Real-Time Locating Systems Applications in Construction

ABSTRACT

Real-time locating systems (RTLSs) are considered an effective way to identify and track the location of an object in both indoor and outdoor environments. Various RTLSs have been developed and made commercially available in recent years. Research into RTLSs in the construction sector is ubiquitous and results have been published in many construction-related academic journals over the past decade. A succinct and systematic review of current applications would help academics, researchers and industry practitioners in identifying existing research deficiencies and therefore future research directions. However, such a review is lacking to date.

This paper provides a framework for understanding RTLS research and development in the construction literature over the last decade. The research opportunities and directions of construction RTLS are highlighted. Background information relating to construction RTLS trends, accuracy, deployment, cost, purposes, advantages and limitations is provided. Four major research gaps are identified and research opportunities and directions are highlighted.

Keywords: Indoor positioning systems; global positioning systems; application areas; sensor technologies; automated data acquisition; real-time locating systems.

INTRODUCTION

In the past decade, there has been a surge of interest in the use of Real-Time Locating System (RTLS) technologies in the construction sector. RTLS is an application used to locate the current geographic position of a person, materials or equipment, facilitating data tracking and management and is considered as one of the innovations that have changed traditional practices in the construction industry over the last two decades. There is no standard definition of RTLS, but it is defined in this study as a combination of hardware and software systems to automatically determine the coordinates of an object in real time within an instrumented area. The data collected by RTLSs may not only be used for real-time purposes but also for further analysis after a set of data is collected. Some types of RTLS consist of location sensors (e.g. receivers) and tags. The tag communicates with the receivers by a signal. The location of the tag is calculated by different algorithms, such as the Received Signal Strength Indicator (RSSI) and Time of Arrival (TOA). Other types, such as vision-based positioning systems do not require tags. Recent developments in RTLS have also extended its application from outdoor positioning to indoor location tracking (Li et al., 2012). Research has shown that indoor positioning has the potential to be applied in the construction industry (Taneja et al., 2012; Vähä et al., 2013). While the use of RTLS is well documented in other industries including the logistic and healthcare industries, such as in the operation of container terminals (Park et al. 2006) and hospital security management (Boulos and Berry, 2012), there is a lack of a systematic review of the use of RTLS technologies in the construction industry. This paper therefore provides such a critical review of the literature and suggestions for further research. In doing so, the paper i) identifies key construction RTLS research; ii) discusses the advantages and disadvantages of the main RTLS technologies available; and iii) identifies a research agenda and opportunities for further research.

RESEARCH METHOD

A two-stage literature review method after Tsai and Wen (2005) and Ke et al. (2009) was used to identify the journal articles that describe and investigate the use of RTLS technologies in the construction industry from 2005 to 2014. First, a comprehensive literature search based on "title/abstract/keyword" (Yang, 2015) was conducted through search engines such as Scopus and the SCI database. Keywords included, but were not limited to, "RTLS", "construction engineering", "construction site", "construction planning", "building design", "building repair and maintenance", "building retrofitting" and "building demolition". A long list of papers obtained in this way was generated for consideration for possible review. However, inspection of the long list revealed that different journals generally have different publication interests and that the selection of the journal had a substantial effect on the research topics involved. The investigation was therefore recommenced and restricted to research articles published in first-tier construction journals only.

Following Xue et al.'s (2012) selection criteria, five well-known academic journals within the area of construction engineering and information technology were selected from the SCI database. The five selected journals are: *Advanced Engineering Informatics* (AEI); the *ASCE Journal of Computing in Civil Engineering* (CCE); *Automation in Construction* (AIC); the *Journal of Construction Engineering and Management* (CEM); and the *Journal of Computer-Aided Civil and Infrastructure Engineering* (CACIE). These journals are accepted by the research community as being prominent and high quality and with an important impact in the construction engineering and management field (Chau, 1997). In the second stage of the literature search, a more focused and comprehensive search within the five targeted journals was conducted with the support of the Scopus/SCI search engine.

Based on Gu et al.'s (2009) survey and Deak et al.'s (2012) review, 10 RTLS technologies and components were selected for review. These are composed of one outdoor positioning system (GPS) and nine indoor positioning systems (IPS) comprising *infrared* (IR), *ultrasound, radio-frequency identification* (RFID), *wireless local area network* (WLAN), *Bluetooth, ultra-wideband* (UWB), *magnetic signals, vision analysis,* and *audible sound*. Papers using RFID technology for data transfer were excluded, as were editorials, book reviews, letters to editors, discussions/closures and comments. Articles and review articles were searched within the same publication period (2005-2014). This involved scanning 3791 publications over the 2005-2014 period, resulting in a sample of 75 relevant articles being identified for analysis (Table 1).

<INSERT TABLE 1>

OVERVIEW OF CONSTRUCTION RTLS-RELATED PUBLICATIONS

As Table 1 indicates, AIC covers around 60% of the identified literature, with 43 (3.92%) of the 1097 articles published by the journal over the period. Apart from CCE (3.07%), other journals contain proportionally much less coverage. Table 2 also indicates an increase in volume of articles in recent years, most significantly since 2009. RFID is by far the most widely discussed (36 times), with infrared technologies (2 times) being the least mentioned in the literature.

<INSERT TABLE 2>

Over half (55.8%) of the articles are based on experimental studies, many of which were carried out off-site - in an existing building for example, or on the campus of a university – while only 33% tried to test or apply their work on a real construction site. The majority of articles focus on verifying the accuracy of the developed RTLS-related technologies. 20% relate to construction process management and 17% to site safety management, the remainder suggesting RTLS technologies could improve property management (5%), maintenance (3.7%), site productivity (2.5%), cost control (1.2%) and the health management (1.2%) of construction projects.

Classification by specific RTLS technologies

The results in terms of most frequent RTLS technologies included in the sample of journals follow.

Radio-frequency identification (RFID)

RFID is a technology that stores and retrieves data by using electromagnetic transmission and a radio frequency (RF) compatible integrated circuit (Ni et al., 2004). The use of RFID is common in complex indoor environments such as in office buildings and hospitals, as it provides a considerably cheap and flexible approach to identifying individual people and devices (Chon et al. 2004).

Although RFID is neither the most accurate nor the most conveniently deployed RTLS, its application in the construction industry has been researched intensively, with 36 positioning studies in our sample. Previous studies of RFID are summarized in Table 3. In 2006, Song et al. (2006) found that using RFID for tracking the location of pipe spools speeded up the installation process. Tracking materials in this way proved to be useful in other studies too (Ergen et al., 2007; Grau et al., 2009; Razavi and Haas, 2010; Razavi and Haas, 2012). RFID has also been used for tracking workers or equipment (e.g. Lu et al., 2007; Ding et al., 2013). Further studies simultaneously track the location of both workers and equipment (Wu et al., 2010; Teizer et al. 2010; Brilakis et al. 2011; Wu et al. 2013) or workers and materials (Costin et al. 2012; Montaser and Moselhi 2014). In general, RFID is used in indoor environments. When used in outdoor environments, it is usually integrated with GPS to cover large open areas (e.g. Ergen et al., 2007; Lu et al., 2007; Grau et al., 2009; Razavi and Haas, 2010).

<INSERT TABLE 3>

It has also proved to be accurate in indoor environments. For 2D positioning, Song et al (2006) report an average error of only 3.7 m, which is similar to that reported by Gu et al. (2009). Later experimental work by Razavi and Moselhi (2012) in indoor environments found an average error of 1.3 m. The accuracy of RFID can be improved by using different locating techniques and algorithms. For example, Montaser and Moselhi (2014) compare accuracy by two locating techniques, triangulation and proximity, while Ko (2010) compares the accuracy of the different algorithms being used.

Some systems are also less costly than others. Experimental work by Costin et al. (2012), for example, has shown that passive systems (where tags are fixed on locations to calculate the real-time location of a receiver) are cheaper than active systems (where receivers are used to read the location of a tag), due to the reduced number of RFID readers involved.

Global positioning system (GPS)

A total of 16 GPS-related publications are identified in this study. GPSs use a triangulation method to obtain the position (x, y, z) of a receiver. The position is calculated by measuring the distance from a set of satellites to the GPS receiver, the duration of travel of the GPS signal from satellite to receiver and the speed of light (Zito et al., 1995). Applications include continuously tracking the location of equipment such as caterpillars and trucks to monitor their arrival and departure times on construction sites (Hildreth et al., 2005) and record the cyclic activities of equipment for further analysis (Pradhananga and Teizer, 2013). Song and Eldin (2012), for example, use real-time data for updating a base model and predicting delays in truck cycles to reduce the prediction error of cycle times by 6%. GPS can also track the location of materials to calculate their installation times and improve traditional material identification. For example, a GPS receiver integrated into current fabricated pipe spool receiving, storing, and issuing processes in lay down yards of a particular industrial project reduced an average of 6 min 47 s to locate a spool to 55 s (Caldas et al., 2006).

