Experimental Study on Location Tracking of Construction Resources Using UWB for Better Productivity and Safety

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ABSTRACT

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There is a growing demand for accurate and up-to-date information in the construction industry. Ultra-Wideband (UWB) Real-Time Location Systems (RTLSs) enable tracking and visualization of resources on site and give more awareness to the construction staff in near real time. This research investigates how UWB technology can improve productivity and safety in construction projects. The requirements of the RTLSs are identified in terms of safety and productivity management. The usability of RTLSs in the construction industry is tested by the collection of data from a construction site and organizing them into useful information needed for management. It was found that UWB is an effective tool to monitor construction resources because it provides accurate information in near real time. However, good understanding of the requirements and filtering the data are necessary in order to get the best benefit of the technology for productivity and safety purposes.

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DEDICATION

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List of acronyms

Acronym	Description
2D	Two-Dimensional
3D	Three-Dimensional
4D	Four-Dimensional
A-GPS	Assisted Global Positioning System
AOA	Angle of Arrival
BIM	Building Information Model
ETO	Engineered to Order
FCC	Federal Communications Commission
GIS	Geographic Information System
GPS	Global Positioning System
HVAC	Heating, Ventilation, and Air Conditioning
ID	Identification
IR	Infrared
JMSB	John Molson School of Business
LADAR	Laser Detection and Range Tracking
NIST	National Institute of Standards and Technology
OBI	On-Board Instrumentation
PDA	Personal Digital Assistant
QOS	Quality of Service
RAPIDS	Real-time Automated Project Information and Decision Systems
RF	Radio Frequency
RFID	Radio Frequency Identification
RSS	Received Signal Strength
RTLS	Real-time Location System
TDOA	Time Difference of arrival
TOA	Time of Arrival
UWB	Ultra-Wideband
VBA	Visual Basic for Applications

Acronym	Description
VHF	Very High Frequency
VSM	Value Stream Mapping
WLAN	Wireless Local Area Network

CHAPTER 1 INTRODUCTION

1.1 General review

Productivity and safety are two of the major concerns for construction management. However, this industry is not taking as much advantage of the technologies available as other industries. The absence of real-time information can affect the ability to monitor the schedule, cost and other performance indicators of a project. This research investigates the definitions of productivity and safety from a global perspective, then the available technologies to assess the monitoring needs. New sensing technologies, including auto-identification (auto-ID) and Real Time Location Systems (RTLSs) are available to provide information about construction activities, their time and location information, and the resources involved in them (Navon and Sacs, 2007).

Recently, Ultra-Wideband (UWB) RTLSs technology has been investigated for automating data capturing, identifying, locating and tracking objects for productivity and safety management in the construction industry (Teizer and Castro-Lacouture, 2007). The UWB applications enable tracking and visualization of resources on site and give more awareness to the construction staff in near real time. However, the specific requirements for the deployment of this technology in construction sites for safety and productivity purposes have not being fully discussed in previous research.

Active sensing technologies are used to alert personnel of the dangers occurring in real time, and to collect data to be analyzed in order to determine the best practices and to make process improvements (Fullerton et al., 2009). In addition, safety management systems have been proposed for tracking workers' trajectories to prevent accidents. Furthermore, applications in which a software graphically reproduces the travel patterns of workers have been developed to provide alerting signals in real time when the worker is within a previously defined dangerous area (Carbonari et al., 2009). These applications show the applicability of those systems in construction sites.

UWB offers several distinct advantages over traditional tracking systems, such as long and reliable readability range, accurate real-time positioning, and better solution to the multipath problem. However, more investigation is needed to test the usability and identify the specific requirements of UWB in tracking construction tasks.

1.2 Research objectives and problem definition

The objectives of this research are: (1) to investigate how UWB technology can improve productivity and safety in construction projects; (2) to identify the requirements of UWB RTLSs in terms of productivity and safety management; and (3) to improve the usability of UWB RTLSs in the construction industry by collecting raw data from construction site and organizing them into useful information needed for real-time management.

1.3 Thesis organization

This study will be presented as follows:

Chapter 2 Literature Review: This chapter presents the location technologies used in the construction industry and their application for productivity and safety purposes. Moreover, the UWB technology and its specific methods are reviewed.

Chapter 3 Proposed Approach: In this chapter the proposed methodology is presented. It starts by identifying the approaches to improve productivity and safety by using UWB technology. Then, the requirements of UWB systems for location tracking of construction resources are defined. Finally, an investigation is done to establish UWB usability for improving productivity and safety.

Chapter 4 Case studies: In this chapter, three case studies are presented to evaluate the accuracy of the system and to show the implementation of the proposed approach in construction environments. In the first case study, the accuracy of the system is measured in the laboratory. The second case study is performed in a real indoor construction site where workers and equipment are tracked. The third case study describes a simulated outdoor construction site where a hydraulic crane is tracked. In all cases the planning and deployment of the experimental conditions are discussed to accomplish the requirements.

Chapter 5 Conclusions and Future Work: This chapter summarizes the present research work, highlights its contributions, and suggests recommendations for future research.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

There is a growing demand for accurate and up-to-date information in the construction industry. RTLSs enable tracking and visualization of resources on site and give more awareness to the construction staff in near real time. The construction industry can take advantage of the automated data capture, auto-ID technologies and RTLSs to achieve efficient management of projects. Available tracking and sensing technologies include Global Positioning System (GPS), Radio Frequency Identification (RFID), barcoding, video and audio, monitoring load gauges, accelerometers, and Laser Detection and Range Tracking (LADAR) (Navon and Sacs, 2007). Workers' locations can be collected automatically at regular time intervals and converted into labor inputs by associating activities with locations, and calculating the quantities of work of each activity (Navon and Goldschmidt, 2003). Recently, UWB RTLS technology has been investigated for automating data capturing, identifying, locating, and tracking objects for productivity and safety management in the construction industry (Teizer and Castro-Lacouture, 2007).

This chapter begins with a general view of productivity and safety in construction which are the major areas to be covered in this research. Next, lean construction, an approach adopted in the construction industry from the manufacturing industry, is introduced. The major benefits of this approach to the construction industry are presented and discussed. Finally, the major sections of this chapter explore the available location tracking technologies that have been applied in construction illustrated with examples of applications from the productivity and safety perspective, and their limitations which are the motivation of this research.

2.2 Location technologies

"Real-time locating systems are wireless systems with the ability to locate the position of an item anywhere in a defined space (local/campus, wide area/regional, global) at a point in time that is, or is close to, real time" (International Organization for Standardization and International Electrotechnical Commission, 2006). A RTLS allows determining the location of assets or people at a specific time and frequency of update. Different technologies can be used in a RTLS such as sound, ultrasound, Bluetooth, Wi-Fi, RFID, ZigBee, UWB, GPS, Cellular, camera vision, infrared and light, among others (Malik, 2009). Location technologies find or estimate a location of a point in two-dimensional (2D) or three-dimensional (3D) space in relation to a coordinate system where some references are known. Distance and observable angles are in most of the cases the base for those findings and can be obtained from different sources such as arrival times, arrival time differences, and field strength among others. The main objective of a location system is to determine the exact position of people or assets by minimizing the errors in the measurements. By knowing the relative location of an object in relation to sufficient reference points, the absolute location of the object can be determined (Ward and Webster, 2009). The sources of errors can be the instruments errors, measurement errors, noise, and inaccurate reference positions. Each location system has its intrinsic and cost limitations. Recently, location technologies are focused on improving the accuracy of the position of one system and data fusion of different systems. To get the maximum benefit of these technologies, different aspects must be taken into account when deciding which technology must be used. Because not every technology is suitable for each application. The accuracy, advantages and limitations are directly related to the final purpose of the location system. Therefore, the requirements of the location system contribute to the accomplishment of the final goal of the RTLSs. "Good applications are those that achieve an adequate equilibrium between system requirements, technological advantages, and associated costs" (Muñoz, 2009). Figure 2-1 compares different location technologies, such as passive RFID, electromagnetic, laser, ultrasound, infrared (IR) proximity, conventional Radio Frequency (RF) timing, UWB, Wireless Local Area Network (WLAN), Received Signal Strength (RSS), and assisted GPS (A-GPS). This comparison is done based on the accuracy and the coverage offered from each technology and identifying the ideal as the technology that can achieve accuracy less than 0.3 m and with coverage more than 100 m (Ward, 2007).

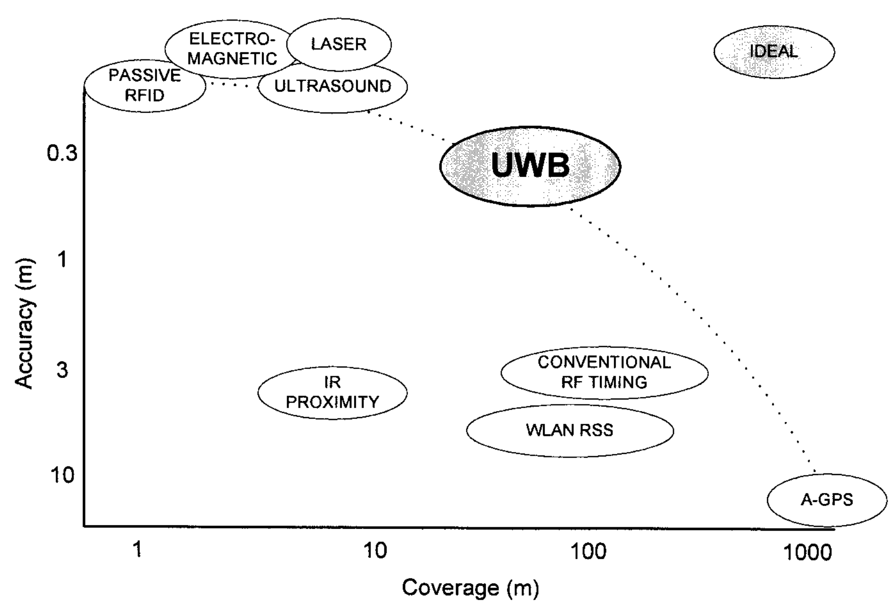


Figure 2-1 Comparison of location technologies (adapted from Ward, 2007)

In the construction industry, different location technologies have been applied and compared. An evaluation comparing WLAN, UWB, and indoor GPS positioning systems was done in a simulated environment. It was concluded that determining which technology must be selected is based on technical criteria, logistic issues and implementation costs (Khoury and Kamat, 2009). The comparison of these technologies is presented in Table 2-1.

Table 2-1 Comparative summary of indoor positioning technologies (Khoury and Kamat, 2009)

	Line of sight	Position uncertainty	Calibration	Deployment and cost
Indoor GPS	Needed (receiver–transmitter)	Very low (1–2 cm)	Needed (few sampling points)	Quite easy but very expensive
UWB	Needed (receiver–reference tag)	Low (0–50 cm)	Not needed	Quite easy but expensive
WLAN (Ekahau)	Not needed	Medium (1.5–2m)	Needed (time-consuming)	Easy and economical

2.3 Productivity in construction

In general terms, productivity can be defined as the relation between inputs and outputs within a process. However, to define productivity in the construction industry is not a simple task because of the complexity of this industry and the particular factors involved, such as the uniqueness of the projects, the technology used, the management styles, and labor organization (Allmon et al., 2000). Therefore, a need for measures of construction productivity at three levels is pointed out by a research group at the National Institute of Standards and Technology (NIST): (1) tasks, (2) project, and (3) industry. It is important to consider the three levels involved to understand how the efforts for improvement are also focused in these three levels. The first one is the task level, which is related with specific construction activities such as installation of heating and ventilation systems or assembling walls. The second one is the project level involving the group of activities required for the construction of a new facility (e.g., a building or a bridge) or renovations. Finally, the third level is the industry, in which measurements are done by the government to determine the productivity of the construction sector as the reunion of the portfolio projects (Huang, 2009). Besides the difficulty in the definition, productivity data have been widely used as performance indicators to evaluate construction operations throughout the entire phase of construction. Research on this area has been conducted because companies have to continuously improve their productivity and efficiency in order to maintain a competitive advantage. Firms must continuously track productivity in order to estimate their performance to maintain profitability and to prepare future biddings (Ghanem and Abdelrazig, 2006). Consequently, after the companies determine how they are performing, they decide to invest in technology as a way to increase productivity. One of the biggest reasons for increasing rates in productivity in the 1980s and 1990s was the technological advances. The increment in resources available such as electronic devices and the development in communication technologies had a big impact on the industry (Allmon et al., 2000). The models created to integrate those available technologies in the construction industry include the concepts of project control, schedule progress, material management and equipment management as the major objectives. As an example, a model based on RFID was proposed to increase productivity, efficiency and accuracy in estimation, and to reduce time required for tracking (Ghanem and Abdelrazig, 2006).

