points whose location was known with precision by a previous surve. The data was then processed by the system engine and imported into the GUI. The locations obtained in this way were then compared with those in the building information model (BIM). An average of ± 1 metre accuracy was found. Although the accuracy of the receiver could be dramatically improved by using a geodetic class GPS receiver, this would be a very costly solution. The alternative adopted in order to obtain a more accurate result to attach an additional active RFID tag to the hook. This enabled the position of the hook to be obtained by two systems. The GPS was used to obtain the position when the hook is at a height where there is no RFID signal, while the RFID was used when the signal became available.

For the RFID system, the accuracy was verified by a similar on-site experiment. A set of eight RFID receivers were fixed to four precise survey points on site by installing them at both ceiling level and floor levels. The RFID receivers were placed in a square pattern two metres apart. The location of the RFID receivers was then imported to the BIM. Active tags were placed at ten different precise survey points within the area covered by the four receivers. The locations of the tags were read and imported into the BIM. The locations of the survey points within the BIM environment were then compared with those of the survey data. The result of the experiment indicated the accuracy of the system to be approximately ± 30 centimetres.

Next, the RTPS system was used in the on-site trial project. An active tag was fixed to the hook of one of the tower cranes in use and the hook made stationary at roof level. Ten construction workers equipped with RFID tags were instructed to locate themselves in the vicinity of the hook. The aim of this experiment was to verify the ability of the system to identify any unauthorised workers near the lifting zone. The result of this study was similar to the previous experiment, with an error of approximately ± 30 centimetres being recorded. All in all, from the experiment, it was found that construction workers within 2.7 to 3.3 metres of the hook would alert the system.

Verifying the use of RTPS on site

The system was used for 1 week on the on-site trial project. As the purpose was to demonstrate the system and verify its accuracy, the RTPS system settings covered only one building block of the construction site as shown in Figure 3. The circles refer to the active tags (workers and tower crane hook) while the triangles represent the location of the RFID receivers. The floor layout was divided into different zones, in which each was covered by eight RFID receivers (four at ceiling level and four at ground level of the same floor). The layout of these receivers were determined according to previous studies (Bouet and dos Santos 2008; Bouet and Pujolle 2008). Twenty construction workers wore safety helmets with an active tag attached and carried out daily work as usual. During the trial, the RTPS system was monitored by the research team, who coordinated with the construction team when incidents were identified, with the safety officer providing site supervision. Another two research team members attended the lifting and landing areas respectively and were responsible for monitoring the workers. These two members ensured that the system did not miss any unauthorised entrance and misidentification.

During the one week trial, the system identified seven real-life incidents in which the workers entered the risk zone without valid reason. The safety officer was immediately alerted by the system and the unauthorised workers were asked to leave the risk zone. No false alerts ocurred and the system did not fail to detect any unauthorised work.

<Take in Figure 3>

Verifying the effectiveness of RTPS

Subsequently, individual semi-structured debriefing interviews were arranged to obtain details of the experiences of the on-site personnel involved. A total of 20 site staff, including 2 construction managers, 3 engineers, 2 safety managers, 3 safety officers and 10 labourers were interviewed separately. The interviewees can be further divided into two categories: 1) Managerial staff, including managers, engineers and officers and; 2) labourers. Due to limited time available, the interviewees provided only very short responses.

The interviewees were asked questions concerning 1. the accuracy of the system; 2. the effectiveness of the system during blind lifting; and 3. any other comments relating to the system. The results are summarised in Table 1. The ten labourers were only required to answer question 7, which aimed to assess the effect of the weight of the tool in practice.

In response, the management staff generally agreed that the accuracy of the system is acceptable. The 20 to 30 centimetres error is relatively small compared with the size of the risk zone (3 metres in the on-site trial). The results of the interviews also indicated that those involved in the trial were generally satisfied with the performance of the RTPS and that its use would effectively reduce the risk of struck-by crane accidents.

The management staff were impressed that the system had successfully identified seven occasions of unauthorised entry during the trial, and stating that it is normally difficult to avoid workers entering risk zones without continual on-site supervision, which is difficult if not impossible to provide due to the limited manpower available. It was also generally agreed by both the labourers and management staff that the use of the RTPS system did not reduce productivity or affect the workers in performing their duties in the normal way due to the relatively small size and light weight of the equipment used. The management staff believed RTPS would provide a valuable tool for maintaining tower crane safety and that they would be are willing to use the system if it is made available to them.