The reported accuracy of GPS varies. Lu et al. (2007), for example, recorded an average error of less than 10 m when using GPS and dead reckoning technology together with the Bluetooth beacon (installed on the road side) to track the location of a truck in a large dense urban area. In contrast, Pradhananga and Teizer (2013) obtained an average error of 1.1 m in an open area in testing the use of GPS for tracking equipment in an urban area - increasing to 2.15 m and 4.36 m in situations with nearby obstacles.

GPS has also been recommended for use with RFID (Torrent and Caldas, 2009). Riaz et al. (2006) believe that, by using the data fusion approach, GPS can monitor construction safety by preventing collisions between workers and equipment. Razavi and Haas (2012) have tested this with a few hybrid fusion approaches, finding that the Dempster Shafer method has an average error to 3.22 m. GPS can also provide a highly accurate result in combination with multiple sensors, with Saeki and Hori's (2006) outdoor experiment of a GPS wireless sensor network having an error of less than 3 cm in the horizontal direction and 5 cm in the vertical direction. Alternatively, Behzadan et al. (2008) have suggested integrating GPS with Virtual Reality for context-specific information delivery on construction sites.

Ultra-wideband (UWB)

17 publications investigating the use of UWB in the construction industry were identified. UWB belongs to the radio frequency (RF) positioning family. It has a short pulse, enabling the reflected signal to be filtered from the original signal to help overcome multi-path distortion in indoor environments and provide more accurate results (Ingram et al., 2004).

Extensive studies have been carried out to verify the accuracy of UWB in different environments. A summary of 10 of these is presented in Table 4. Its performance has been extensively tested in both indoor and outdoor environments. Overall, it has an average error of within 50 cm. The performance of UWB is less accurate when it is deployed in large areas such as laydown yards of 65 000 m^2 (Cheng et al., 2011) and 100 000 m^2 (Saidi et al., 2011). The accuracy is also considerably lower when there are obstacles such as boxes involved (Cho et al., 2010; Saidi et al., 2011). Another factor that may decrease the accuracy of UWB is the distance between tags (Shahi et al., 2012). Cheng et al. also (2011) consider the frequency of the tag in conducting tests in open areas and a construction environment (covering 65 000 m^2), finding the accuracy of the system to be 0.41 m for a 1 Hz tag and 0.34 m for a 60 Hz tag in a construction pit. Another experiment in a lay down yard found the accuracy to be 1.26 m for 1 Hz tag and 1.23 m for 60 Hz tag. The results indicate that the frequency of the tag may slightly improve the accuracy of the system while obstructions can have a dramatic effect on accuracy.

<INSERT TABLE 4>

To assess the influence of the environment, Maalek and Sadeghpour (2013) conducted seven experiments to determine the performance of UWB indoors and under metal, with different deployment and obstacle configurations and positioning techniques. The accuracy of the system in open areas is 20 cm (70% confidence) in 2D and 40 cm

(70% confidence) in 3D as shown in Table 5.

<INSERT TABLE 5>

Construction applications include general tracking workers (Yang et al., 2011) and equipment (Cheng et al., 2011); for example, to estimate the working cycle of an excavator (Vahdatikhaki and Hammad, 2014) The main application of UWB in construction, however, has been in the safety and training of workers. Cheng and Teizer (2013), for example, have developed a construction safety and monitoring system by visualization of the data collected by UWB. This has been helpful in preventing collisions, by monitoring the movement of tower cranes and other equipment on site (Hwang, 2012) and simultaneously tracking the real-time location of both workers and equipment (Carbonari et al., 2011). A UWB system has also been deployed in a safety-training center for ironworkers to check that trainees are correctly located and understand the trainers' instructions (Teizer et al., 2013). In the latter case, this was also helpful in improving productivity, where the installation time of a beam was gradually reduced from 500 s to 100 s after using the positioning system in training. Shahi et al. (2013) have also used UWB positioning data to estimate the path lengths and progress of pipe installation, with a 5.01 m error and 16.59 m absolute error over a total distance of 276.63 m. The highly accurate results obtained by UWB also provide opportunities to collect thoracic posture data of construction workers (Cheng et al., 2013b) for physiological status monitoring and ergonomic analysis (Cheng et al., 2013a).

One of the limitations of UWB is that its deployment requires the connection of a local-area-network (LAN) to the receivers (e.g. Cheng et al. 2011; Cheng et al., 2012; Zhang et al., 2012), while a LAN may not be available at the initial stage of construction work.

Vision Analysis

Vision-based positioning can provide results with 88% accuracy and was proposed for use in indoor environments as early as 2000 (Krumm et al. 2000). For vision-based positioning, the target object does not need to carry any device. Vision-based systems can cover a relatively large area but are also limited by the surrounding environment. For example, lighting and background color may affect the accuracy of the system. The system is also less accurate when used in a dynamic environment (Gu et al., 2009).

A total of 11 previous studies relating to vision-based positioning for construction use were identified. Park et al. (2011) track a worker, concrete bucket, timer, dozer and wheel loader on site to examine the errors occurring under different conditions, such as illumination, occlusion and sale variation. Improvements in the technology and the development of new algorithms later improved object identification to 99% precision and with a 0.67 s time lapse for identifying workers wearing safety vests (Park and Brilakis, 2012). Han and Lee (2013) use vision-based positioning to capture unsafe worker behavior, the developed system automatically detecting 88% of all identified unsafe behaviors. Memarzadeh et al. (2013) carried out a six-month experiment of a vision-based positioning system and recorded a total of 300 hours video streams for five construction projects. Although theirs was not a real-time positioning system, it can recall more than 98% of workers, 82% of excavators and 84% of trucks from the video streams. Yang et al. (2014) extend the use of vision-based systems to track the position of tower cranes and successfully estimate the locations of tower cranes to track on-going activity. An average error of 10 to 15% was recorded in the study. Similar work was also conducted by Ray and Teizer (2012), who used a range camera to capture the detailed working posture of workers for ergonomic analysis.

The errors in vision-based positioning vary considerably between these studies. Teizer and Vela's (2009) comparison of four visual tracking algorithms: 1) Mean-shift tracking; 2) Bayesian contour tracking; 3) Active contour tracking; and 4) Graph-cut tracking, indicate Bayesian contour tracking to have the least average error (0.81 to 3.32 unit in pixels). Active contour and graph-cut lose track in the presence of similar colored nearby barrels or during the first few frames are negatively affected. Yang et al. (2010) have carried out experiments in an outdoor environment and found that pan-tilt-zoom cameras, with an average error between 2.41 and 8.45 m, provide a better result but fail in situations that are strongly shadowed, occluded and involve changes in workers' appearance. Brilakis et al. (2011) use a 65 mm truck model to test the accuracy of vision-based positioning, recording a maximum error of 0.095 m, which projects to 9.17 m in the full-size case. Yang et al. (2011) test the accuracy of both UWB and vision-based positioning systems, finding the accuracy of the vision-based positioning system to be within 1 m. Park et al. (2012) conducted a test on a construction site involving a steel-frame to track both a van and workers, finding the best result to be a 0.658 m error.

Wireless local area network (WLAN)

Four previous studies use WLAN. A WLAN-based positioning system can reuse the infrastructure of an existing WLAN. It usually calculates the position of an object according to signal strength. Bahl and Padmanabhan (2000) propose an indoor positioning system called *RADAR*, which uses the triangulation method, signal strength and signal-to-noise ratio to obtain the 2D location of the target object to an accuracy of about 4 m. A limitation is the need for the target to be connected to the WLAN, which makes it difficult, if not impossible, to track the location of a person. Recent developments, however, make WLAN usable in wireless network environments, so that tracking a moving object is now a possibility.

Three of the previous studies tested the WLAN performance. Khoury and Kamat (2009), for example, tested WLAN in a laboratory, with an average error of 2 m. Woo et al. (2011) tested a WIFI-based WLAN positioning system in a shield tunnel construction project, using received signal strength indication (RSSI) from each access point (AP) to calculate the location of workers. When the tag was static, the average error was 6.89 m in the vertical direction and 4.53 m in the horizontal direction. Another two experiments were carried out to find the accuracy of the system when the tag was moving. Errors between 0.63 m and 4.38 m in the second experiment and 2.93 m to 5.92 m in the third experiment were reported. Taneja et al.'s (2012) study also indicated that WLAN could have errors between 1.5 to 4.57 m (95% confidence) for a static target and 7.62 m error (95% confidence) for a moving object. The errors were found to depend on the frequency of the wireless network, signal strength, device and orientation.