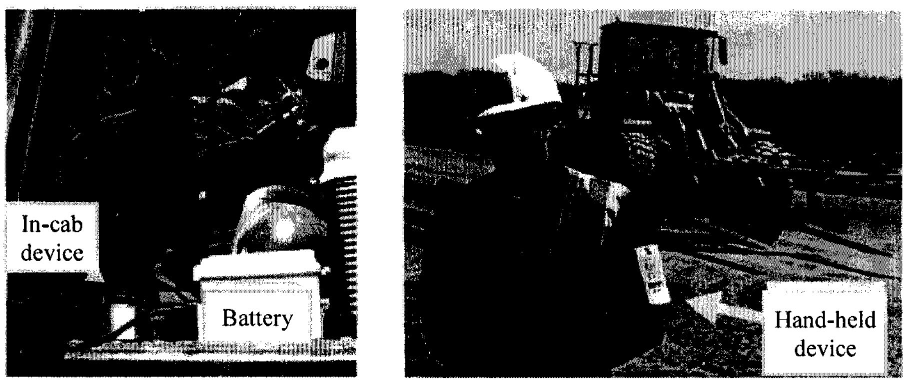
GPS has been used to monitor the activity of major construction equipment in real time. For example, in earthmoving projects, GPS and total stations are used to accurately position the blade of the excavator in real time, significantly reducing material overages and dramatically improving contractors' productivity and profitability, and increasing operator comfort (Adalsteinsson, 2008). Navon et al. (2004) have developed a tracking and control system using GPS and on-board instrumentation (OBI) to monitor in real time the activities of major construction equipment, such as tower cranes, concrete pumps, etc.

As discussed by the National Research Council (2009), in the United States, the construction industry still relies heavily on manual methods of placement and assembly. Automated technologies have penetrated other industries, while the construction industry is still behind these technological advances. Different factors influence this gap, such as the lack of innovation in construction processes or manufacturing processes of construction materials, lack of innovation due to building codes, the nature of the construction operations (exposure to open spaces where climatic issues affect the productivity of the operations), production by project, and the costs related to the operation and maintenance of automated and heavy equipment.

Managing activities and demands on construction sites is not an easy task due to the dynamic conditions and the different stakeholders participating in the projects. Opportunities for efficiency improvement were identified when time, money, and resources are wasted in situations such as the following examples: the workplaces are crowded, the crews are not on time due to lack of communication, the different resources such as materials and equipment are not easy to locate and need to be moved several times. That waste could be reduced if information technologies such as RFID and personal digital assistants (PDAs) are applied to obtain real-time project information (National Research Council, 2009).

2.4 Safety in construction

From the safety perspective, a construction site is dynamic, which requires continuous updating of the location data of all moving objects, including equipment and workers, to mitigate safety risks. Riaz et al. (2006) have tracked vehicles and workers using GPS and sensors to reduce accident rates. However, GPS is unavailable without direct line of sight from the satellites, and accurate GPS receivers are expensive to install on every moving object on site. Therefore, other tracking technologies have been applied in several research projects, such as infrared, optical, ultrasound, and RFID technologies. Chae and Yoshida (2008) have discussed collecting data on site using RFID active tags for preventing collision accidents. BodyGuard - Vehicle Proximity Alert and Collision Avoidance System (Orbit Communications, 2010) is an RFID-based system that offers continuous detection and notification of proximity between a moving object and other moving or fixed objects by setting up protection zones around a vehicle, equipment, and buildings to offer continuous protection for valuable resources. However, RFID can only give approximate locations. Teizer et al. (2010) presented a pro-active real-time proximity and alert technology for daily construction operations. The system employed in that research used a special secure wireless communication line of Very-High Frequency (VHF) active RF technology. The system is composed of an in-cab device to be used in the equipment and a hand-held device to be used by the workers. Figure 2-2 shows the location of alert devices on personnel and equipment during the field testing. The main purpose was to provide visual and audio alert to on-site workers and equipment operators when there is proximity and a possible collision is detected.



(a) (b)

Figure 2-2 Location of alert devices on personnel and equipment (adapted from Teizer et al. 2010)

The warning and alert technology was tested in realistic construction environments and the devices where effective at giving signals to alert personnel. Data recording has not been implemented; however, the usefulness of this information to improve positioning of workers and equipment and to assist in the development of new safety concepts and training was identified (Teizer et al., 2010).

2.5 Lean construction

One important way to improve productivity and reduce costs in the construction industry is to minimize waste of materials, time and effort within the projects, in order to generate the maximum possible amount of value (Koskela et al., 2002). For this purpose, a concept primarily introduced in the manufacturing industry is helpful: lean construction. Defined as "a holistic pursuit of concurrent and continuous improvements in all dimensions of the built and natural environment: design, construction, activation, maintenance, salvaging and recycling. This approach tries to manage and improve construction processes with minimum cost and maximum value by considering customer needs" (Hardin, 2009). The transition of the concepts of lean manufacturing to the construction industry can be done by understanding the specific type of production involved. Construction is production of a one-kind-product where there is a flow of work and a creation of value (Bertelsen and Koskela, 2004). Therefore, implementation of lean production management has been shown to substantially improve productivity in construction projects. For example, the implementation of lean techniques in a Chilean project has led to an improvement of 86% in project productivity as a consequence of the improvement in work flow reliability (Ballard et al., 2002).

Other studies have concluded that improving labor flow is an important step towards increasing productivity as part of lean management of construction projects. By measuring the radio of inefficient vs. efficient labor hours, it was observed that more reliable material, information, and equipment availability contributes to better performance. As a conclusion, it was proposed that workforce management strategies that improve labor utilization will lead to better labor performance (Thomas et al., 2003). This improvement in the work force flow has to be linked with the principles of lean construction practices that aim to attack and reduce variability, setup times, and product defects (Ballard et al., 2005). In addition to the workforce management, the processes can be visualized with one of the tools proposed by lean approaches: Value Stream Mapping (VSM). The objective of using this tool is to improve the process of production by identifying value and waste. It shows the flow of both information and material (Bae and Kim, 2008).

The applicability and effectiveness of lean thinking principles applied to construction projects has been illustrated by Kung et al. (2008) in the installation of water and sewer services. It was also stated that optimizing the flow of activities is a key factor in guaranteeing that the production will be done without interruption. Furthermore, all activities used in the production process should be based on demand by applying the pull principle. Coupled with those applications, computer-aided visualization of the construction process can facilitate reporting of project status and can support decision making to achieve stable work flows (Sacks et al., 2009). In addition, process flow visualization (Kanban) is proposed to determine which operations had been accomplished with messages such as "under construction" and "available" for construction phases. Concepts such as takt time for operations to be accomplished are linked with the four-dimensional (4D) model of the building and with the Gantt diagram by applying Building Information Model (BIM) to support the visualization (Sacks et al., 2010). The need for visual tools for production management during construction and their benefits are discussed. However, the specific technologies to accomplish that visualization have not been explored.

2.6 Automated project performance control in construction

Construction industry can take advantage of the automated data capture, auto-ID technologies and RTLSs to achieve efficient management of projects. As explained above, monitoring technologies such as GPS, ground-based RF systems, RFID, barcode, video, audio, load gauges, accelerometers and LADAR have been explored in the construction industry (Navon and Sacs, 2007). From the productivity perspective, the feasibility of automatically collecting worker's locations and converting them into labor inputs controlled with an automated model was explored. The systems proposed for automated data collection were GPS, for building activities in open spaces, and ground-based RF system, for measuring the location of workers performing indoor activities. Workers' locations can be collected automatically at a regular time intervals and converted into labor inputs using computerized algorithms. The conversion model proposes to associate the activities with locations and calculates the quantities of work of each activity to compute the labor inputs. The conversion is done by: (1) geometrical association between the worker and the vicinity of a building element associated with the activity, and (2) logical association to compare the labor inputs to the planned values and reports about deviations. By comparing the results obtained from the model with the manual collection, a difference of less than ±12% is obtained in productivity measurements (Navon and Goldschmidt, 2003). A new algorithm has been studied to determine which building element is worked on at each given time based on RFID (Navon, 2009). However, this algorithm has not been implemented. The relationship between the monitoring needs in construction and potential technologies to satisfy them has been discussed taking into account factors such as the materials, personnel and equipment, as shown Table 2-2 (Navon and Sacks, 2007).

Table 2-2 Monitoring needs and potential technologies to satisfy them (Navon and Sacks, 2007)

Technologies / Needs		GPS		RFID	Barcode	Video	Audio	Load gauges	Accelerometers	Equipment location	LADAR
		Indoor	Outdoor								
Materials	Bulk		X	X		X	X	X			X
	ETO*	X	X	X	X	X	X	X	X	X	X
Personnel	Interior	X		X					X		
	Exterior		X			X			X		
Equipment	Building					X		X	X	X	X
	Earth-moving		X			X		X	X	X	X
	People-moving							X		X	
Activity progress		X	X	X	X	X	X				X
Hand tools				X	X		X		X		
Refuse/waste materials				X				X			

Note: * Engineered-to-order (custom) components (e.g. doors, windows, precast pieces, HVAC equipment, etc.).

Each technology has benefits and limitations when used in construction environments to automatically locate and track construction resources. GPS can offer cost-effective applications to track and determine the position of larger resources. However, this technology has limited accuracy in indoor environments due to the excess loss of signals and multipath effect (Teizer et al., 2008). To reduce problems in existing manual methods of identifying, tracking and locating highly customized prefabricated components, an automated system using RFID technology combined with GPS technology, requiring minimal worker input was proposed by Ergen et al. (2007) and Song et al. (2006). Field experiments have demonstrated that the approximate 2D location of materials can be determined by attaching RFID tags to materials and using a mobile GPS to track the material's location. This approach did not add more work to the regular operations and showed better results in construction sites because it does not require a line of sight for

GPS localization. A unified platform to automate the tracking of materials and components in multiple stages of the project life cycle was also proposed (Song et al., 2007). The following benefits of applying GPS to locate materials in large industrial projects were presented by Caldas et al. (2006): savings in labour time and costs, improvement of processes, reduction in the number of lost items, standardization and automation of processes, enhancing data entry, and optimizing route sequences and layout.

The impact of tracking materials on labor productivity was also discused by Grau et al. (2009b). Results of their study indicate that labor productivity is positively affected by the use of information technologies. Furthermore, opportunities for affecting labor productivity performance derived from the application of tracking procedures were described. Those opportunities were identified as reduction of locating times by the workers at the lay-down yard, reduction in the percentage of not-immediately-found components and re-work related with this process, increase of reliable support for installation processes by providing materials on time, and improved monitoring of components in the installation area by defining their status. The automated materials tracking was based on the combination of localization algorithms, and GPS and RFID technologies with the set up presented in Figure 2-3 where the tags were attached to 45 steel components. In this case, the RFID receiver captured the signals emitted by the surrounding tagged components while the writers' GPS receiver determined its own coordinates (Grau and Caldas, 2009).