The interviewees also suggested that the RTPS coukld be useful in other areas, such as when working at height, where it is believed that it could help actively manage the position of workers and equipment. According to the interviewees, the RTPS is capable of reducing the workload of safety management and providing a useful tool for safety manager to simultaneously oversee hundreds of workers in real time.

In terms of the problem areas encountered, the interviewees noted that the RTPS was somewhat difficult to setup on the construction site during the trial. This may be caused by the inexperience in setting up as it was the first trial of the system, however, and may be overcome with a more continued and regular use of the system. A further point was that, in the trial, only 10 active tags were used and attached to safety helmets. An active tag, however, requires the use of a battery and the tag turns off at the end of the battery's life. This causes little difficulty for a few tags but is likely to become a significant management problem if hundreds of tags are used on one site. The capacity of the system should therefore be assessed if hundreds of tags are monitored at the same time. A few of the interviewed labourers also expressed their concern about privacy, as their real-time locations are monitored continuously within the construction site. The interviewees were worried that their supervisor would evaluate their performance based on the system.

CONCLUSION

Tower cranes and mobile cranes are one of the most common forms of construction plant but their use is also associated with one of the highest fatality rates in the construction industry. One of the most serious problems involved is the risk of operatives being struck by the crane during the course of its operation, especially where blind lifting is involved. To date, little is done to help prevent struck-by crane accidents caused by blind lifting except by giving instructions to operatives in advance and providing continual on-site supervision simultaneously in several locations.

In order to improve the situation, a system using real time GPS and RFID has been developed to prevent struck-by accidents by monitoring the crane and nearby construction activity. The on-site trial of the system demonstrated that it performs well in practice, is sufficiently accurate and practicable on-site (the size, weight and installation being accepted by those involved) and does not affect productivity or the daily operation of the workers and tower crane. It is believed that the use of the system will prevent unauthorised entrance to blind lifting areas and thus reduce the number of struck-by accidents caused by tower cranes and eventually improve crane safety in general.

Additional remarks centre on the potential for the system to reduce the workload of safety management and enable safety managers to simultaneously oversee hundreds of workers in real time. Further benefits envisaged also include the possibility for use in other areas, such as when working at height, where it is believed that the system could help actively manage the position of workers and equipment. In addition, it is noted that the system could also help in analyzing the working pattern of operatives and the routes and logistics of different materials in order to create a more efficient and safer layout on construction sites.

REFERENCES

Ajmal Deen, M.S., Ali, N.R., Babu, K., and Varghese, K. (2005). "Collision free path planning of cooperative crane manipulators using genetic algorithm." *Journal of Computing in Civil Engineering,* 19(2), 182–193.

Bernold, L.E., Lorenc, S.J., and Luces, E. (1997). "On-line assistance for crane operators." *Journal of Computing in Civil Engineering,* 11(4), 248–259.

Bouet, M., and Pujolle, G. (2008). “A Range-Free 3-D Locatization Method for RFID Tags Based on Virtual Landmarks.” In: *IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications*, September 2008, 1-5.

Bouet, M., and dos Santos, A. L. (2008). “RFID tags: Positioning principles and localization technique.” In: *WD 2008 1st IFIP Wireless Days*, Nov. 2008, 1-5.

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

Cheng, T. and Teizer, J. (2011). “Crane Operator Visibility of Ground Operations”, Proceedings of the 28th International Symposium on Automation and Robotics in Construction, Seoul, Korea, June 29-July 2, 2011.

Cheng, T., Venugopal, M., Teizer, J., and Vela, P.A. (2011). “Performance Evaluation of Ultra Wideband Technology for Construction Resource Location Tracking in Harsh Environments”, Automation in Construction, Elsevier, 20(8), pp. 1173-1184.

Cheng, T., Mantripragada, U., Teizer, J., and Vela, P.A. (2011). “Automated Trajectory and Path Planning Analysis Based on Ultra Wideband Data”. ASCE Journal of Computing in Civil Engineering, 26(2), 151-160.