Ultrasound

The development of ultrasound positioning systems has been inspired by the ultrasound signals naturally used by bats to navigate in a dark environment. *Cricket* (Priyantha et al., 2000; Priyantha, 2005) is an ultrasound based positioning system, which uses TOA and triangulation location to track an object. With *Cricket*, however, the object carries a receiver while the emitters are mounted on the walls or ceiling in known positions. The system uses RF as a second method to provide location data when insufficient emitters are available. Experiments show that *Cricket* can track the location of an object with an error of 10 cm and orientation accuracy of 3^o.

Ultrasound positioning systems, however, do have some limitations. For example, ultrasound signals cannot penetrate walls and can be distorted by reflected signals and noise such as that caused by metal objects.

In this study, only four related publications were identified. Skibniewski and Jang (2009), for example, compare the performance of ultrasound+RF with RF alone by numerical simulation and find ultrasound+RF to be the more accurate. This system uses US for positioning and RF serves as a trigger to emit ultrasound pulses from a remote node – the pulses being used as a sender of time-stamp messages generated in the remote node. Jang and Skibniewski (2009a) then use the system for tracking assets on site, finding the accuracy of the system to be less than 0.2 m (80% confidence) in line-of-sight LOS conditions (ultrasound waves cannot penetrate objects without sufficient signal strength). The ranging distance of the system is from 1 to 15 m. Another experiment conducted by Jang and Skibniewski (2009b) found an average error of 0.97 m in an outdoor environment. By simulating the environment of a construction site, Jang and Skibniewski (2009b) showed that the system has the potential to save up to 64% of labor costs for material tracking.

Infrared (IR)

IR enables LOS communication between transmitters and receivers. It is widely used for the remote control of various devices, such as TVs, printers and cell phones (Casas et al. 2007). Two previous studies were identified. Teizer et al. (2007) initially propose the use of a 3D range camera to detect and track construction resources, including walls, workers and skid steer loaders. Their experiments show the dimension error to be less than 0.12 m (11% of the size of the object). However, the range camera can only obtain positioning data of an object at a distance of 7.5 m. Chi et al. (2009) propose using a range camera "Swiss Ranger SR-2", which is a high-frame-rate sensor, to capture the 3D image of four objects: 1) a box; 2) a pipe; 3) a wallboard; and 4) a human. The results indicate the matching rate to be only 37% to 73%. The cost of IR-based positioning was within the $1000 reported by Lytle et al. (2005). IR is limited by its relatively short ranging distance (approximately 7.5 m) but it is thought that future hardware upgrades may eventually solve the problem (Teizer et al., 2007).

Summary

In general, the articles surveyed indicate that researchers in the construction industry to date have responded quickly to newly available RTLS as, in addition to the ten selected technologies, they contains several new RTLS application ideas, such as inertial measurement units (IMU) (Taneja et al., 2012) and indoor GPS systems (Khoury and Kamat, 2009). The indoor GPS system described by Khoury and Kamat (2009) uses laser and infrared to obtain the position of the receiver by the triangulation method. An average error of 0.01 to 0.02 m was achieved by the system in the LOS environment, but the system was expensive. The IMU also recorded a drift error from 3.8 m to 13.1 m for the two routes (Taneja et al., 2012). The experimental results for IMU are heavily influenced by the environment, where errors increase dramatically with the level of electromagnetic interference.

This section summarized the findings of the study categorized by technologies. While RFID has attracted the most interest in the last decade, the use of positioning technologies such as Bluetooth, infrared, audible sound and magnetic signals have yet to be studied (or reported) in the construction industry. The use of other positioning systems, their performance and limitations are discussed in the next section.

RESULTS AND DISCUSSION

Performance of the RTLS

Numerous previous studies have evaluated the performance of RTLS in construction and indoor environments. These are summarized in Table 6 for the ten RTLS considered here. The results (e.g. by experiments and case study) indicate a similar accuracy to that of commercially available RTLS (Gu et al., 2009). New calculation techniques and algorithms have often been developed by researchers who have tried to improve the performance of RTLS in the construction environment. Examples of these are listed in Table 7. In some cases, such as with RFID, the accuracy has been found to be better than that claimed by the commercial hardware developer. Montaser and Moselhi’ s (2014) tests on the accuracy of their RFID-based system, for example, indicate a 1 m average error in locating a person in an indoor environment compared with an error of 2-3 m claimed by a commercial RFID developer (Gu et al., 2009).

A further issue concerns false alarms, generated because of the inaccurate positioning of workers or equipment. As a result of their experimental work on this with UWB, Carbonari et al. (2011) developed a new framework that reduced the occurrence of false alarms but were unable to achieve their total elimination. Although this is clearly an important practical area of research, no other studies have yet been made in the construction context.

<INSERT TABLE 6>

<INSERT TABLE 7>

RTLS application in the building life cycle

The study of RTLS in the planning and design of buildings has been very limited to date. The only literature encountered is Garcia et al. (2006), who propose the use of RTLS to collect traffic data near the construction site for planning purposes. For the construction stage, many of the studies focus on real-time location data analysis for management purposes, in particular for construction safety and process management (Table 7), which uses a virtual fencing approach to cordon off hazardous areas. Through monitoring the real-time location of workers, this aims to identify those who enter such hazardous areas.

For construction process management, the majority of the sample articles focus on monitoring the location of equipment and materials. Less than half the previous studies (Han and Lee, 2013; Teizer et al. 2013; Wu et al. 2010; Garcia et al., 2006; Cheng et al., 2013; Cheng et al. 2013b; Grau et al., 2009; Demiralp et al., 2012) try to analyze the position data to extract useful information, with the majority using RTLS to obtain real-time data for real-time management.

During the construction phase, RTLS has been used to monitor safety by tracking the locations of both workers (e.g. Ding et al., 2013) and equipment (e.g. Li and Liu, 2012). Wu et al. (2010) propose using RTLS to capture and report near-miss accidents. RTLS has also been suggested for use in safety training (Teizer et al., 2013). The detailed posture of workers can be captured by more accurate positioning data, which allows for ergonomic analysis (Cheng et al. 2013) and the analysis of worker behavior (Han and Lee, 2013).

Other than safety management, the use of RTLS has been proposed to enhance the management of the construction process, such as in improved productivity (e.g. Cheng et al. 2013b), resource management (e.g. Costin et al., 2012) and materials management (Ergen et al. 2007). Additionally, the real-time data being collected can be used for construction monitoring (Akula et al., 2013) and simulation (Vahdatikhaki and Hammond, 2014).

RTLS has also been advocated for use in asset management (Kumar and Sommerville, 2012) and facilities management, such as in HVAC control for power saving (e.g. Dzeng et al. 2014), maintenance (Taneja et al. 2012) and concrete monitoring (Adhikari et al., 2014). Seven articles in the sample focus on improving building operation and maintenance. These aim to track the real-time location of assets within the building for management purposes (Kumar and Sommerville, 2012; Motamedi et al., 2013; Li et al., 2013). RTLS can also be used to track the location of occupants to optimize function-space assignment (Dzeng et al., 2014) and HVAC operations (Li et al., 2012).

<INSERT TABLE 8>

RTLS benefits

It is well accepted that RTLS has the potential to track the location of materials. Grau et al. (2009) estimate that RTLS-based materials tracking can improve traditional tracking from 36.8 min to 4.56 min and has the potential to save $121,507, while Jang and Skibniewski (2009) estimate that RTLS-based materials tracking can save up to 64% of labor costs for a 24 month duration construction project. Using real-time data for simulation has also helped Song and Eldin (2012) to estimate an additional delay of 16.3 min to truck cycles and thus reduce cycle-time prediction error by 6%. Real time data also enables the estimation of cyclical activities of equipment (Pradhananga and Teizer, 2013). Alternatively, Han and Lee (2013) demonstrate the potential of vision-based positioning systems for safety monitoring. The automatic detection of unsafe behavior provides an innovative approach to improve the safety of construction workers. Detecting the number of occupants within an area by using RTLS can also help formulate the most suitable strategy for the use of facilities and power saving (Li et al., 2012b).