Figure 2-3 GPS and RFID technology set up (Grau and Caldas, 2009)

In addition to the technical set up, the trial design at the lay-down yard is presented in Figure 2-4 where two boiler support steel structures were tagged and the processes related with their installation were compared. The comparison was possible because the installation process for both was identical and the time was measured for the activities involved. In the traditional tracking process, the components were recorded based on grid position; while in the automated model the data was collected with GPS/RFID. After determining which components need to be installed, the components were located based on grids in the traditional tracking process and based on maps in the automated tracing process. Three metrics where defined to quantify the impact of the automated identification: (1) Labor productivity at the lay-down yard, (2) Components not immediately found, and (3) Steel erection productivity. This research showed the benefits of automated identification technologies for tracking components in construction sites by increasing the steel erection process productivity by 4.2% and the positive benefit-to-cost ratio (Grau et al., 2009a).

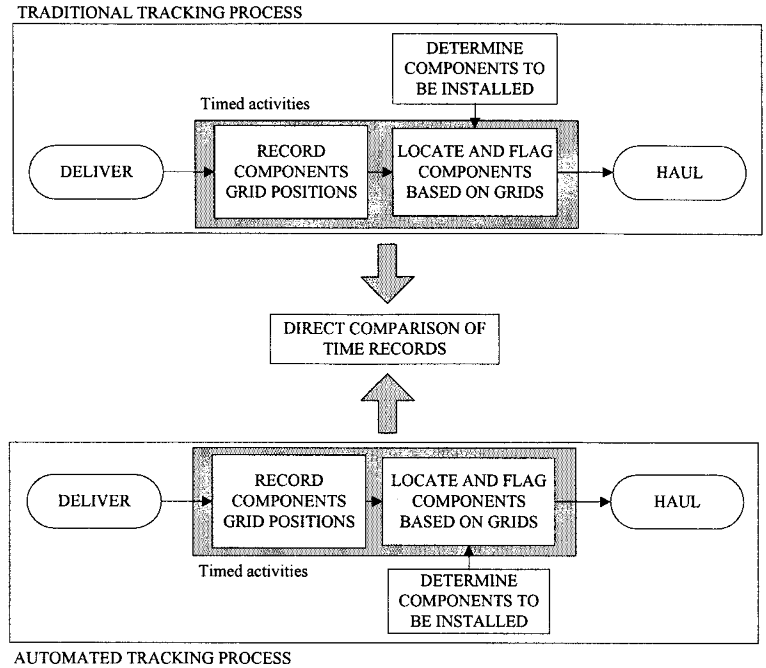


Figure 2-4 Trial design at the lay-down yard (adapted from Grau et al., 2009a)

The benefits of RTLSs have been also explored from the research perspective as one of the major needs for construction industry. In a workshop organized by the Construction Industry Institute (Back, 2008), it was found that the "Utilization of Sensors in Construction" was ranked as the number one short-term research topic, defined as areas of study that are likely to present an immediate opportunity or that address an immediate need. Additionally, "Real Time Construction Site Monitoring" was ranked as the number one mid-range topics, defined as areas of study that would likely require multiple research projects to be adequately addressed. Finally, "Real Time Project Management Tools" was ranked as the number one long-range research topics that are often characterized as emerging trends.

2.7 Ultra-wideband technology

UWB is any radio technology that employs a wide bandwidth (exceeding 500 MHz or 20 percent of the arithmetic center frequency, whichever is lower). UWB is a carrierless communication scheme that is usually used in short-range wireless applications. The advantages of using this technology are that it can carry high data rates with low power (less than 0.5 milliwatts) and limited interference over a distance up to 70 meters. The early applications of UWB technology were primarily related to radar. Table 2-3 lists the categories of applications approved by the Federal Communications Commission (FCC) for UWB (Malik, 2009).

Table 2-3 UWB applications (Malik, 2009)

Application/Class	Frequency
Communications and measurement systems	3.1-10.6 GHz
Imaging: ground-penetrating radar, wall, medical imaging	Less than 960 MHz or 3.1-10.6 GHz
Imaging: through walls	Less than 960 MHz or 3.1-10.6 GHz
Imaging: surveillance	1.99-10.6 GHz
Vehicular	24-29 GHz

UWB is used as a RTLS by different industries for manufacturing, logistic, transit and transportation, military, hazardous environments, immersive media and retail applications. As discussed in Section 2.1, RTLSs can track and identify the location of objects in near real time using tags attached to objects, and sensors that receive the wireless signals from these tags to determine their locations. Due to the extremely low emission levels currently allowed by regulatory agencies, UWB systems tend to be short-range and used indoors. The components of a UWB RTLS are: (1) Tags: Electronic devices that send UWB pulses, which usually are short and have low repetition rates, typically 1-100 megapulses per second. The tags have a battery and can include different interactive applications such as buzzer, buttons or leds and they are provided for use by personnel or in equipment. The tags are usually small and are attached to the objects to track. (2) Location sensors (UWB receivers): Devices which support two-way communication and use angles and signal timing to calculate the precise location of tags. (3) Location engine: The software that computes the location of the tags using the data provided by the sensors and using techniques such as Time of Arrival (TOA) and Time Difference of Arrival (TDOA). (4) Middleware: "The software that connects the disparate applications, allowing them to communicate with each other and to exchange data. It is the software that resides among the pure RTLS technology components (tags, sensors, and the location engine) and the business applications" (Malik, 2009). (5) Application: "The software that interacts with the RTLS middleware and does the work users are directly interested in" (Malik, 2009).

UWB has the ability to carry signals through doors and other obstacles that tend to reflect signals at more limited bandwidths and a higher power. With conventional RF, reflections in congested environments distort the direct path signal, making accurate pulse timing difficult. While with UWB, the direct path signal can be distinguished from the reflections, making pulse timing easier. Thus, the accuracy of the UWB system could be up to 15 cm in good conditions (Muthukrishnan and Hazas, 2009). These advantages make it possible to attach UWB tags to construction equipment and other moving objects on site and collect accurate location data.

2.8 Methods used in UWB RTLSs

UWB technology is used as an indoor location system that measures distances or angles between known points and unknown position. There are commonly used methods to calculate those distances and angles, such as in RSS, Angle of Arrival (AOA), TOA and TDOA (Correal et al., 2003). All this methods can be affected by the obstructions and reflections in indoor environments. A combination of TDOA and AOA can be used to obtain a high accuracy in the location measurement (Abdul-Latif et al., 2007).

In the TDOA method, the difference in time at which the signal from the tag to be positioned arrives at different receivers is measured. Each time difference is then converted into a hyperboloid with a constant distance difference between two receivers. The position is found by solving equations if the coordinates of the receivers is known (intersection of the corresponding hyperboloids). In 3D, at least four receivers are required and this technique requires synchronization of the receivers' clocks (Ghavami et al., 2004). Figure 2-5 illustrates this principle for 3 sensors.

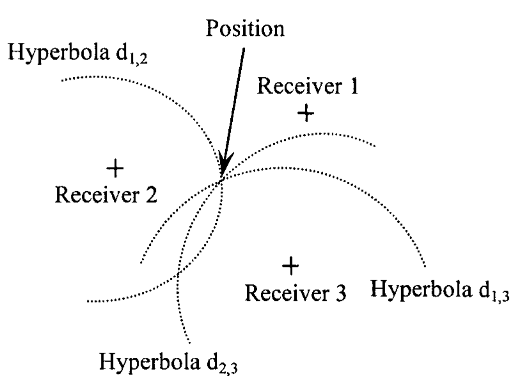


Figure 2-5 TDOA positioning principle (Ghavami et al., 2004)

In AOA method, the angle of arrival of the signal sent by the tag to be positioned is measured at several stationary receivers. Each measurement forms a radial line from the receiver to the tag. In 2D positioning, the position of the tag is defined at the intersection of two directional lines of bearing. This method has the advantage of not requiring synchronization of the receivers nor an accurate timing reference. On the other hand, receivers require regular calibration in order to compensate for temperature variations and mismatches (Ghavami et al., 2004). Location estimate of the tag is calculated at the intersection of these lines. In theory, direction-finding systems require only two receiving sensors to locate a tag, but in practice, improve accuracy and compensate for finite angular resolution, multipath and noise, more than two references are needed (Muñoz et al., 2009). Figure 2-6 illustrates this principle for 3 sensors.

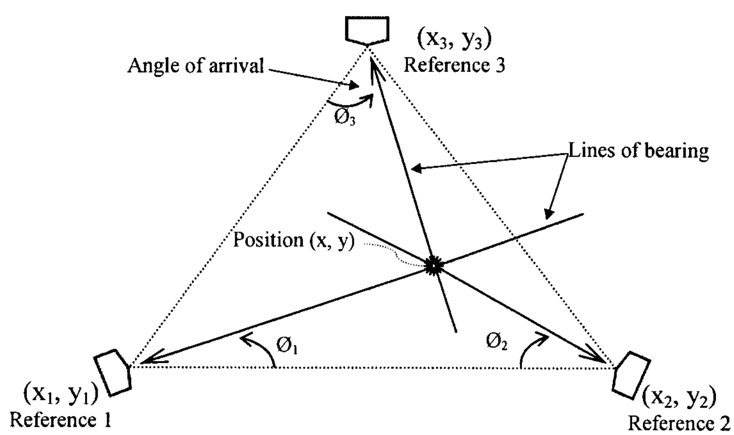


Figure 2-6 AOA positioning principle (adapted from Muñoz et al., 2009)

The multipath effect would affect the time and angle of an arrival signal decreasing the accuracy of estimated location. Another alternative is to estimate the distance of the mobile unit from some set of measuring units, using the attenuation of emitted signal strength. Signal attenuation-based methods attempt to calculate the signal path loss due to propagation. AOA and TDOA accuracy can be improved by utilizing the premeasured RSS contours centered at the receiver or multiple measurements at several base stations (Liu et al., 2007).

In the specific UWB system used in this research (Ubisense, 2009), the location position techniques are combined TDOA and AOA. This combination provides greater system robustness. A sensor cell is constructed by several sensors connected together into a single operating unit. That captures the location of tracked objects. The software component is a computer system which collects all the available TDOA and AOA data from the receivers that detected a tag's signal. Then, this data is used to compute a solution for the tag position best matching the input data. The system may attribute different weights to each item of data used in the position calculation (Ward, 2009). Sensors are synchronized using a timing signal (distributed by cables) from each sensor to the timing source. A master sensor is defined to receive and synchronize the timing data from the other sensors. Each tag registers with its containing sensor cell, and is inserted into the schedule for that cell. The schedule determines when the tag should emit UWB signals to be located by the cell. The schedule is optimized to give attention to each tag as close as possible to its requested quality of service, while maintaining enough space in the schedule for new tags to register. When a tag emits a signal, this signal is picked up by one or more sensors in the cell, as shown in Figure 2-7. The slave sensors decode the UWB signal and send the angle of arrival and timing information back to the master sensor through an Ethernet connection. The master sensor accumulates all sensed data and computes the location based on triangulation (Ubisense, 2009).