Dharwadkar, P.V., Varghese, K., O'Connor, J.T., and Gatton, T.M. (1994). "Graphical visualization for planning heavy lifts." *Proceedings of the 1st Congress on Computing Civil Engineering*, ASCE, Washington, DC, pp. 759– 766.

Everett, J.G., and Slocum, A.H., (1993). "CRANIUM: device for improving crane productivity and safety." *Journal of Construction Engineering and Management*, 119(1), 23–39.

Gong, J., and Caldas, C. H. (2008). "Data processing for real-time construction site spatial modeling." *Automation in Construction*, 17(5), 526-535.

Giretti, A., Carbonari, A., Naticchia, B., and De Grassi, M. (2009). "Design and first development of an automated real-time safety management system for construction

Hinze, J.W., and Teizer, J. (2011). "Visibility-Related Fatalities Related to Construction Equipment", Journal of Safety Science, Elsevier, 49(5), pp. 709-718.

Kang, S., and Miranda, E. (2006). "Planning and visualization for automated robotic crane erection processes in construction." *Automation in Construction*, 15(4), 398–414.

Kim, B.H. and Song, M.R. (1997). "Semi-automation of Tower Cranes, a Study on the Development of Semi-automatic Equipment of Construction Machinery (VI)." *Korea Institute of Construction Technology*, Ilsan, Korea.

Kim. C. W., Haas, C. T., Liapi, K. A., and Caldas, C. H. (2006). “Human-assisted obstacle avoidance system using 3D workspace modeling for construction equipment operation.” *Journal of Construction Engineering and Management*, 20(3), 177-186.

Kwon, S. W., Bosche, F., Kim. C. W., Haas, C. T., and Liapi, K. A. (2004). “Fitting range data to primitives for rapid local 3D modeling using sparse range point clouds.” *Automation in Construction*, 13(1), 67-81.

Lee, J.H., Park, S.J., Oh, S.W., and Kim, Y.S. (2002). “A study on the work efficiency improvement of tower crane operation using GPS and machine vision.” *Journal of Architectural Institute of Korea,* 18(11), 133–140.

Lee, U. K., Kang, K. I., Kim, G. H., and Cho, H. (2006). “Improving tower crane productivity using wireless technology.” *Computer-Aided Civil and Infrastructure Engineering*, 21 (8), 594–604.

Leung, W.T., and Tam, C.M. (1999). “Models for assessing hoisting times of tower cranes.” *Journal of Construction Engineering and Management*, 125(6), 385–391.

Lin, K.L., and Haas, C.T. (1999). “Multiple heavy lifts optimization.” *Journal of Construction Engineering and Management*, 122(4), 354–362.

Lee, G., Kim, H.-H., Lee, C.-J., Ham, S.-I., Yun, S.-H., Cho, H., Kim, B. K., Kim, G. T., and Kim, K. (2009). “A laser-technology-based lifting-path tracking system for a robotic tower crane.” Automation in Construction, 18(7), 865–874.

Lozano-Perez, T., and Wesley, M.A., (1979). “An algorithm for planning collision-free paths among polyhedral obstacles.” *Communications of the ACM*, 22(10), 560–570.

Mok, E., Xia, L., Retscher, G., and Tian, H. (2010). “A case study on the feasibility and performance of an UWB-AoA real time location system for resources management of civil construction projects.” *Journal of Applied Geodesy*, 4, 23-32.

Occupational Safety and Health Council (2006). “The safe use of tower crane”, Green cross, Hong Kong, May/June, viewed 10th September 2010, http://www.oshc.org.hk/download/publishings/1/1876/34.pdf.

Peurifoy, R. L., Schexnayder, C. J., and Shapira, A. (2006). *Construction planning, equipment, and methods*, 7th Ed., McGraw-Hill, Boston.

Rosenfeld, Y., and Shapira, A. (1998). “Automation of existing tower cranes: economic and technological feasibility.” *Automation in Construction*, 7(4), 285–298.

Sertyesilisik, B., Tunstall, A., and McLouglin, J. (2010). “An investigation of lifting operations on UK construction sites.” Safety Science, 48(1), 72–79.

Shapira, A., and Glascock, J. D. (1996). “Culture of using mobile cranes for building construction,” J. Constr. Eng. Manage., 122(4), 298-307.

Shapira, A., Lucko, G., and Schexnayder, C. J. (2007). “Cranes for building construction projects,” J. Constr. Eng. Manage., 133(9), 690-700.