Characteristics of different RTLS

The use and deployment of RTLS creates different problems in dynamic environments. For example, GPS does not work in indoor environments and its accuracy decreases in highly dense areas when signals are blocked (Lu et al., 2007; Pradhananga and Teizer, 2013). Ultrasound can provide the most accurate result but requires LOS configuration, as ultrasound can only penetrate objects with sufficient signal strength (Jang and Skibniewski, 2009a). Similar to ultrasound, vision-based systems suffer from illumination, occlusion and scale variation (Park et al., 2011). Vision-based systems can lose track of an object when its appearance changes too much or is strongly shadowed (Yang et al., 2010). For UWB and RFID, as both of the systems are radio frequency based, their receivers require a LAN connection in order to provide accurate positioning data. Removing the LAN connection results in a dramatic decrease in accuracy (Maalek and Sadeghpour, 2013). For construction work, it can be difficult to deploy a LAN over the entire site, especially in large open areas, and outdoor cables may be required when using UWB and RFID (Zhang et al., 2012), although this may also increase the cost. UWB and RFID also suffer from metal effects (Shahi et al., 2012; Kim et al., 2010). Obstructions, such as walls and workers on a construction site, is another factor affecting their performance (Goodrum et al., 2006; Li et al., 2012a; Maalek and Sadeghpour, 2013). WLAN-based positioning systems provide the most inaccurate results when compared with other RTLS (see Table 6). When using RTLS, therefore, careful consideration needs to be made of factors such as the environment, cost and the required accuracy.

Based on these limitations, GPS is the most suitable RTLS for tracking objects in large and open areas, especially when accuracy is not the primary concern. Ultrasound can provide the most accurate results in LOS conditions. UWB and RFID have a huge potential in facilities management where LAN is completely deployed in the building. Cost could be reduced by using existing LAN infrastructure. WLAN-based positioning systems can also reuse the infrastructure of existing LAN and is an economical solution when compared with UWB (Khoury and Kamat, 2009), as well as providing reasonably accurate positioning data. Vision-based positioning systems work in both indoor and outdoor environments when occlusion problems do not exist. Such systems can precisely capture the detailed posture of workers and tower cranes for further analysis (Han and Lee, 2013; Yang et al., 2014).

Limitations of previous work

Despite this topic having been extensively studied in the past decade, several aspects have received little or no attention to date. Cost and deployment are two important factors affecting the choice of RTLS in construction projects, but only a few studies (e.g. Grau et al., 2009; Costin et al. 2012) have considered the costs involved. This makes it difficult for the industry to adopt RTLS. Li et al.'s (2012) tests of the use of virtual tags to improve the robustness of their RFID-based positioning system is the only example for RTLS infrastructure. The robustness of other RTLS also needs to be tested in order to identify their potential benefits or limitations for use with construction work.

Reported accuracy levels vary widely between studies and it is believed that the experimental setting involved is one of the reasons for this. However, several studies do not give details of their settings. Razavi and Haas (2012), for example, test the performance of an RFID system on a construction site but do not mention the existence or otherwise of any obstacles or anything else that may affect the system; while Khoury and Kamat (2009) carry out an experiment in a maze with walls that appear to be only 1-2 m high. While the results of these experiments would certainly be affected by the surrounding environment, the absence of detailed information makes interstudy comparisons difficult. There are also studies, such as by Hand and Lee (2013), that uses RTLS to capture real-time data for analysis off-line. Real-time analysis is a big data issue that has the potential for provide a significant improvement.

DIRECTION FOR FUTURE WORK

One of the benefits of a review of this kind is to reveal a grander view than is usual with single individual studies. This is a particular benefit in identifying important aspects that have yet to be fully investigated and therefore main areas for future research. These are summarized in this section in terms of RTLS re-use of real-time data, health and occupational issues, FM applications, false alarms and latest developments.

Re-use of real-time data

Using RTLS to capture the location of tags (workers, resources and materials) within a site involves collecting a large set of data. After analysis, this can provide useful information other than for real-time management, such as the patterns of movement of workers to observe the daily routes to their workplaces. As Petzold et al. (2005) observe, people usually follow a routine in their working environment, so their location can be predicted by using previous locational information. By comparing the daily route of workers with a 4D simulation of the construction schedule, it is possible to anticipate potential collisions. This would help identify workers with a higher risk of entering areas of *ad hoc* equipment operations, such as tower crane dismantlement. In fact, Akula et al. (2013) have shown that comparing real time locations with simulation in this way offers a practicable approach to real-time drill management.

Health and occupational issues

As mentioned earlier, RTLS provides only the geometric data of the tag. To extend the use of RTLS, another potential activity is to increase the type of data being collected. For example, personal health monitoring devices are cheap and in common use and precisely capture the health index of a person, such as heart rate, blood pressure and body temperature. This can be attached to a wireless sensor network for personal health monitoring (Milenković et al., 2006). Implementing this on construction sites would mean that both the location and health data of workers could be collected for further analysis or real-time worker management. Another method is to use RTLS to capture extra information, such as in Han and Lee's (2013) use of vision-based analysis to capture the detailed posture of workers for carrying out behavior analysis (Han and Lee, 2013).

Application in facilities management

As noted previously, the use of RTLS for facilities management (FM) is an under-researched area (only seven publications being identified, see Table 8), which is surprising as FM is an important activity and RTLS lends itself well to the operation phase of buildings as it allows a more complex deployment process and longer deployment time. Using RTLS for FM could also help in recording the movements of occupants for further analysis, such as in fire escape simulation.

Effect of false alarms

Also as described earlier, real-time safety management systems create false alarms due to the inaccuracy of the RTLS being used (Carbonari et al., 2011), affecting the productivity and safety attitudes of workers. It would be beneficial for future research to investigate workers' response to false alarms in the workplace and develop new mechanisms to distinguish between false and correct alarms.

Latest development in RTLS

Future research could also focus on the latest developments in RTLS. The accuracy of RTLS has dramatically improved in recent times. For example, Kul et al.'s (2014) tests of a new IEEE802.11 WLAN based real time indoor positioning system found it to be very accurate, inexpensive and compatible with the smartphone and tablet. Similarly, Lopes et al.'s (2014) tests on a wireless sensor network and non-invasive audio based indoor positioning system found an average error of only 0.1 m with 95% confidence while the system is also compatible with smartphones. The use of smartphones can eliminate problems, such as power and deployment problems, that can occur when tagging construction workers. To further improve the accuracy of RTLS in indoor environments, Xu et al. (2015) propose using a flexible indoor map and simple route-planning algorithm as a reference value to the indoor navigation system design. Other innovative methods, such as using plane models for improving accuracy (Lu et al., 2015), new positioning algorithms (Zhao and Wu 2015) or alternative technologies (i.e. inertial sensors) for positioning (Liu et al., 2015), are also being considered in electrical engineering studies. Some of these new developments have the potential to increase the accuracy of the system in the construction environment.

Meanwhile, the cost of the RTLS is another area that could be improved. For example, Carboni et al. (2015) introduce an infrastructure-free navigation system based on the smartphone. The system uses an accelerometer, gyroscope, camera and the internet to obtain the real-time location of the user. The system is infrastructure-free so that its installation cost is very low. There is limited information in previous studies concerning the installation time and cost of using RTLS for construction work and the infrastructure-free system may suit the dynamic nature of construction environments, where the structure of the building changes rapidly.

The use of mobile phones for positioning purposes, as suggested by Xue et al. (2015) and Lopes et al. (2014) may also provide a new opportunity to the construction industry, as some workers are concerned about the size and the weight of the tags, which may be an encumbrance in their daily work. On the other hand, workers generally bring their mobile phones to work in order to communicate with their supervisor and fellow workers, providing an alternative to tags in tracking their location.

Limitations of the study

The aim of this study was to identify and analyze all the literature concerning the use of RTLS with construction work. With over 3000 such articles found by the search engines, it was necessary to select a sample of these. Choosing 5 journals solved the problem, resulting in the acquisition of the 75 academic journal articles. As with all non-random sampling, this necessarily has the potential to introduce some bias into the results and obviously overlooks some related previous work. For example, papers published in conference proceedings (e.g. Teizer et al., 2007) are not included. Similarly, articles in non-construction areas, such as transportation research (Teizer et al., 2008), iron and steel technology (Marks and Teizer, 2012) are also excluded. Han and Lee's pioneering work in vision-based analysis is retained, while previous significant work in ergonomics (e.g. Kim et al. 2011) is excluded. Future research could examine the use of RTLS in different industries for potential application in construction.