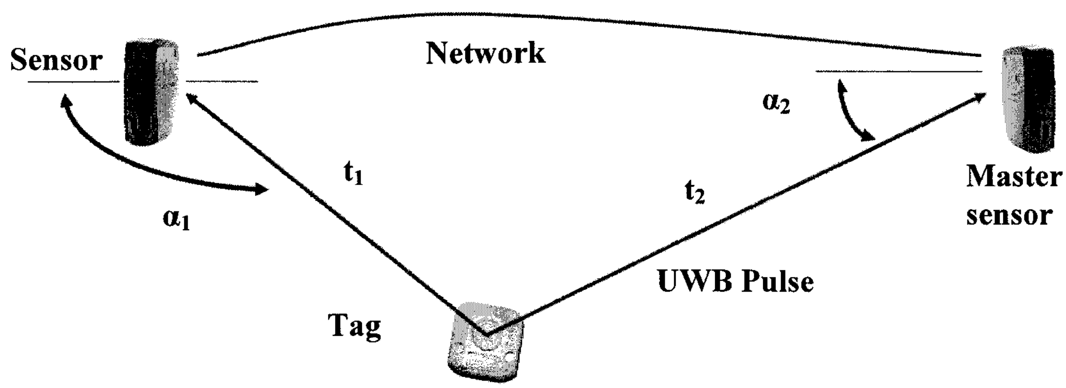


Figure 2-7 Signals sent to sensors are used to calculate the 3D position of a tag (Ubisense, 2009)

2.9 Data quality improvement

The measurements taken need to be as free from errors as possible in order to have high-quality data. As discussed by Muñoz et al. (2009), the RTLSs ideal goal is to determine a specific location in time of an object being tracked with zero estimation errors. Due to cost constraints and intrinsic limitations, this goal cannot be achieved. However, different techniques can be applied to minimize those errors and to provide adequate estimates. Sources of errors are the reference system related with the location, instrument errors, electronic or quantum noise, variation in component parameters, parameter acquisition and measurement procedures. In an RTLS, resolution is an important property that can be defined as the ability to discriminate among near locations and this property depends on the application. In radio position location systems, major sources of error are related to signal-propagation phenomena. As an illustration, reflection, refraction, absorption, and diffraction may cause the measurements to deviate from ideal nominal values. These variations are usually treated as random and are described using statistical models because their deterministic description is not feasible (Muñoz et al. 2009).

In order to improve the localization accuracy, different techniques can be applied. Many RTLSs use a temporal smoothing technique, where all the location estimates in a fixed-sized sliding window are averaged to produce the smoothed estimate. The average is computed as the geometric mean of the coordinates of the location estimates in the sliding window (this applies for coordinate-based systems). Another technique is snapping, which constrains coordinate-based location estimates using the boundaries in the physical environment; this is usually applied in indoor applications. Fusion techniques such as the effective use of two or more different types of sensor observations and tracking techniques, such as modelling the motion of a device or a person being tracked, can also improve the accuracy.

Other more advanced techniques such as Kalman filters and particle filters can be applied to the location systems to effectively obtain better locations from a system (LaMarca and De Lara, 2008). Figure 2-8 shows a simplified functional block diagram of radio positioning and tracking. The system receives a signal which is sensed and the values of RSS, TOA and AOA are obtained. Those are the inputs of the position estimation algorithm which calculates coordinate estimates. Finally, techniques such as kalman filter or least-squares are used to obtain smoothed coordinate estimates to track the object (Yu et al., 2009).

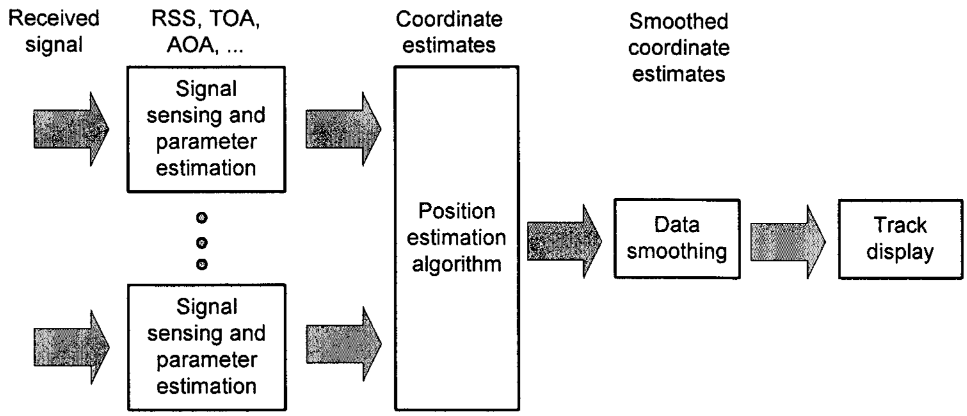
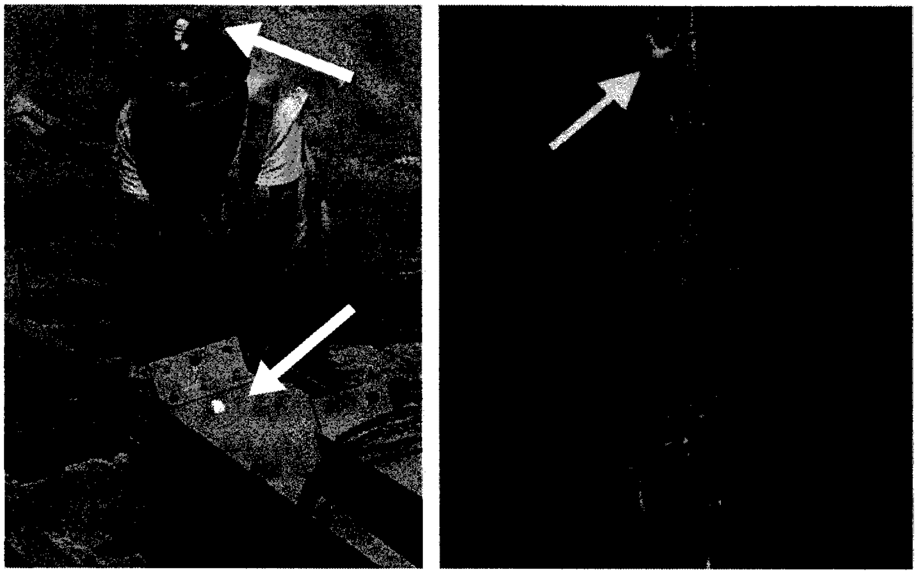


Figure 2-8 Simplified functional block diagram of radio positioning and tracking (Yu et al., 2009)

2.10 UWB in construction

UWB RTLS technology has been investigated for automating data capturing, and identifying, locating and tracking objects for productivity and safety management in the construction industry. As presented in Section 2.7, UWB is a real-time location technology that allows determining 3D resource location information in construction environments in near real time. This technology can be used to track equipment, components and workers to determine if the plans had been accomplished as it was planned. Researchers have started to investigate the usability of UWB on construction sites. Applications such as work zone safety (Giretti et al., 2009), material and work task productivity tracking (Teizer et al., 2008) demonstrated the applicability of UWB for construction. Figure 2-9 presents tags attached to a worker, material and to the hook of a crane.



(a) UWB tag on worker and material (b) UWB tag on crane hook

Figure 2-9 UWB tag on resources (adapted from Teizer et al., 2008)

Giretti et al. (2009) have indicated that UWB behavior is rather constant during most parts of the construction progress. They noted that in an open area, tests confirmed an accuracy of about 30 cm. They have also discussed a safety management system. Indoor laboratory experiments had been conducted by defining algorithms for warning alarms in work zones described as hazardous and for obstacle avoidance. The results obtained at the Real-time Automated Project Information and Decision Systems (RAPIDS) laboratory (Teizer et al., 2008) show that tracking construction resources is possible with errors less than 1 m with this technology. In addition to the indoor test, an outdoor experiment was conducted in a steel erection process. However, the results of this experiment indicated that data need to be filtered using an automated threshold criteria in a tracking algorithm (Teizer et al., 2007; Teizer et al., 2008). UWB technologies can be successfully applied to obtain accurate and real-time position tracking of workers and assets in construction sites for management purposes if the installation is properly designed. Simulation of an excavation process and worker movement inside a building under construction has been conducted (Carbonari et al., 2009; Giretti et al., 2008). In another study, an UWB tag has been attached to the hook of a crane to track the position of the hook for safety (Teizer et al., 2007). UWB have been also combined with other technologies such as Range Image Sensing for productivity and safety monitoring in real time (Teizer and Castro-Lacouture, 2007).

Active sensing technologies are used for safety purposes in two ways: proactive safety technology which works in real time to alert personnel of the dangers occurring, and reactive technology which collects data in real time to be analyzed in order to determine the best practices and to make process improvements (Fullerton et al., 2009).

2.10.1 Productivity management using UWB

As discussed in Section 2.3, productivity in construction management can be defined from different levels such as task, project and industry. Workforce productivity analysis is not one of the major research areas in the construction industry (Teizer and Vela, 2009). That affirmation represents an opportunity to explore the application of suitable technologies to automatically monitor trajectories of workers for process analysis. The present research focuses on task and project levels for productivity management. UWB technology has been explored in indoor and outdoor construction activities (Carbonari et al., 2009; Giretti et al., 2009; Teizer et al., 2007; Teizer et al., 2008). Scenarios where this technology can be useful are: data collection and processing for planning, productivity monitoring process, visualization for active resource management, documentation and learning, information sharing, risk management and control, and decision making (Teizer et al., 2008). Although the practices for managing information in construction projects continue to be mostly manually, there is an evolution towards progress monitoring by visualizing the phases and the percentage complete in what is called 4D models. They include the visualization of the construction in 3D and also the progress of the project with time. The progress is divided in packages that can be monitored, and this is the link with workforce monitoring because it is assumed that for task completion workers and equipment involvement is crucial. Construction projects manage different information from the design to the delivery, therefore, the benefit of interchange this information through a standardized method such as BIM can lead to an effective and reliable progress monitoring tool for projects (Teizer and Vela, 2009). Studies have been conducted to determine the feasibility to automate the process of capturing information. For example, Teizer and Vela (2009) have used video cameras for personnel tracking in construction sites and found that this is feasible based on tracking algorithms. The benefits of the tracking procedures can be extended to alternative technologies such as UWB which is the principal focus of this research. Teizer et al. (2008) analyzed the travel patterns of construction workers by employing UWB mostly for obstacle avoidance. Their conclusions include that UWB technology can be used to determine the worker travel patterns in construction sites not only for safety but also for efficiency purposes.

2.10.2 Safety management using UWB

Safety is one of the major concerns in the construction industry due to the complexity of the construction sites that can lead to fatal accidents (e.g. excavation, hazardous locations and on-site heavy equipment). For that reason, an automated safety management system has been proposed for tracking worker's trajectories (Giretti et al., 2009). The main objective of this system is preventing workers from being involved in hazardous situations and preventing collisions between personnel and heavy equipment or materials. A research feasibility study was conducted, with the purpose of designing an automated real-time safety management system for construction sites. The system uses UWB technology as a real-time position tracking and introduces a real-time prediction of hazardous events. The experimental work was conducted in three phases: (1) Simulation of workers and facilities moving within an excavation area. It was conducted in a parking area where workers were monitored with accuracy near 0.3 m when there are no obstacles. A decrease to 1 m in accuracy was observed when the tags were placed inside the facilities cabins. (2) Construction site after the erection of the structure concrete frame. A comparison was made between the real position of workers and those ones tracked by the system. (3) Building after the completion of the walls and with the scaffolding presence along its perimeter. In this phase, the results of the location sensed where divided into the areas where the position tracking was discrete, good or bad. This test indicates in which areas the system was not capable of pointing 3 receivers simultaneously. Therefore, it is concluded that obstacles could be one of the causes of the decrease in the quality monitoring (Giretti et al., 2009). A software interface was developed to graphically reproduce and store the travel patterns of workers. It was developed to provide alerting signals in real time when the worker is within a dangerous area previously defined. The areas were differentiated and those areas where a higher risk exists were identified to act as a virtual fencing (Giretti et al., 2009). The algorithm logic of this system is presented in Figure 2-10. The operators' position is obtained and a validation is conducted to determine if the operator is within the red or yellow area to send the warnings required.