Shapira, A., and Lyachin, B. (2009). “Identification and analysis of factors affecting safety on construction sites with tower cranes.” Journal of Construction Engineering and Management, 135(1), 24–33.

Shapira, A., Rosenfeld, Y., and Mizrahi, I. (2008). “Vision System for Tower Cranes.” *Journal of Construction Engineering and Management*, 134(5), 320-332.

Shapira, A., and Simcha, M. (2009). “AHP-based weighting of factors affecting safety on construction sites with tower cranes.” J. Constr. Eng. Manage., 135(4), 307–318.

Shapiro, H. I., Shapiro, J. P., and Shapiro, L. K. (2000). “Cranes and derricks”, 3rd edition., McGraw-Hill, New York.

Sivakumar, P.L., Varghese, K., and Babu, N.R., (2003). “Automated path planning of cooperative crane lifts using heuristic search.” *Journal of Computing in Civil Engineering*, 17(3), 197–207.

Siwiak, K., Withington, P., and Phelan, S. (2001). “Ultra-Wide Band Radio: The Emergence of an Important New Technology.” *Vehicular Technology Conference(VTC 2001-Spring)*, IEEE VTS 53rd, Rhodes, Greece, May 6-9, 1169-1172.

Song. J., Haas, C. T., and Caldas, C. H. (2006). “Tracking the location material on construction job sites.” *Journal of Construction Engineering and Management*, 132(9), 911-918.

Tam, V. W. Y., and Fung, I. W. H. (2011). “Tower crane safety in the construction industry: A Hong Kong Study.” *Safety Science*, 49(2), 208-215

Teizer, J., Allread, B.S., Fullerton, C.E., and Hinze, J. (2010). “Autonomous Pro-Active Real-time Construction Worker and Equipment Operator Proximity Safety Alert System”. Automation in Construction, Elsevier, 19(5), pp. 630-640.

Teizer, J., Caldas, C. H., and Haas, C. T. (2007). “Real-time three-dimensional occupancy grid modeling for the detection and tracking of construction resources.” *Journal of Construction Engineering and Management*, 133(11), 880-888.

Varghese, K., Dharwadkar, P., Wolfhope, J., and O'Connor, J.T. (1997). “A heavy lift planning system for crane lifts.” *Microcomputers in Civil Engineering*, 12(1), 31–42.

Wang, C., Wu, H., and Tzeng, N. F. (2007). “RFID-Based 3-D Positioning Schemes.” In: 26th IEEE International Conference on Computer Communications, May 2007, 1235-1243.

Woo, S., Jeong, S., Mok, E., Xia, L., Choi, C., Pyeon, M., and Heo, J. (2011). “Application of WiFi-based indoor positioning system for labor tracking at construction sites: A case study in Guangzhou MTR." *Automation in Construction*, 20(1), 3-13.

Yu, S.N., Kim, B.H., and Han, C.S. (2005). "Development of the semi-automation system for tower crane using position measuring device and carriage control algorithm." *Journal of Architectural Institute of Korea*, 21(12), 157–166.