CONCLUSION

This paper summarizes the use of different RTLS in construction research from 2005 to 2014 from 75 articles identified in 5 selected journals. RFID, UWB and GPS are the major RTLS technologies covered in the sample articles, and researchers have explored their use for different construction-related purposes, such as in construction process management, safety management and, in many cases, on-site resource management. RTLS can track the location of objects as small as hand tools and as large as the movement of a tower crane. The applications considered occur mostly during the production stage, with few in design and maintenance and none for any other stages of the project life cycle. The benefits, limitations, costs and characteristics of the RTLS are also discussed and summarized. Each RTLS has different characteristics and none can be applied in all environments. This study summarizes the available information, which is a useful reference for industry, based on its requirements, budget and conditions.

The accuracy of the RTLS is of paramount importance, in avoiding false alarms for instance, and RTLS such as Bluetooth and infrared are known to be extremely accurate in indoor environments. However, these, and several other technologies, have not been considered for possible use in the construction sector due to their unsuitable properties. For example, audible sound-based positioning systems are sensitive to background noise; magnetic signal positioning systems have a short cover range and are therefore of limited application in a dynamic construction environment; and Bluetooth can only obtain two-dimensional positioning data. Over 50% of the articles relate to experimental work and very few have been fully implemented in real construction projects. As a result, little is known of the practical issues involved in implementation, such as deployment time, cost and decrease in accuracy of the system due to noise, time taken, etc. These issues seem to have a greater effect on the more accurate systems, and ways are needed of overcoming these problems.

In addition, while most of the research to date focuses on using the positioning data of workers, resources and materials for management, it is advocated that future research should further extend the use of RTLS to capture more information, such as that relating to health and safety and facilities management.

REFERENCES

Adhikari, R. S., Moselhi, O., & Bagchi, A. (2014). Image-based retrieval of concrete crack properties for bridge inspection. Automation in Construction, 39, 180-194.

Akula, M., Lipman, R. R., Franaszek, M., Saidi, K. S., Cheok, G. S., & Kamat, V. R. (2013). Real-time drill monitoring and control using building information models augmented with 3D imaging data. Automation in Construction, 36, 1-15.

Bahl, P., & Padmanabhan, P. (2000). "RADAR: An in-building RF based user location and tracking system", Proc. IEEE INFOCOM, vol. 2, pp. 775 -784.

Behzadan, A. H., Aziz, Z., Anumba, C. J., & Kamat, V. R. (2008). Ubiquitous location tracking for context-specific information delivery on construction sites. Automation in Construction, 17(6), 737-748.

Beliveau, Y. J. (1996). What can real-time positioning do for construction? Automation in Construction, 5(2), 79-89.

Boulos, M. N. K., & Berry, G. (2012). Real-time locating systems (RTLS) in healthcare: a condensed primer. International Journal of Health Geographics, 11(1), 25.

Brilakis, I., Park, M. W., & Jog, G. (2011). Automated vision tracking of project related entities. Advanced Engineering Informatics, 25(4), 713-724.

Brumitt, B., Meyers, B., Krumm, J., Kern, A., & Shafer, S. (2000). Easyliving: Technologies for intelligent environments. In Handheld and Ubiquitous Computing (pp. 12-29). Springer Berlin Heidelberg.

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

Carbonari, A., Giretti, A., & Naticchia, B. (2011). A proactive system for real-time safety management in construction sites. Automation in Construction, 20(6), 686-698.

Carboni, D., Manchinu, A., Marotto, V., Piras, A., & Serra, A. (2015).

Infrastructure-free indoor navigation: a case study. Journal of Location Based Services, (ahead-of-print), 1-22.

Casas, R., Cuartielles, D., Marco, A., Gracia, H. J., & Falco, J. L. (2007). Hidden issues in deploying an indoor location system. IEEE Pervasive Computing, 6(2), 62-69.

Chae, S., & Yoshida, T. (2010). Application of RFID technology to prevention of collision accident with heavy equipment. Automation in Construction, 19(3), 368-374.

Chau, K. W. (1997). The ranking of construction management journals. Construction Management & Economics, 15(4), 387-398.

Cheng, T., & Teizer, J. (2013). Real-time resource location data collection and visualization technology for construction safety and activity monitoring applications. Automation in Construction, 34, 3-15.

Cheng, T., Mantripragada, U., Teizer, J., & Vela, P. A. (2012). Automated trajectory and path planning analysis based on ultra wideband data. Journal of Computing in Civil Engineering, 26(2), 151-160.

Cheng, T., Migliaccio, G. C., Teizer, J., & Gatti, U. C. (2013a). Data fusion of real-time location sensing and physiological status monitoring for ergonomics analysis of construction workers. Journal of Computing in Civil Engineering, 27(3), 320-335.

Cheng, T., Teizer, J., Migliaccio, G. C., & Gatti, U. C. (2013b). Automated task-level activity analysis through fusion of real time location sensors and worker's thoracic posture data. Automation in Construction, 29, 24-39.

Cheng, T., Venugopal, M., Teizer, J., & Vela, P. A. (2011). Performance evaluation of ultra wideband technology for construction resource location tracking in harsh environments. Automation in Construction, 20(8), 1173-1184.

Chi, S., Caldas, C. H., & Kim, D. Y. (2009). A methodology for object identification and tracking in construction based on spatial modeling and image matching techniques. Computer-Aided Civil and Infrastructure Engineering, 24(3), 199-211.

Cho, Y. K., Youn, J. H., & Martinez, D. (2010). Error modeling for an untethered ultra-wideband system for construction indoor asset tracking. Automation in Construction, 19(1), 43-54.

Chon, H. D., Jun, S., Jung, H., & An, S. W. (2004). Using RFID for Accurate Positioning. Journal of Global Positioning Systems, 3(1-2), 32-39.

Costin, A., Pradhananga, N., & Teizer, J. (2012). Leveraging passive RFID technology for construction resource field mobility and status monitoring in a high-rise renovation project. Automation in Construction, 24, 1-15.

Deak, G., Curran, K., & Condell, J. (2012). A survey of active and passive indoor localisation systems. Computer Communications, 35(16), 1939-1954.

Demiralp, G., Guven, G., & Ergen, E. (2012). Analyzing the benefits of RFID technology for cost sharing in construction supply chains: A case study on prefabricated precast components. Automation in Construction, 24, 120-129.

Ding, L. Y., Zhou, C., Deng, Q. X., Luo, H. B., Ye, X. W., Ni, Y. Q., & Guo, P. (2013). Real-time safety early warning system for cross passage construction in Yangtze Riverbed Metro Tunnel based on the internet of things. Automation in Construction, 36, 25-37.

Dzeng, R. J., Lin, C. W., & Hsiao, F. Y. (2014). Application of RFID tracking to the optimization of function-space assignment in buildings. Automation in Construction, 40, 68-83.

Dziadak, K., Kumar, B., & Sommerville, J. (2009). Model for the 3D location of buried assets based on RFID technology. Journal of Computing in Civil Engineering, 23(3), 148-159.

Ergen, E., Akinci, B., & Sacks, R. (2007). Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS. Automation in Construction, 16(3), 354-367.

Garcia, C., Huebschman, R., Abraham, D. M., & Bullock, D. M. (2006). Using GPS to measure the impact of construction activities on rural interstates. Journal of Construction Engineering and Management, 132(5), 508-515.

Goodrum, P. M., McLaren, M. A., & Durfee, A. (2006). The application of active radio frequency identification technology for tool tracking on construction job sites. Automation in Construction, 15(3), 292-302.

Grau, D., Caldas, C. H., Haas, C. T., Goodrum, P. M., & Gong, J. (2009). Assessing the impact of materials tracking technologies on construction craft productivity. Automation in Construction, 18(7), 903-911.

Gu, Y., Lo, A., & Niemegeers, I. (2009). A survey of indoor positioning systems for wireless personal networks. Communications Surveys & Tutorials, IEEE, 11(1), 13-32.

Han, S., & Lee, S. (2013). A vision-based motion capture and recognition framework for behavior-based safety management. Automation in Construction, 35, 131-141.

Hildreth, J., Vorster, M., & Martinez, J. (2005). Reduction of short-interval GPS data for construction operations analysis. Journal of Construction Engineering and Management, 131(8), 920-927.

Hwang, S. (2012). Ultra-wide band technology experiments for real-time prevention of tower crane collisions. Automation in Construction, 22, 545-553.