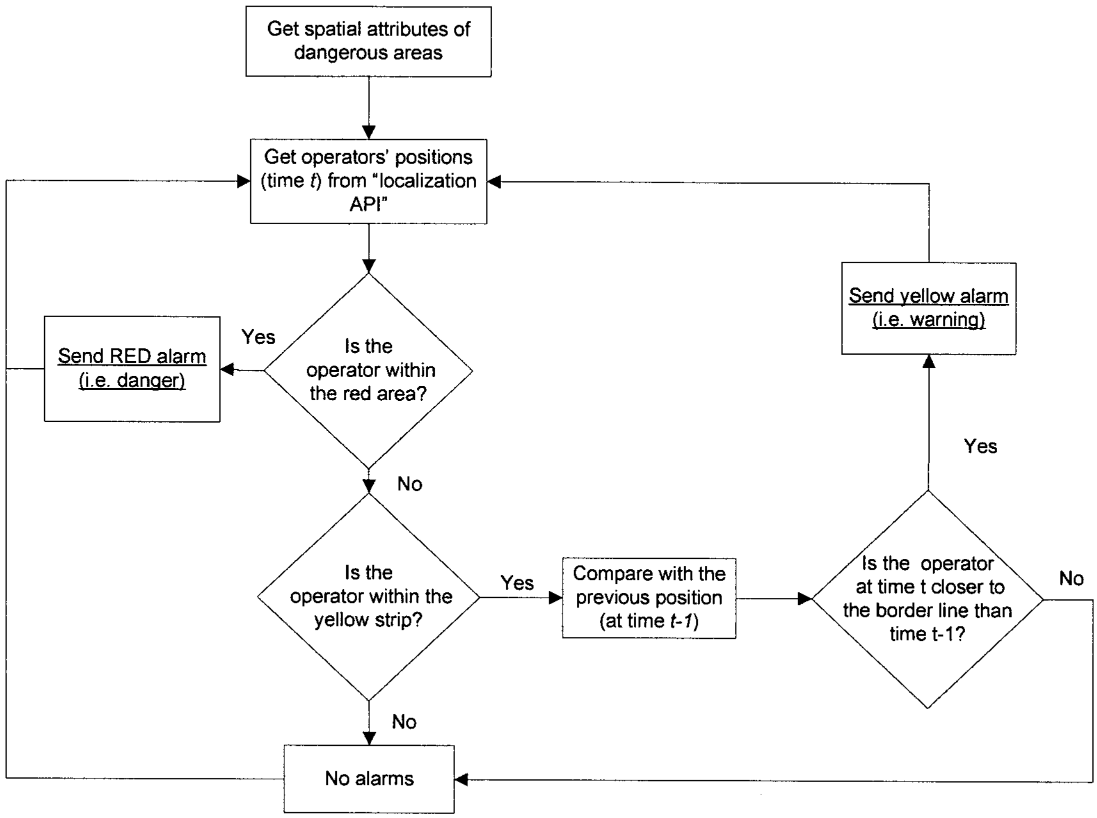


Figure 2-10 Algorithm logic for safety management system (adapted from Giretti et al., 2009)

Preliminary test in a laboratory environment shows that filtering tracked measurements is required in order to minimize the errors obtained from the system. Those errors were determined as absence of alarms, false red alarm and false warning alarms. This feasibility study concluded that UWB systems can be successfully applied in construction sites with an appropriate system design. Tags with update rates of 1 Hz and 3 Hz were used, and a higher update frequency was suggested to reduce the warning strip and increase the algorithm reliability (Giretti et al., 2009). The benefits obtained for productivity can be added to those of the safety purposes.

A scenario for automated proactive work zone safety in infrastructure construction has been developed where the concepts of integration of the data collected with the analysis can lead to safer and more productive decision in construction sites (Teizer et al., 2008). Figure 2-11 shows a scenario for automated proactive work zone safety and the overall framework for real- time decision making.

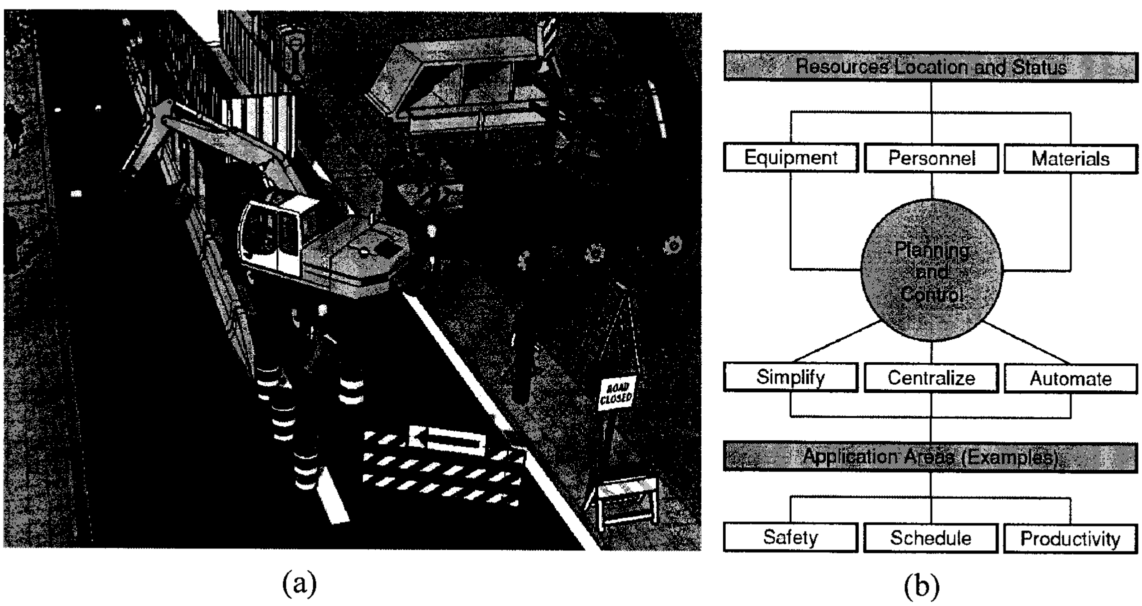


Figure 2-11 Scenario for automated proactive work zone safety in infrastructure construction and overall framework for real-time decision making: (a) example of a hazardous work zone, and (b) methodology of real-time safety frameworks (Teizer et al., 2008)

2.11 Requirements for the UWB system

There is detailed research related with the specific requirements of the UWB system when applied in construction. Some of the aspects to consider in the deployment of an

UWB RTLSs were presented for emergency purposes, where UWB is the preferred solution, as it has the specific advantage of high accuracy even in the presence of severe multipath. Features such as the deployment of terminals, surveying, integration with GPS and solving for position are explored (Ingram et al., 2003; Ingram et al., 2004). Extension of these requirements to construction applications was started by Teizer et al. (2007; 2008) and is described as follows: (1) Accuracy: less than 30 cm and update rates of at least 1 Hz were defined acceptable for many infrastructure applications such as automated material, work zone safety and location tracking and navigation. (2) Installation cost: the system should be affordable based on the application and the frequency of use. (3) Ease of use and operational cost: the hardware should be maintainable at a reasonable cost and in a simple way. (4) Size and weight: the sensors and tags should be of a size suitable for the object to be tagged and the place where they will be installed and should ideally offer wireless operation. (5) Standards and regulations: each country has its own regulations that have to be followed. Low-powered commercially available UWB systems have no restrictions. (6) Interoperability: the system must interface with wireless communication technologies and needs to cohabit with other signals in the RF spectrum. (7) Range: to work in construction environments the system must be useable over 150 m between fixed and potentially mobile receivers and it needs to work in object-cluttered environments. (8) Interferences (multipath): the system must have a good performance in environments with obstructions that cause multipath signals. Previous research has identified the general requirements in construction sites which are dynamic and include several variables. Furthermore, Zhang et al. (2009) stated that tags should be located to fulfill the visibility, orientation, and accuracy to apply UWB for safety requirements. However, the specific requirements for productivity and safety applications of UWB system have not been defined and analyzed and they represent an opportunity in this area.

Cho et al. (2010) have discussed error modeling for an untethered UWB system for construction indoor asset tracking. Based on their experiment, elevated tags give a better line-of-sight path between the tags and the sensors, and the average accuracy is 17 cm, while the tethered system gives 10 cm accuracy in open space. They suggested that the accuracy of locations is related to the height and facing angle of sensors, which affect the chance of having a line-of-sight transmission path to mobile tags.

2.12 Summary and conclusions

RTLSs have been applied to construction operations for productivity and safety purposes. Specifically UWB technology can be used to identify and track components to better manage projects. However, to apply UWB systems for productivity or safety purposes, the requirements of the location data must be defined more specifically. The quality of the data obtained from UWB RTLSs has not been analyzed for the different applications. Moreover, location data quality can be described in terms of data accuracy, data completeness and data timeliness (Westfall, 2010). As a conclusion, further investigation of the requirements to apply UWB in construction is required.

CHAPTER 3 PROPOSED APPROACH

3.1 Introduction

To achieve the objectives of this research, the proposed methodology starts by identifying the approaches to improve productivity and safety by using UWB technology. Then, the requirements of UWB technology for location tracking of construction resources are defined to establish its usability for improving productivity and safety.

3.2 Improving productivity and safety using UWB tracking

3.2.1 Improving productivity

In a construction environment, there are dynamic changes in the site layout due to the interaction of different contractors in the same space during the construction phases. Therefore, the use of UWB can lead to a better space management and productivity can be increased by assigning areas and resources more effectively. The following process improvement approaches are expected to increase productivity:

(1) Measuring the percentage of the wasted time in unnecessary movements: The ratio between the time the worker is focusing on a specific task and the time used to move between different locations (e.g., searching for tools or materials) can be estimated based on the tracking data.

(2) Automating repetitive processes: For example, by automatically driving the scissor lift to the position of the next operation (e.g., fixing studs for supporting the false

ceiling in a large room as shown in Figure 3-1), the time wasted to manually operate the scissor lift can be saved.

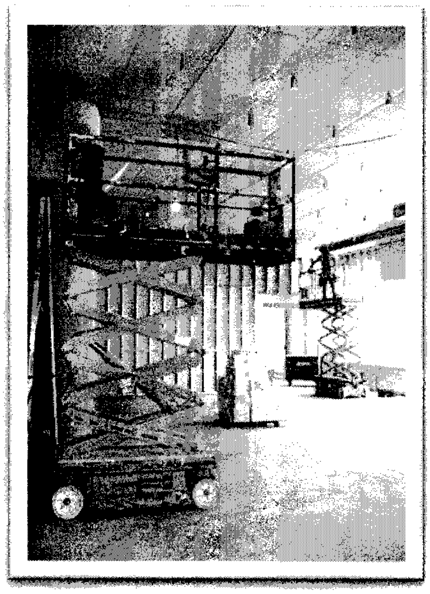


Figure 3-1 Installation of false ceiling (Rodriguez, 2009)

(3) Optimizing the routes of workers in the building by using indoor navigation, which will help workers find the place where the work has to be accomplished and locate the required equipment.

(4) Standardizing the work by re-playing and analyzing the recorded activities. Data collected for specific tasks can be analyzed to compare different methods and select better ones for future projects.

(5) Determining the progress of the project by linking location data with operations and schedules.

(6) Reducing the conflicts for resources (e.g. space, tools, equipment) between different crews by predicting the location of moving objects in near real time. Figure 3-2

shows two workers performing activities in the same area that can be predicted in advance.

Figure 3-2 Conflict at the working area (Rodriguez, 2009)

The above mentioned process improvement approaches based on monitoring resources are an important step towards lean construction, which is a production management based approach to project delivery aiming to maximize value and minimize waste.

3.2.2 Improving safety

To improve safety of construction equipment operations and provide more awareness on site, several analyses could be done:

(1) Identifying geometry of obstacles by using multiple tags attached to different components of equipment. Therefore, moving objects should be tracked, identified, and modeled in a way that the full geometry, speed, moving direction, and all the relative information of the task are used to prevent collision accidents.

(2) Checking the compliance with safety regulations and engineering constraints to prevent accidents. For example, in some jurisdictions workers are not allowed to move on the scissor lift to a new position unless the lift is down.

(3) Achieving more advanced intelligent support by integrating path planning algorithms to generate a collision-free path. Once a potential collision is detected, re-planning of the equipment motion can be done based on updated environment information.

3.3 Purposes of tracking equipment and workers

After defining the purpose of UWB tracking in construction as increasing productivity and safety, the following step is to determine the purposes of tracking equipment and workers and the information to be collected and processed in near real time or post-processed. Multi-purpose tagging increase the benefit derived from RTLSs and allows sharing the cost of implementing this relatively new technology between different functions.