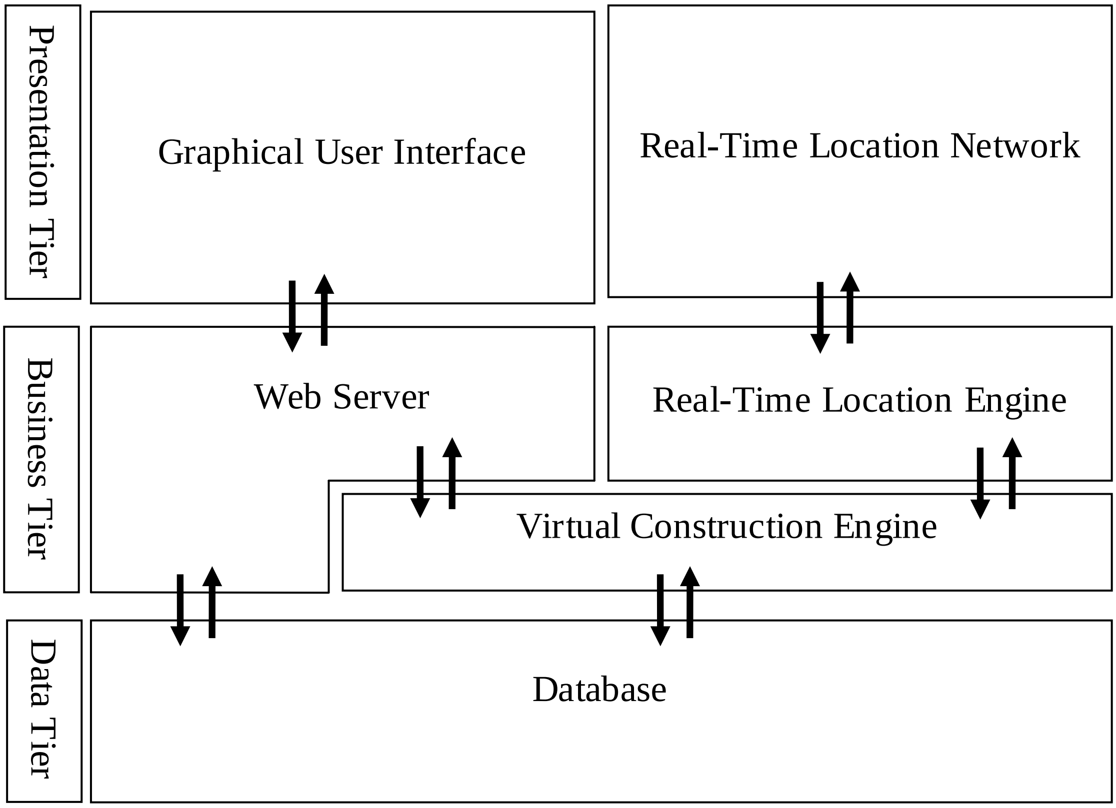

Figure 1. System architecture

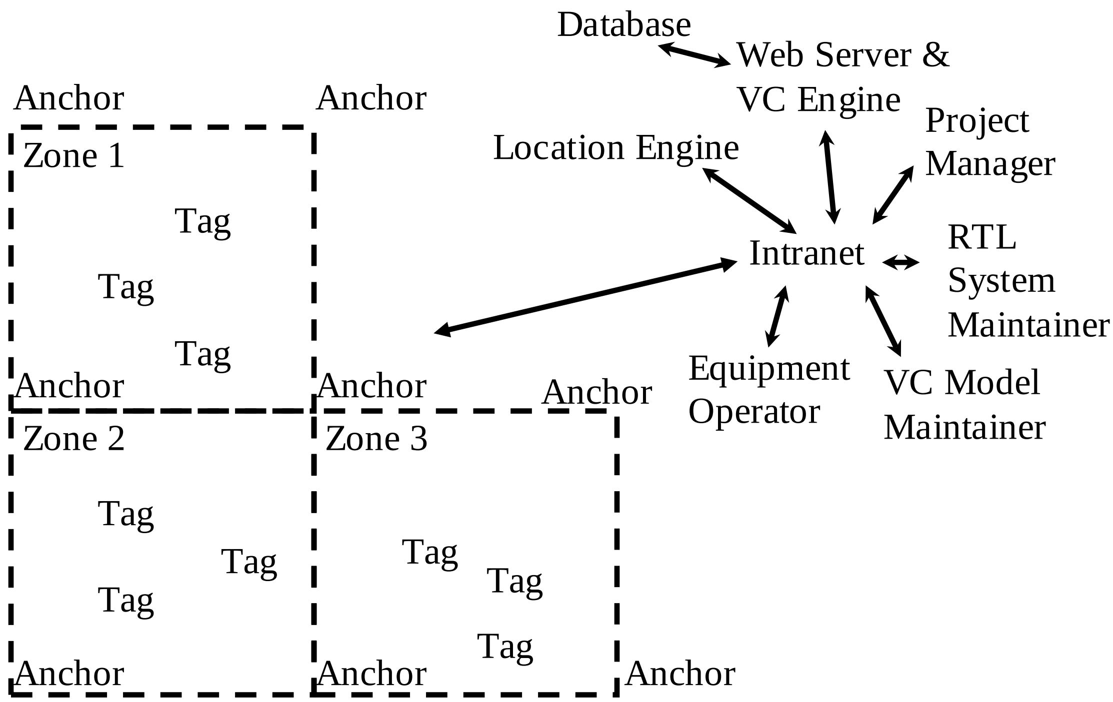

Figure 2. Setup of the RFID positioning system

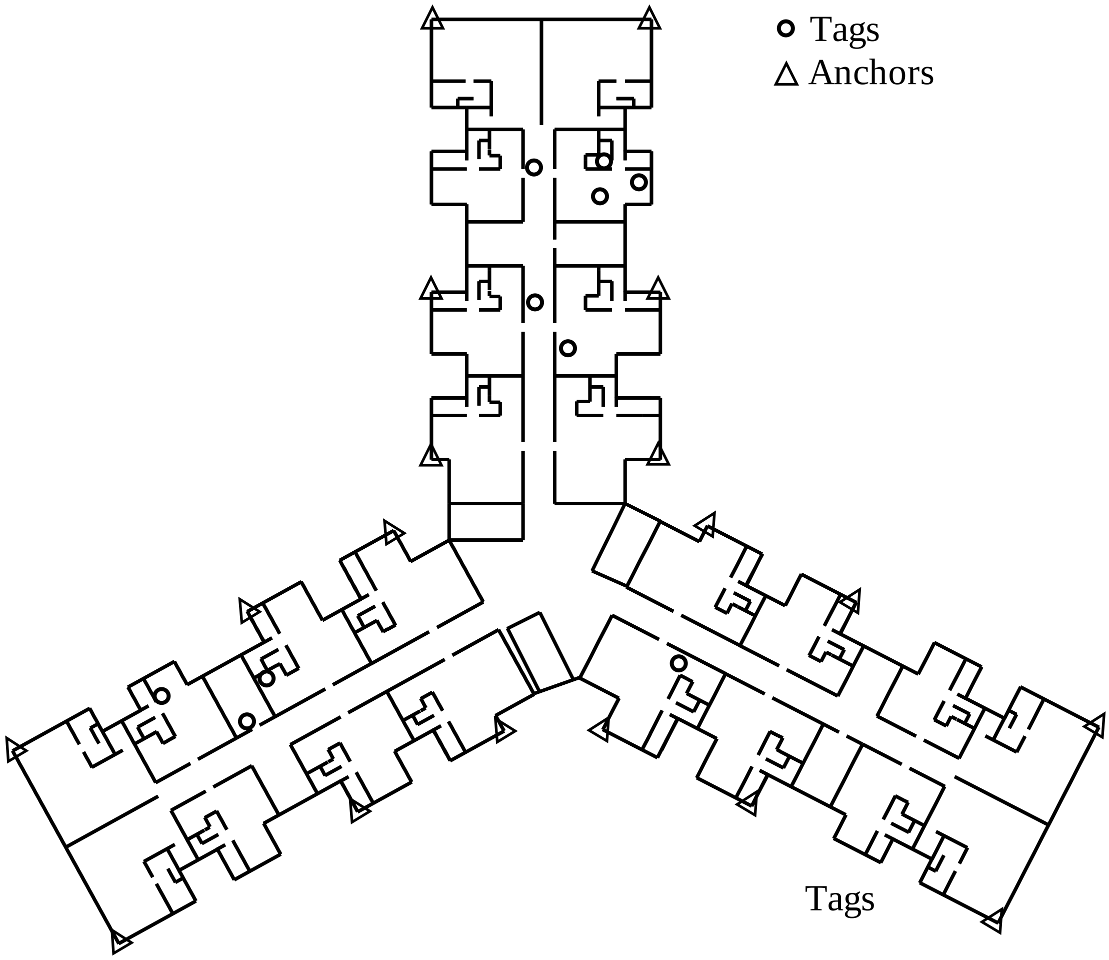

Figure 3. Layout of the on-site trial

1.	Can RTPS accurately detect any unauthorised working activity within the defined area?
2.	Can RTPS effectively reduce the chance of struck-by accidents caused by tower cranes?
3.	Can RTPS improve the efficiency of safety management by allowing the management team to manage safety in an active manner?
4.	Can RTPS reduce the workload of the management team?
5.	Is RTPS difficult to setup and use on site?
6.	Does RTPS have the potential to be used in other areas of the construction industry?
7.	Do the tags inside the safety helmet affect the workers in performing their daily duties?

Table 1. The interview questions

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