Ingram, S. J., Harmer, D., & Quinlan, M. (2004, April). Ultra wideband indoor

positioning systems and their use in emergencies. In Position Location and Navigation Symposium, 2004. PLANS 2004 (pp. 706-715). IEEE.
Jang, W. S., & Skibniewski, M. J. (2009). Embedded system for construction asset tracking combining radio and ultrasound signals. Journal of Computing in Civil Engineering, 23(4), 221-229.
Ke, Y., Wang, S., Chan, A. P., & Cheung, E. (2009). Research trend of public-private partnership in construction journals. Journal of Construction Engineering and Management, 135(10), 1076-1086.
Khoury, H. M., & Kamat, V. R. (2009). Evaluation of position tracking technologies for user localization in indoor construction environments. Automation in Construction, 18(4), 444-457.
Kim, C., Kim, H., Ryu, J., & Kim, C. (2010). Ubiquitous sensor network for construction material monitoring. Journal of Construction Engineering and Management, 137(2), 158-165.
Kim, C., Kim, H., Ryu, J., & Kim, C. (2010). Ubiquitous sensor network for construction material monitoring. Journal of Construction Engineering and Management, 137(2), 158-165.
Ko, C. H. (2010). RFID 3D location sensing algorithms. Automation in Construction, 19(5), 588-595.
Krumm, J., Harris, S., Meyers, B., Brumitt, B., Hale, M., & Shafer, S. (2000). Multi-camera multi-person tracking for easyliving. In Proceedings Third IEEE International Workshop on Visual Surveillance, (pp. 3-10). IEEE.
Kul, G., Özyer, T., & Tavli, B. (2014). IEEE 802.11 WLAN Based Real Time Indoor Positioning: Literature Survey and Experimental Investigations. Procedia Computer Science, 34, 157-164.
Kumar, B., & Sommerville, J. (2012). A model for RFID-based 3D location of buried assets. Automation in Construction, 21, 121-131.
Lee, H. S., Lee, K. P., Park, M., Baek, Y., & Lee, S. (2012). RFID-based real-time locating system for construction safety management. Journal of Computing in Civil Engineering, 26(3), 366-377.
Li, N., Calis, G., & Becerik-Gerber, B. (2012a). Measuring and monitoring occupancy with an RFID based system for demand-driven HVAC operations. Automation in Construction, 24, 89-99.
Li, N., Li, S., Becerik-Gerber, B., & Calis, G. (2012b). Deployment strategies and performance evaluation of a virtual-tag-enabled indoor location sensing approach. Journal of Computing in Civil Engineering, 26(5), 574-583.
Li, N., Li, S., Calis, G., & Becerik-Gerber, B. (2013). Improving In-Building Asset Localization by Offset Vector and Convergence Calibration Methods. Journal of

Computing in Civil Engineering, 27(4), 337-344.

Li, Y., & Liu, C. (2012). Integrating field data and 3D simulation for tower crane activity monitoring and alarming. Automation in Construction, 27, 111-119.

Liu, W., Zhang, Y., Yang, X., & Xing, S. (2015). Pedestrian navigation using inertial sensors and altitude error correction. Sensor Review, 35(1), 68-75.

Lopes, S. I., Vieira, J. M., Reis, J., Albuquerque, D., & Carvalho, N. B. (2014). Accurate smartphone indoor positioning using a WSN infrastructure and non-invasive audio for TDoA estimation. Pervasive and Mobile Computing, 20, 29-46.

Lu, M., Chen, W., Shen, X., Lam, H. C., & Liu, J. (2007). Positioning and tracking construction vehicles in highly dense urban areas and building construction sites. Automation in Construction, 16(5), 647-656.

Lu, W., Huang, G. Q., & Li, H. (2011). Scenarios for applying RFID technology in construction project management. Automation in Construction, 20(2), 101-106.

Lu, T. T., Yeh, S. C., & Wu, S. H. (2015). Actualizing real□time indoor positioning systems using plane models. International Journal of Communication Systems, doi: 10.1002/dac.2982.

Luo, X., O'Brien, W. J., & Julien, C. L. (2011). Comparative evaluation of Received Signal-Strength Index (RSSI) based indoor localization techniques for construction jobsites. Advanced Engineering Informatics, 25(2), 355-363.

Lytle, A. M., Katz, I., & Saidi, K. S. (2005). Performance evaluation of a high-frame rate 3D range sensor for construction applications. In Proceedings of the 22nd International Symposium on Automation and Robotics in Construction.

Maalek, R., & Sadeghpour, F. (2013). Accuracy assessment of Ultra-Wide Band technology in tracking static resources in indoor construction scenarios. Automation in Construction, 30, 170-183.

Madhavapeddy, A., Scott, D., & Sharp, R. (2003, January). Context-aware computing with sound. In UbiComp 2003: Ubiquitous Computing (pp. 315-332). Springer Berlin Heidelberg.

Mandal, A., Lopes, C. V., Givargis, T., Haghighat, A., Jurdak, R., & Baldi, P. (2005, January). Beep: 3D indoor positioning using audible sound. In CCNC. 2005, Second IEEE Consumer Communications and Networking Conference. (pp. 348-353). IEEE.

Memarzadeh, M., Golparvar-Fard, M., & Niebles, J. C. (2013). Automated 2D detection of construction equipment and workers from site video streams using histograms of oriented gradients and colors. Automation in Construction, 32, 24-37.

Milenković, A., Otto, C., & Jovanov, E. (2006). Wireless sensor networks for personal health monitoring: Issues and an implementation. Computer Communications, 29(13), 2521-2533.

Modsching, M., Kramer, R., ten Hagen, K., 2006. Field trial on GPS Accuracy in a medium size city: The influence of built-up. In 3rd Workshop on Positioning, Navigation and Communication, pp. 209-218.

Montaser, A., & Moselhi, O. (2014). RFID indoor location identification for construction projects. Automation in Construction, 39, 167-179.

Motamedi, A., Soltani, M. M., & Hammad, A. (2013). Localization of RFID-equipped assets during the operation phase of facilities. Advanced Engineering Informatics, 27(4), 566-579.

Naticchia, B., Vaccarini, M., & Carbonari, A. (2013). A monitoring system for real-time interference control on large construction sites. Automation in Construction, 29, 148-160.

Ni, L. M., Liu, Y., Lau, Y. C., & Patil, A. P. (2004). LANDMARC: indoor location sensing using active RFID. Wireless Networks, 10(6), 701-710.

Park, D. J., Choi, Y. B., & Nam, K. C. (2006, August). RFID-based RTLS for improvement of operation system in container terminals. In APCC'06, Communications Asia-Pacific Conference, pp. 1-5.

Park, M. W., & Brilakis, I. (2012). Construction worker detection in video frames for initializing vision trackers. Automation in Construction, 28, 15-25.

Park, M. W., Koch, C., & Brilakis, I. (2011). Three-dimensional tracking of construction resources using an on-site camera system. Journal of Computing in Civil Engineering, 26(4), 541-549.

Park, M. W., Makhmalbaf, A., & Brilakis, I. (2011). Comparative study of vision tracking methods for tracking of construction site resources. Automation in Construction, 20(7), 905-915.

Petzold, J., Pietzowski, A., Bagci, F., Trumler, W., & Ungerer, T. (2005). Prediction of indoor movements using Bayesian networks. In Location-and Context-Awareness (pp. 211-222). Springer Berlin Heidelberg.

Peyret, F., Bétaille, D., & Hintzy, G. (2000). High-precision application of GPS in the field of real-time equipment positioning. Automation in Construction, 9(3), 299-314.

Pradhan, A., Ergen, E., & Akinci, B. (2009). Technological assessment of radio frequency identification technology for indoor localization. Journal of Computing in Civil Engineering, 23(4), 230-238.

Pradhananga, N., & Teizer, J. (2013). Automatic spatio-temporal analysis of construction site equipment operations using GPS data. Automation in Construction, 29, 107-122.

Priyantha, N. B. (2005). The cricket indoor location system (Doctoral dissertation, Massachusetts Institute of Technology).

Priyantha, N. B., Chakraborty, A., & Balakrishnan, H. (2000). The cricket location-support system. In Proceedings of the 6th annual international conference on Mobile computing and networking (pp. 32-43). ACM.

Raab, F. H., Blood, E. B., Steiner, T. O., & Jones, H. R. (1979). Magnetic position and orientation tracking system. IEEE Transactions on Aerospace and Electronic Systems, (5), 709-718.

Ray, S. J., & Teizer, J. (2012). Real-time construction worker posture analysis for ergonomics training. Advanced Engineering Informatics, 26(2), 439-455.

Razavi, S. N., & Haas, C. T. (2010). Multisensor data fusion for on-site materials tracking in construction. Automation in Construction, 19(8), 1037-1046.