3.3.1 Tracking equipment

The purpose of tracking equipment is described as follows:

(1) To prevent accidents. By tagging equipment and with an appropriate feedback system it is possible to prevent collisions in the construction sites.

(2) To locate equipment on demand. In outdoor or indoor activities, equipment can be shared among crews and the localization can be difficult if the activities are

performed in different areas of the construction site. Tagging the equipment would facilitate locating the equipment when is required.

(3) To track and trace equipment. For determining where certain equipment was at a specific time and which crew used it. In the case of rented equipment, this information can be useful to analyze costs related with each activity by monitoring the usage.

(4) To improve equipment utilization. The analysis of equipment locations and length of time spent in particular locations can lead to an understanding of how often various pieces of equipment are used, where they are most often used, and what they are used for. It allows determining productivity ratios between equipment used and time to accomplish activities. The results of these analyses can help to enable optimum work usage, and when to schedule equipment maintenance.

(5) To manage and plan inventory. Real-time inventory is necessary when there is a big number of equipment being used in the construction site. It is useful to determine the resources that are going to be need in a specific phase of the construction and when they have to be available.

(6) To protect equipment. For security purposes a RTLSs is beneficial. If equipment is out of the area where it supposed to be it can be identified immediately and it can prevent equipment from being stolen or lost.

3.3.2 Tracking workers

The purpose of tracking workers is described as follows:

(1) To prevent accidents. Location information can prevent accidents by alerting workers and visitors which areas are dangerous in a construction site and to manage restricted areas. It allows prevention of collisions with equipment.

(2) To provide emergency response and manage evacuations. If the localization of a worker in an emergency is easy to find, it will allows the emergency response to be more effective.

(3) To locate workers on demand. When different crews are performing activities, tracking workers will facilitate locating them when required in outdoor or indoor activities.

(4) To track people. Activities can be linked with locations to find productivity ratios and relate them with cost.

(5) To improve workflow. By monitoring movements and analyzing trends significant improvements in work practices and methodologies can be achieved.

Figure 3-3 shows a proposed cycle which starts with workers and equipment are tracked in near real time for safety, security, progress management and supply chain visibility purposes. As a result of this data processing, the construction site improvements are derived in short time. However, data are post-processed for productivity, lean construction, continuous quality improvement, key performance indicators, ergonomic operations (decrease fatigue) and claim resolution purposes. As a result, there are derived construction practices improvement which have a long-term impact. Then, the cycle starts again with the tracking operations as a cycle that aims to improve construction operations.

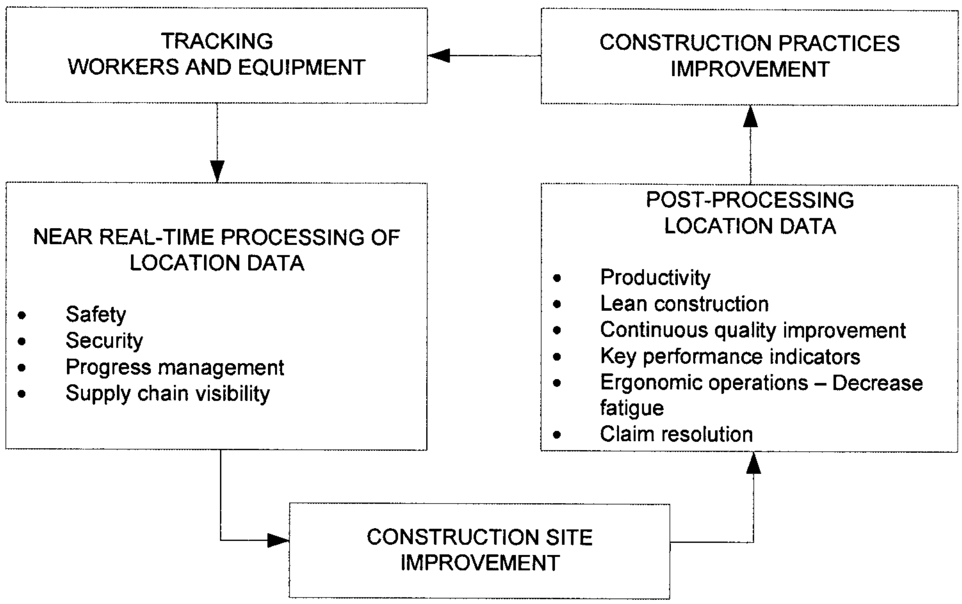


Figure 3-3 Proposed approach for tracking construction resources

3.4 Requirements for the deployment of UWB RTLSs in construction sites

This research explores the following requirements for the application of UWB in construction to improve safety and productivity: accuracy, visibility, scalability and real-time, real-time filtering, tag form factor, power consumption, and networking requirements. The number of tags, number of sensors, and location and orientation of sensors should be decided to meet these requirements.

Accuracy requirements: Accuracy is the most important requirement to guarantee that valuable data are collected. AOA and TDOA are used in UWB RTLSs to locate tags based on trilateration. If only AOA method is used, two sensors are theoretically required to locate a tag in 3D; however, to improve accuracy, more sensors are needed in practice to reduce the influence of multipath and noise (Muñoz et al., 2009). If only TDOA method is used, at least three sensors are required for 2D positioning and four sensors for 3D positioning (Ghavami et al., 2004). Table 3-1 summarizes the combinations of the location method and the result. To get the highest possible accuracy, the combination of AOA and TDOA should be applied (Abdul-Latif et al., 2007). Two sensors deliver a robust localization with an accuracy of up to 15 cm in ideal conditions (Ubisense, 2010). In practice, more sensors enable greater confidence in the accuracy and higher availability, leading to a more robust solution.

Table 3-1 Combinations of the location methods and the results (adapted from Ubisense, 2010)

Location method	Number of sensors detecting tag	Other information required	Result
Single-sensor AOA	1	Known height of tag	2D horizontal position (+ known height)
AOA	2 or more	None	3D position
TDOA+AOA	2 or more	None	3D position (highest accuracy)
TDOA only	3	Known height of tag	2D horizontal position (+ known height)
TDOA only	4 or more	None	3D position

To gain accurate location data, calibration of the sensors is essential. A local coordinate system is defined by the user, and based on that the coordinates of each sensor should be measured precisely using surveying tools, such as total stations. Each sensor should be levelled after the installation. One tag should be placed at a location with known coordinates in the local coordinate system. As a result, the pitch and yaw angles of each sensor can be calculated and recorded in the system.

Data filtering should be applied to reduce errors in near real time and improve the accuracy. This filtering could be applied to validate the individual AOA and TDOA measurements against a predicted position, and then apply them to calculate a new estimate of position. In this case, the motion model for the filter has to be defined by specifying the constraints on the motion that the tracked object can undergo. For example, a tag could be free to move in 3D or constrained to move horizontally with a certain motion model of position and velocity and Gaussian noise on velocity. Filtering could be applied on the location data resulting from the trilateration. For example, Cho et al. (2010) have claimed that the total accuracy is improved by 25% after applying an error model using a Kalman smoother. However, applying these filters needs several assumptions about the motion model which may not be easy in the case of workers in a construction site or equipment such as scissor lifts and cranes.

Visibility requirements: The sensors should be set in a way to utilize their antenna pattern both in the azimuth and the elevation. The field of view may be different from one UWB system to another. The maximum range of sensors can be potentially up to 200 ft (61 m); therefore, a reasonable monitoring area should be defined considering the coverage of the sensor cell. If the area to cover is big, more sensors should be installed to cover this area using one or more cells. In addition, multiple tags attached to the same object should be considered as a way to improve the visibility of that object by increasing the probability of detecting these tags. For example, multiple tags can be attached to a worker's hardhat or the boom of a crane as will be explained in Subsection 3.5.1.

Scalability and real-time requirements: Since in commercial UWB systems there is only a single UWB channel used in time division mode, only one tag can be located at a time in each sensor cell. As mentioned in the visibility requirement, multiple tags can be used even for an individual object; therefore, the suitable number of tags attached to an object should be decided based on the frequency of the system and the size of the sensor cell. The number of time slots per second depends on the frequency of operation of the UWB system. For the Ubisense system with a nominal cell frequency of R=160 Hz, one second is divided into 153 time slots, each has a duration of 6.5 ms. Different slot intervals can be selected to determine how often the tags' locations are updated, and how often the system listens for data and schedule messages from the master sensor. The shortest slot interval can be set to 4 slots, which means the update interval is 26 ms, corresponding to a maximum update rate per tag of approximately 38 Hz.

With a large number of tags in a sensor cell, the update rate of tags will decrease to allow the system to cover all tags with the fixed total number of time slots. For example, if the time slot is set to 4 and only 4 tags are in the cell, the four tags are updated every 26 ms (38 Hz). When more tags are detected in the system, e.g., 8 tags, the update rate is decreased to 19 Hz. The more tags in the system, the bigger the slot interval should be selected, and the lower the update rate. A specific update rate can be set for an individual tag or a group of tags. One consideration when setting the update rate is the moving velocity of the object. Objects with high velocity need more frequent updates to accurately track their traces. Therefore, selecting a suitable number of tags with an appropriate update rate based on their velocity is essential for achieving the balance between the conflicting requirements of visibility and accuracy in near real time.

Figure 3-4 shows how the system assigns updates for 4 tags with a slot interval of 4 time slots. Table 3-2 shows the update intervals and rates for different slot intervals for

Ubisense 160 Hz system (Ubisense, 2009). Appendix A presents the complete update intervals for 160 Hz and 40 Hz systems.

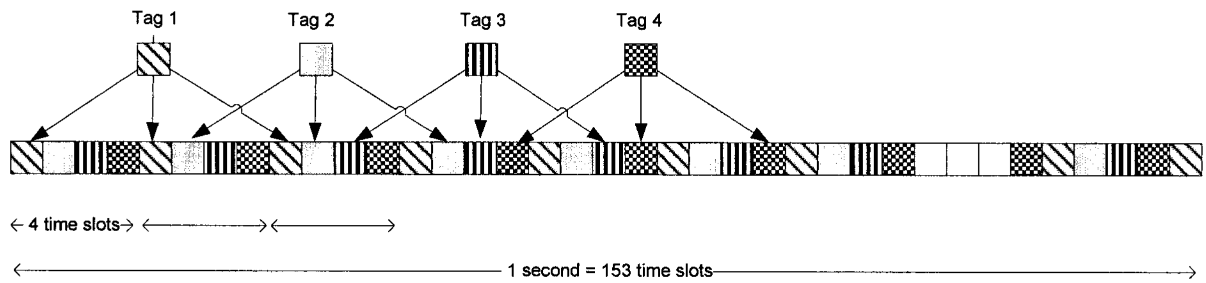


Figure 3-4 Tag updates for a 160 Hz system with slot interval 4 time slots

Table 3-2 Update intervals and rates for different slot intervals for Ubisense 160 Hz system (adapted from Ubisense, 2009)

Slot interval	Update interval (ms)	Nominal update rate for each tag (Hz)
4	26	38
8	52	19
16	104	10
32	208	5
64	416	2.4
128	832	1.2
...	...	...

To maximize the update rate, one heuristic rule can be defined as follows (Hammad et al., 2010):

$$m \leq 4 \times 2^n \qquad (1)$$

Where m is the number of tags in the system, n is the minimum value that meets the inequation, and 4×2^n is the time slot interval that should be set. For example, if there are

10 tags in the system, the minimum value of n is 2; therefore, the time slot interval should be set to 16 (i.e., update rate of 9.6 Hz).