Razavi, S. N., & Haas, C. T. (2011). Using reference RFID tags for calibrating the estimated locations of construction materials. Automation in Construction, 20(6), 677-685.

Razavi, S. N., & Haas, C. T. (2012). Reliability-based hybrid data fusion method for adaptive location estimation in construction. Journal of Computing in Civil Engineering, 26(1), 1-10.

Razavi, S. N., & Moselhi, O. (2012). GPS-less indoor construction location sensing. Automation in Construction, 28, 128-136.

Riaz, Z., Edwards, D. J., & Thorpe, A. (2006). SightSafety: a hybrid information and communication technology system for reducing vehicle/pedestrian collisions. Automation in Construction, 15(6), 719-728.

Saeki, M., & Hori, M. (2006). Development of an Accurate Positioning System Using Low-Cost L1 GPS Receivers. Computer-Aided Civil and Infrastructure Engineering, 21(4), 258-267.

Saidi, K. S., Teizer, J., Franaszek, M., & Lytle, A. M. (2011). Static and dynamic performance evaluation of a commercially-available ultra wideband tracking system. Automation in Construction, 20(5), 519-530.

Shahi, A., Aryan, A., West, J. S., Haas, C. T., & Haas, R. C. (2012). Deterioration of UWB positioning during construction. Automation in Construction, 24, 72-80.

Shahi, A., West, J. S., & Haas, C. T. (2013). Onsite 3D marking for construction activity tracking. Automation in Construction, 30, 136-143.

Skibniewski, M. J., & Jang, W. S. (2009). Simulation of Accuracy Performance for Wireless Sensor-Based Construction Asset Tracking. Computer-Aided Civil and Infrastructure Engineering, 24(5), 335-345.

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

Song, J., Haas, C. T., & Caldas, C. H. (2007). A proximity-based method for locating RFID tagged objects. Advanced Engineering Informatics, 21(4), 367-376.

Song, J., Haas, C. T., Caldas, C., Ergen, E., & Akinci, B. (2006). Automating the task of tracking the delivery and receipt of fabricated pipe spools in industrial projects. Automation in Construction, 15(2), 166-177.

Song, L., & Eldin, N. N. (2012). Adaptive real-time tracking and simulation of heavy construction operations for look-ahead scheduling. Automation in Construction, 27, 32-39.

Taneja, S., Akinci, B., Garrett, J. H., Soibelman, L., Ergen, E., Pradhan, A., Tang, P., Berges, M., Atasoy, G., Liu, X., Mohsen Shahandashti, X., & Anil, E. B. (2010). Sensing and field data capture for construction and facility operations. Journal of construction engineering and management, 137(10), 870-881.

Taneja, S., Akcamete, A., Akinci, B., Garrett Jr, J. H., Soibelman, L., & East, E. W. (2012). Analysis of three indoor localization technologies for supporting operations and maintenance field tasks. Journal of Computing in Civil Engineering, 26(6), 708-719.

Teizer, J., Allread, B. S., Fullerton, C. E., & Hinze, J. (2010). Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system. Automation in Construction, 19(5), 630-640.

Teizer, J., Caldas, C. H., & 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.

Teizer, J., Cheng, T., & Fang, Y. (2013). Location tracking and data visualization technology to advance construction ironworkers' education and training in safety and productivity. Automation in Construction, 35, 53-68.

Teizer, J., & Vela, P. A. (2009). Personnel tracking on construction sites using video cameras. Advanced Engineering Informatics, 23(4), 452-462.

Tsai, C. C., & Lydia Wen, M. (2005). Research and trends in science education from 1998 to 2002: A content analysis of publication in selected journals. International Journal of Science Education, 27(1), 3-14.

Vähä, P., Heikkilä, T., Kilpeläinen, P., Järviluoma, M., & Gambao, E. (2013). Extending automation of building construction—Survey on potential sensor technologies and robotic applications. Automation in Construction, 36, 168-178.

Vahdatikhaki, F., & Hammad, A. (2014). Framework for near real-time simulation of earthmoving projects using location tracking technologies. Automation in

Construction, 42, 50-67.

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings—Literature review and future needs. Automation in Construction, 38, 109-127.

Want, R., Hopper, A., Falcao, V., & Gibbons, J. (1992). The active badge location system. ACM Transactions on Information Systems (TOIS), 10(1), 91-102.

Woo, S., Jeong, S., Mok, E., Xia, L., Choi, C., Pyeon, M., & 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.

Wu, W., Yang, H., Chew, D. A., Yang, S. H., Gibb, A. G., & Li, Q. (2010). Towards an autonomous real-time tracking system of near-miss accidents on construction sites. Automation in Construction, 19(2), 134-141.

Wu, W., Yang, H., Li, Q., & Chew, D. (2013). An integrated information management model for proactive prevention of struck-by-falling-object accidents on construction sites. Automation in Construction, 34, 67-74.

Xu, R., Liu, J., Zhu, J., & Jiang, X. (2015). The Design and Construction of WLAN-Based Indoor Navigation System. In Geo-Informatics in Resource Management and Sustainable Ecosystem (pp. 437-446). Springer Berlin Heidelberg.

Xue, X., Shen, Q., Fan, H., Li, H., & Fan, S. (2012). IT supported collaborative work in A/E/C projects: A ten-year review. Automation in Construction, 21, 1-9.

Yang, J., Arif, O., Vela, P. A., Teizer, J., & Shi, Z. (2010). Tracking multiple workers on construction sites using video cameras. Advanced Engineering Informatics, 24(4), 428-434.

Yang, J., Cheng, T., Teizer, J., Vela, P. A., & Shi, Z. K. (2011). A performance evaluation of vision and radio frequency tracking methods for interacting workforce. Advanced Engineering Informatics, 25(4), 736-747.

Yang, J., Vela, P., Teizer, J., & Shi, Z. (2014). Vision-Based Tower Crane Tracking for Understanding Construction Activity. Journal of Computing in Civil Engineering, 28(1), 103-112.

Zhao, H., & Wu, Y. (2015, April). An Improved Positioning Algorithm Based on PSO and PLS. In 2015 International Conference on Advances in Mechanical Engineering and Industrial Informatics. Atlantis Press.

Zhang, C., Hammad, A., & Rodriguez, S. (2012). Crane pose estimation using UWB real-time location system. Journal of Computing in Civil Engineering, 26(5), 625-637.

Zito, R., d'Este, G., & Taylor, M. A. (1995). Global positioning systems in the time domain: how useful a tool for intelligent vehicle-highway systems? Transportation Research Part C: Emerging Technologies, 3(4), 193-209.

Table 1: RTLS-related articles analyzed

Journal	Range	Number of publications	% of 75
Advanced Engineering Informatics (AEI)	Volume 19(1), 2005 to 28(1), 2014	8 (1.92% of 417)	10.67%
ASCE Journal of Computing in Civil Engineering (CCE)	Volume 19(1), 2005 to 28(2), 2014	14 (3.07% of 456)	18.67%
Automation in Construction (AIC)	Volume 14 (1), 2005 to (43), 2014	43 (3.92% of 1097)	57.33%
Journal of Construction Engineering and Management (CEM)	Volume 131(1), 2005 to 140(4), 2014	7 (0.57% of 1234)	9.33%
Journal of Computer-Aided Civil and Infrastructure Engineering (CACIE)	Volume 20 (1), 2005 to 29(4), 2014	3 (1.05% of 287)	4.00%

Table 2: Distribution of technologies used

Year	*RFID*	*GPS*	*UWB*	*vision analysis*	*WLAN*	*ultrasound*	*Infrared*	*Bluetooth*	*magnetic signals*	*audible sound*	*Total*
2014	2	0	1	1	0	0	0	0	0	0	*4*
2013	4	2	6	3	0	0	0	0	0	0	*15*
2012	8	2	4	2	1	0	0	0	0	0	*17*
2011	4	0	4	3	1	0	0	0	0	0	*12*
2010	5	1	1	1	0	1	0	0	0	0	*9*
2009	7	2	1	1	1	3	1	0	0	0	*16*
2008	0	1	0	0	1	0	0	0	0	0	*2*
2007	3	3	0	0	0	0	1	0	0	0	*7*
2006	3	4	0	0	0	0	0	0	0	0	*7*
2005	0	1	0	0	0	0	0	0	0	0	*1*
Total	36	16	17	11	4	4	2	0	0	0	*90*