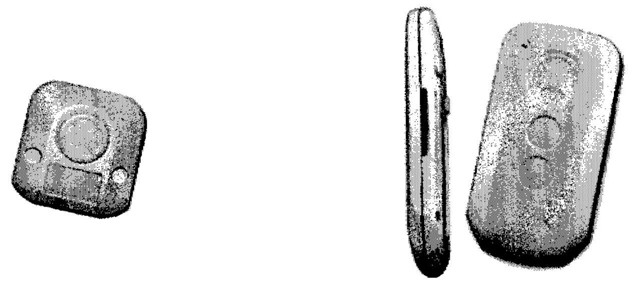
On the other hand, if the update rate is defined, another heuristic rules can be defined as follows:

$$R/r \geq 4 \times 2^n \qquad (2)$$

Where R and r are the update rates of the cell and the tags, respectively, n is the maximum value that meets the inequality, and 4×2^n is the time slot interval that should be set. For example, if an update rate of $r = 8$ Hz is required for the tags, the maximum value of n is 2, and the time slot interval can be set to 16. According to inequality (1), a maximum of 16 tags can be used in the system to get this update rate.

As mentioned above, r should be set according to the velocity of the objects. For example, in the case of tracking a crane's boom, if the velocity of the tip of the boom is 0.5 m/s, with an UWB system that has an accuracy of 15 cm, at least 4 Hz is needed to update the location of the boom's tip to avoid potential collisions. However, if the tracking purpose is only items localization or monitoring the productivity of the process, that frequency can be decreased.

Tag form factor requirements: Even if the basic functionality of the tag is the same, tags come in different form factors. Some tags are basically designed to be worn by a person as a badge; others are designed to be attached to an object or asset. In addition to its tracking capabilities, tags can include a buzzer to provide basic messaging capabilities and push buttons to trigger events. These tags can be used in safety applications when, for example, a buzzer signal indicates that a worker is entering a danger zone. Figure 3-5 shows two tags with different functionalities.



(a) Compact tag (b) Slim tag

Figure 3-5 Tag forms (adapted from Ubisense, 2010)

Power requirements: The sensors must be connected to a stable power source for precision measurements. Tags require a battery which life depends on the update rate established for the system. The tag's update rate can be dynamically and automatically varied depending on the activity of the tag. If the tag is moving quickly, a high update rate can be assigned for best tracking; if it is moving slowly the update can be reduced for best battery lifetime. When stationary, tags go to sleep mode to conserve power, and an in-built motion detector ensures that the tag transmits again as soon as it is moved.

Networking requirements: The sensors can be connected by cables or wirelessly to the location server. Both data cables and timing cables are needed for a wired system. The wireless system depends only on the AOA calculations as wireless communication is not fast enough to support TDOA. The decision about the type of the network (wired vs. wireless) has a direct impact on accuracy (Cho et al. 2010).

In the ideal tracking situation the higher requirements are applied (i.e. safety) to get advantage of better safety and productivity. For example for safety purposes, accuracy and scalability are more critical requirements than for productivity. The reason is that for safety the consequences of a bad decision can be catastrophic, in the case of productivity, a bad decision can conduct more to strategic errors. However, the sensing needs have to be analyzed by taking into account the risks associated with both aspects to obtain the maximum benefit of UWB technology.

3.5 UWB system setting for satisfying the requirements

In order to test the performance of the UWB system against the above requirements, the following two scenarios are used to investigate the setting of UWB system for tracking workers and equipment:

(1) Tracking the movement of workers and equipment during the installation of Heating, Ventilation, and Air Conditioning (HVAC) ducts in an indoor construction site.

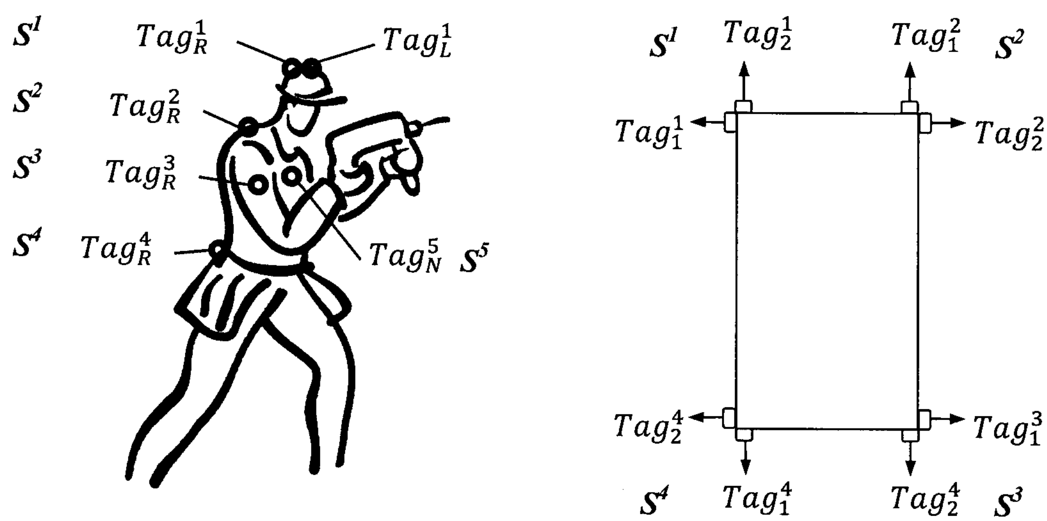
(2) Tracking the movement of a hydraulic crane.

The specific details about these tests are given in Chapter 4.

3.5.1 Location of tags for workers and equipment

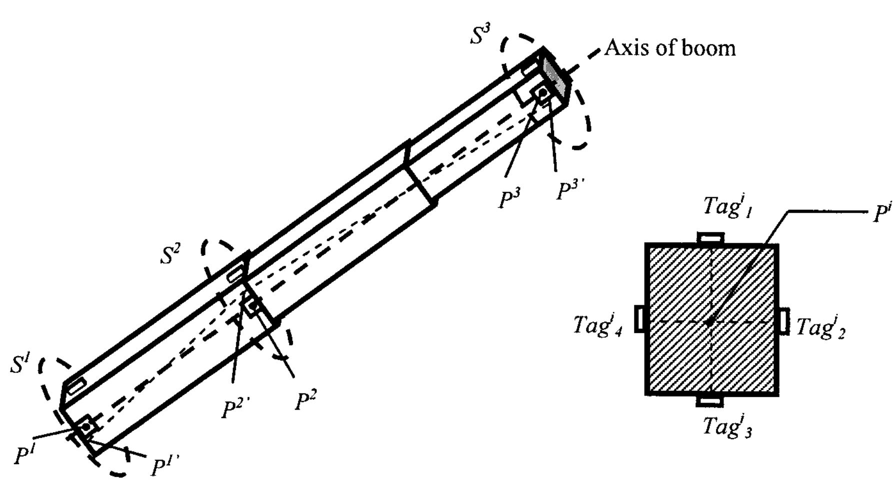
The tags must be attached to workers in a way that does not interfere with the work that is going to be realized and does not disturb the comfort of workers. For that reason, the tags should be attached to the hardhat of the worker, his tools belt, his shoulders or his arms fixed with hook-and-loop fabric bands. In all those cases, the tags must be attached in a way that guarantees that the tags are going to stay attached at the same position. There are two types of tags available, which are slim tags and compact tags. Slim tags are designed to be wear by a person as a necklace and include additional features such as a buzzer to provide basic messaging capabilities and push buttons to trigger events. However, the human body interferes with the signals from the tag to the sensors. Compact tags are more suitable to be attached to workers due to their omni-directional antenna. Compact tags are suitable for equipment where multi-tags can be attached to determine the pose of the object tracked. Figure 3-6 shows the proposed locations for tags on a worker and on a scissor lift as an example of construction equipment used in indoor construction sites. On a worker, five sets of tags (S^1, S^2, S^3, S^4, and S^5) are attached to the helmet, shoulders, arms, belt or worn as a necklace on a worker. Each set S^i includes two tags (Tag_R^i and Tag_L^i) fixed on each side of the human body and where R represents right side and L left side. The exception is S^5 which has one slim tag worn as a necklace (Tag_N^5). On the scissor lift, four sets of tags are attached (S^1, S^2, S^3 and S^4), one at each corner. Each set S^i includes two tags (Tag_1^i and Tag_2^i). This redundancy improves the visibility of tags attached to the worker and equipment to be located by the sensors at a construction site.

In the case of monitoring the movement of a hydraulic crane, multiple tags should be attached to its different components to identify its pose. Tags can be attached to the base of the first part of the boom and its tip for easy installation and to avoid damaging the tags. Figure 3-7 shows a schematic boom with three sets of tags (S^1, S^2, S^3) attached to it. Each set S^i includes four tags (Tag_1^i, Tag_2^i, Tag_3^i, and Tag_4^i) fixed on each side of the boom. This redundancy improves the visibility of tags attached to the boom by the sensors when the boom rotates. The approximate location of the center point of a cross section P^i can be calculated based on averaging the locations of all or some of the four tags of set S^i. The orientation and the length of the boom can be obtained by connecting the two axis points P^1 and P^3. The purpose of having an additional set of tags S^2 is to get a third point P^2 on the axis of the boom so as to increase the accuracy by having more points along the axis, which allows to interpolate the line representing the axis.



(a) Tag locations on a worker (b) Tag locations on a scissor lift

Figure 3-6 Location of tags on workers and equipment



(a) Locations of tags on the boom (b) Cross section of the boom

Figure 3-7 Locations of tags on the boom and the cross section of the boom

3.5.2 Sensor coverage

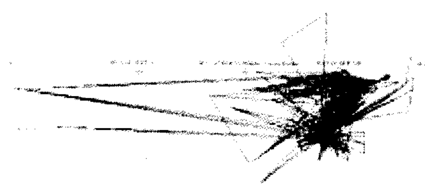
One sensor cell can be constructed with four sensors and can cover up to 70 x 70 square meters. However, for large construction sites, the number of cells has to be determined based on the area to be covered. The four sensors of a cell are usually located at the corners of a rectangular monitoring area at a high position facing down towards the center of the area. For monitoring activities, the locations of the sensors have to be designed considering the following issues: (1) Maximum coverage; (2) Minimum cable length, (3) Avoiding interference with workers and equipment (e.g. work zone of scissor lift), and (4) Avoiding gateway blockage.

In the case of monitoring the movement of a large hydraulic crane, the sensors should be fixed at a high position and their pitch angle should be adjusted to cover all the tags attached to the crane.

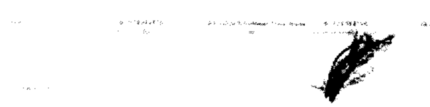
3.6 UWB data processing

3.6.1 Filtering algorithms based on sensed data

As discussed in Section 2.7, there are different methods to obtain the location in UWB such as TOA, TDOA, RSS, and AOA. All these methods have problems to determine the real position because obstacles and reflections in the line of sight between tags and sensors. The basic location algorithms receive signals and reject all but the first signal to arrive. However, this first signal can be a reflection and affect the sensed position. To resolve the true position, reflection-rejecting location algorithms are needed (Ward, 2007). Figure 3-8 shows the difference between the basic location algorithm and the measurements computed after filtering algorithms are applied (proprietary from Ubisense). The real paths are shown in green and the measured ones in red. This presents the need of application of filtering and averaging techniques to determine the location of the objects to be tracked.



(a) Basic location algorithm



(b) Reflection-rejecting location algorithm

Figure 3-8 Location algorithms comparison (Ward, 2007)

UWB RTLSs can provide a dynamic control of the tags by defining parameters as scheduling and filtering by asking each tag to generate a UWB pulse depending on their profile. Those properties can be set either for a range of tags, or for individual tags. Data can be filtered in near real time in order to reject individual measurements that may be reflections or corrupted by noise. For that purpose, different algorithms are available for estimating tag positions from sensor measurements. By defining some parameters, the behavior of the algorithm can be controlled. In the case of Ubisense system there are two options for collecting data: No filtering or filtering. In the first case, the readings are raw sensed positions and no filter is applied. In the information filtering algorithm, the previous motion of the tag is used to predict its position at the time a new sighting is made. The information from AOA and TDOA measurements are individually validated against the predicted position, and then are applied to give a new estimate of position. The motion model for the filter has to be defined by specifying the constraints on the motion that the tracked object can undergo. The filtering options are: (1) Information filtering, in this case the tag is free to move in 3D and the motion model is of position and velocity with Gaussian noise on velocity. (2) Fixed height information filtering, the tag is constrained to move horizontally and the motion model is of position and velocity with gaussian noise on velocity. (3) Static information filtering, the tag is free to move in 3D and the motion model is of position with gaussian noise on position. (4) Static fixed height information filtering, the tag is constrained to move horizontally and the motion model is of position with Gaussian noise on position. In addition to those filters, a filter can be created based on the purpose of the tracking system. Another point to consider is that those filters can be applied to individual tags or to a set of tags based on the objective of the tracking system (Ubisense, 2009).