Table 3: Summary of RFID related studies

Previous studies	Accuracy	Environment	Remark
Song and Haas (2006); Song et al. (2007)	3.7 m (2D, 68% confidence)	Outdoor area, 36 m^2. Divided in square cells with sides 1.2 m (total 900 cells)	Proximity localization
Skibniewski and Jang (2009)	2.8 m (50 MHz) 5.5 m (25 MHz) 17.4 m (8 MHz)	Outdoor, a 70 m x 70 m square-shaped path	
Pradhan et al. (2009)	10.7 m (87% confidence)	Indoor, with wall and metallic objects.	Distance between readers was 1.52 m. 015 MHz RFID system was used.
Dziadak et al. (2009)	Depth ±100 mm	Field test, pipes being buried.	
Torrent and Caldas (2009)	3.22 m (2D, Centroid method) 3.78 m (2D, Proximity method)	In a construction site	The RFID reader was equipped with a GPS to read the location of the reader.
Luo et al. (2011)	1.22 to 2.58 m (MinMax method) 1.69 to 2.76 m (ROCRSSI method) 2.52 to 3.79 m (Maximum likelihood method) 1.45 to 2.93 m (KNN method, result relying on k value)	Indoor, obstacle-free environment.	
Razavi and Haas (2011)	8.05 to 11.68 m (2D, Weighted averaging method) 8.11 to 11.68 m (2D, Centroid method) 7.83 to 11.70 m (2D, Calibrate method)	Construction site, from July 2007 to August 2008.	375 tags were being used in the experiment.
Li et al. (2012a)	1.94±0.17 m	6x7 m conference	915 MHz RFID,

	(stationary target) 1.42±0.49 (mobile target)	room, with obstacle such as wall.	34 tags were being used in the experiment. Virtual tags was proved to be able to improve the robustness of the system. With virtual tag, the accuracy of the system was also proved to be more stable when some of the reference tags became malfunction.
Lee et al. (2012)	86.5±63.62 cm (mobile target) Max error is 2.6 m	Indoor, construction site.	2.45 Ghz RFID. Assistant tag can reduce 63% error.
Razavi and Haas (2012)	2 m to 8 m (in control experiment) 7 m to 10 m (construction site environment)	Both control experiment and construction site.	
Taneja et al. (2012)	30 m (95% confidence)	Indoor, with obstacles such as walls, overhead pipes and metallic artifacts on walls.	915 MHz RFID. Poor result may due to the long serving time of the RFID tags (4 years).
Razavi and Moselhi (2012)	1.3 m	Construction site and laboratory environment	Cost of the system was $4000.
Kumar and Sommerville (2012)	Depth ±100 mm	Field test, pipes being buried.	
Li et al. (2013)	3.3±1.41 m (stationary target, warehouse) 3.82±1.74 m (stationary target, office)	15x25 m warehouse and 15x24 m office, with obstacles.	
Motamedi et al. (2013)	0.28 m to 0.51 m (without obstacles)	Indoor, obstacle free environment is 5x7.5	

	0.77 m to 1.55 m (with obstacles)	m and environment with obstacles is 35x25 m.	

Table 4: Summary of UWB related studies

Previous studies	Accuracy	Environment	Remark
Khoury and Kamat (2009)	10 cm to 50 cm	A maze located in indoor environment	
Cho et al. (2010)	17.02 cm (2D)	Indoor, without obstacle	Untethered configuration
	10 cm (2D)	Indoor, without obstacle	Tethered configuration
	63 cm (H=0) 46 cm (H=94 cm) 58 cm (H=130)	Inside a wood framed building with obstacle	Value H represents the height of the tag in the experiments
	56 cm (H=0) 39 cm (H=104 cm)	Inside a steel framed building with obstacle	Value H represents the height of the tag in the experiments
	41 cm (H=0) 50 cm (H=104 cm)	Fully furnished office	Value H represents the height of the tag in the experiments
Yang et al. (2011)	<100 cm	Open area	
Cheng et al. (2011)	41 cm (1 hz tag) 34 cm (60 hz tag)	Construction pit (2400 m^2)	
	126 cm (1 hz tag) 123 cm (60 hz tag)	Lay down yard (65000 m^2)	
Saidi et al. (2011)	87 cm±1 cm	Open area	2D positioning data
	46.6 cm±4 cm	Open area	3D positioning data
	125 cm (47% confidence) 250 cm (87% confidence)	Lay down yard (100000 m^2) with obstructions such as workers, machines and built structure	
Zhang et al. (2012)	30 cm	Outdoor with obstacle (car)	
Shahi et al. (2012)	15 cm (tag placed in wood box) 45 cm (tag placed in metal box)	Indoor	
	60 cm (3D)	Indoor, with obstacles	Error increased to 1.2 m when tags were put closely together

Cheng et al. (2013a)	30 cm	Indoor (500 m^2), without obstacle	
Maalek and Sadeghpour (2013)	20 cm (2D, 70% confidence) 40 cm (3D, 70% confidence)	Indoor, with obstacles	
Cheng et al. (2013b)	30 cm	Indoor, without obstacle	

Table 5: Different effect on the accuracy of UWB performance

Condition	Effect
Obstacle exists between tags and receivers	Accuracy decrease more than 200%
Tag is attached on metal surface	Accuracy decrease more than 8%
Removing the cable connection to the receivers	Accuracy decrease more than 114.2% for 2D positioning and 58.9% for 3D positioning
Tracking more than 1 tag	Tracking more tags simultaneously will decrease the accuracy of UWB. The system maintains the accuracy within 1 m for tracking 15 tags at the same time.
Reducing the number of receivers from 8 to 2	Accuracy dropped to 89 cm in 2D and 105 cm in 3D.

Table 6: Accuracy of the RTLS

RTLS Technologies	Construction publications (Best result)	Gu and Lo (2009)
RFID	0.86 m to 2.6 m (Lee et al., 2012)	2 m to 3 m
GPS	2.15 m to 4.36 m (Pradhananga and Teizer, 2013)	15 m
UWB	0.3 m (Cheng et al. 2013b)	0.15 m
Vision Analysis	0.658 m (Park et al., 2012)	Not available
WLAN	1.5 m to 4.57 m (Taneja et al. 2012)	4 m (2D)
Ultrasound	0.04 m (Maalek and Sadeghpour, 2013)	0.03 m
Infrared	Not available	3 mm

Table 7: Examples of research into construction RTLS performance

Scope	References
Evaluate the performance of RTLS	Skibniewski and Jang (2009); Chi et al. (2009); Saeki and Hori (2006); Taneja et al. (2012) Pradhan et al. (2009); Jang and Skibniewski (2009); Yang et al. (2011); Maalek and Sadeghpour (2013); Shahi et al. (2012)
Explore new calculation technique or algorithm	Li et al. (2013); Razavi and Haas (2012); Luo et al. (2011); Song et al. (2007); Memarzadeh et al. (2013)
Alternative deployment methods	Li et al. (2012b)

Table 8: RTLS-related studies in site management

Scope	References
Process Management	
Near real-time simulation using tracking technologies	Vahdatikhaki and Hammad (2014); Song and Eldin (2012)
Real-time construction monitoring	Akula et al. (2013)
Construction activity tracking	Shahi et al. (2013)
Productivity management	Cheng et al. (2013b); Grau et al. (2009)
Construction resources management	Costin et al. (2012); Lu et al. (2007); Goodrum et al. (2006); Yang et al. (2014); Zhang et al. (2012); Park et al. (2011); Cheng et al. (2012)
Cost sharing in construction supply chain	Demiralp et al. (2012)
Materials management	Ergen et al. (2007); Song et al. (2006); Kim et al. (2010); Song et al. (2006b)
Safety Management	
Real-time safety management on workers	Ding et al. (2013); Cheng and Teizer (2013); Wu et al. (2013); Carbonari et al. (2011); Teizer et al. (2010); Riaz et al. (2006); Lee et al. (2012)
Safety training	Teizer et al. (2013)
Behavior based safety	Han and Lee (2013)
Real-time safety management on equipment	Li and Liu (2012); Hwang (2012); Chae and Yoshida (2010)
Reporting near-miss accidents	Wu et al. (2010)
Study traffic data near the construction site	Garcia et al. (2006)
Ergonomics analysis and physiological status monitoring	Cheng et al. (2013)
Facilities Management	
Asset management	Kumar and Sommerville (2012); Motamedi et al. (2013); Li et al. (2013)
Facilities management	Dzeng et al. (2014); Li et al. (2012a)
Concrete crack properties monitoring	Adhikari et al. (2014)
Maintenance	Taneja et al. (2012)