3.6.2 UWB real-time data processing

As described in Figure 3-3 real-time data processing can be used for purposes such as safety, security, progress management and supply chain visibility that lead to improvement in the construction site. The geometry and position of objects can be determined in near real time. For that reason, the data sensed have to be processed and converted into useful information to achieve those objectives as fast as possible to take decisions that prevent accidents. Raw location data captured from the UWB system cannot be directly used to compute the pose of the monitored object they are attached to because of the following reasons:

Synchronization: The data from different tags are not synchronized. As explained in Section 3.4, the UWB radio signals are emitted from each tag based on a precise schedule where only one tag can emit a signal at any point of time in a predefined cycle. To approximately synchronize the locations of different tags, we define a small time period T based on the actual update rate r of a tag. Assuming $t = 1/r$, T should be equal to t or a multiplication of t big enough to capture at least one reading of each tag in the UWB cell and small enough for near real-time applications (e.g., if r is high enough and the application can tolerate a delay of $\delta t = 2t$, then T could be set to $2t$). If more than one location is captured for the same tag within T, these locations can be averaged to obtain a single reading for that period.

Figure 3-9 shows the real-time location data processing of two tags (Tag_i and $Tag_{i'}$) in the simplified case of tags allowed to move only on the x axis, and where $t = 1/r$, and $T = 2/r$. Figure 3-9(a) shows the raw traces where points $p_i^{t_j}$ and $p_{i'}^{t_j}$ represent the locations of Tag_i and $Tag_{i'}$ at time t_j, respectively. Figure 3-9(b) shows the processed traces where points $P_i^{T_k}$ and $P_{i'}^{T_k}$ represent the average locations of Tag_i and $Tag_{i'}$ at time T_k, respectively. As shown in the upper-left part of Figure 3-9(a), there is a shift in the timing of the readings of the two tags because of the scheduling of the UWB system.

Accuracy errors: Each tag location has certain error because of radio reflections, etc. These accuracy errors could be filtered in two stages: First, they could be filtered from raw locations captured by the UWB system based on the data of a single tag before synchronization. Second, they could be filtered after synchronization by exploiting geometric constraints between the tags attached to the same object.

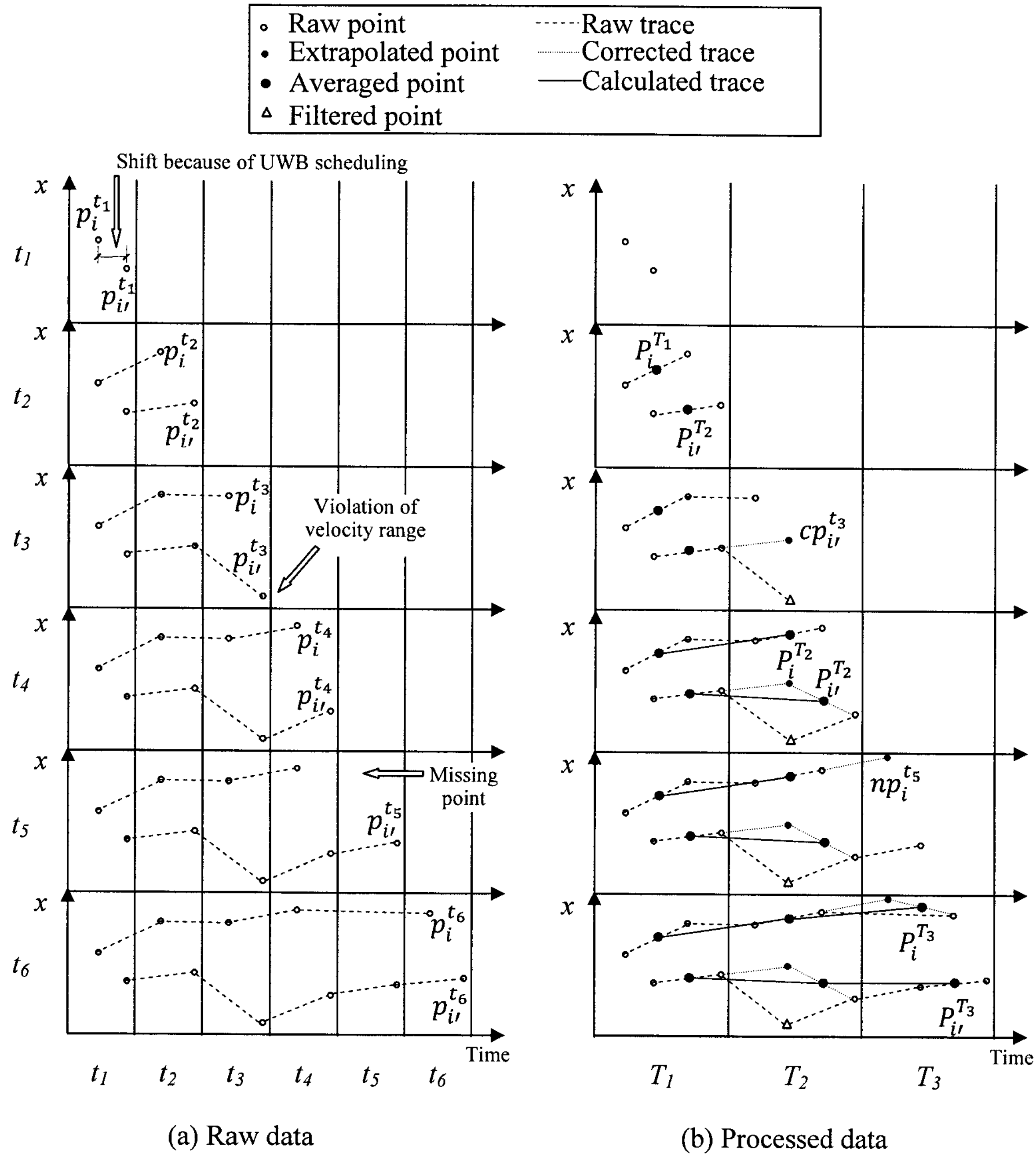


Figure 3-9 Real-time data processing of two tags

Filtering based on the data of a single tag can be done by applying one of the following methods: (a) Applying the filters provided by the UWB system during trilateration (as discussed in the accuracy requirement); (b) Checking if the reading of a tag location is outside the monitored area or outside the expected height range of the object to which it is attached; (c) Checking the patterns of movement where a location does not satisfy certain heuristic rules. For example, assuming the maximum expected velocity (v_{max}) of an object is known, if the measured velocity based on the distance between the past captured location $p_i^{t_{j-1}}$ of Tag_i at time t_{j-1} and the new one $p_i^{t_j}$ is out of range, this indicates that $p_i^{t_j}$ has an accuracy error and should be eliminated. This elimination would result in a missing-point error that will be processed as explained below. Other heuristic rules could be applied based on the specific constraints of the movement of tags, such as the acceleration of movement.

Filtering based on comparing data from different tags can be done by applying geometric constraints between multiple tags attached to a solid object at known locations. These constraints can be used to check the accuracy of the location data. For example, in Figure 3-7(b), the calculated distance between the two tags attached to the top and bottom sides of a section of the boom should be almost equal to the actual distance.

Figure 3-10 shows a 2D example of the actual paths of two tags (Tag_i and $Tag_{i'}$) attached to the same object. These paths are parallel with a fixed distance $D_{ii'}$. The figure also shows the traces based on the locations of tags at time T_k after averaging. It is noticed that all points $P_i^{T_k}$and $P_{i'}^{T_k}$have certain amount of accuracy errors. However, the distances between the traces $d_{ii'}^{T_k}$are expected to be within the range of [$D_{ii'}$ - 2ε, $D_{ii'}$ + $2\ \varepsilon$], where ε is the nominal accuracy of the UWB system (e.g., 30 cm). If $d_{ii'}^{T_k}$ is outside this range, then $P_i^{T_k}$and/or $P_{i'}^{T_k}$ should be checked for possible elimination. For example, in Figure

3-10, if $d_{ii'}^{T_5}$ is out of range compared with $D_{ii'}$, and $P_{i'}^{T_5}$ has been calculated based on an extrapolated point, there is a higher probability that $P_{i'}^{T_5}$ should be eliminated.

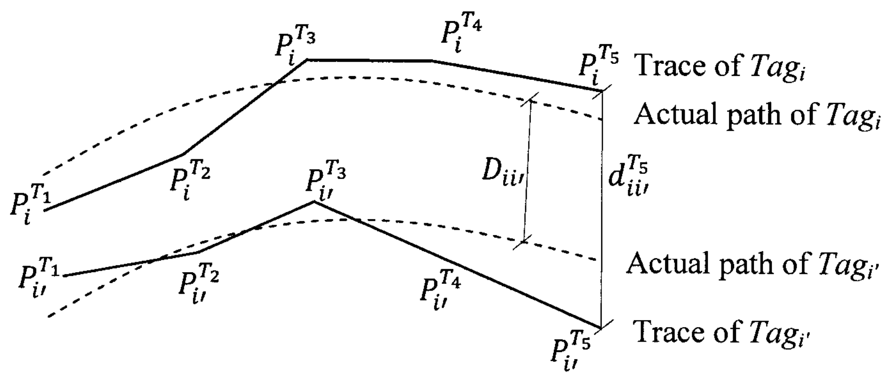


Figure 3-10 Example of using geometric constraints to detect errors

Missing-point errors: There could be some missing data because of lack of visibility (i.e., the tag is not detected during a certain period t_j because of lack of direct line of sight to some sensors) or because of the filtering of data. Extrapolation can be used after filtering to fill the missing points for one or more periods assuming that the object is moving with a known velocity. However, this could affect the quality of the location data if several points are missing in a row. Another type of extrapolation/interpolation can be done based on the geometric relationship between the tags attached to the same object. For example, in Figure 3-7(a), if the locations of the tags Tag_1^2 and Tag_1^3 at the upper side of cross sections S^2 and S^3 are known at time t_j, the location of Tag_1^1 in cross section S^1 can be calculated by extrapolation. As an example of missing-point errors, Figure 3-9 shows that an accuracy error occurred in t_3, where the velocity of $Tag_{i'}$ exceeded the maximum expected velocity. Extrapolation is used to calculate a new location $cp_{i'}^{t_3}$ for $Tag_{i'}$ based on its previous locations and the assumption that the tag is moving with the same velocity. Another missing-point error occurred in t_5 for Tag_i. Extrapolation is also used here to calculate a new location $np_i^{t_5}$ for Tag_i at time t_5.

Based on the above discussion, the steps shown in Figure 3-11 can be applied to improve the quality of the UWB data in near real time: (1) The tags are identified and grouped based on their geometric relationships with respect to the objects they are attached to (e.g., tags attached to the three sections of a boom). T is defined based on the update rate for the purpose of synchronization; (2) Readings of each tag are filtered within time t_j based on the methods described in Accuracy Errors; (3) Missing data for each tag caused by missing-point error or accuracy error are calculated using extrapolation based on the tag's previous locations; (4) Tag locations are averaged during T_k to synchronize different tags; (5) Errors are filtered based on geometric constraints of multiple tags; (6) After filtering, missing data can be calculated based on extrapolation of data of other tags either in the same group or in different groups as explained above; (7) Locations of multiple tags in the same group are averaged (e.g., averaging the locations of the tags shown in Figure 3-7(b) to get the center point of the cross section); and (8) The position or pose of the object is calculated based on the positions of the tags attached to it. For example, the pose of the boom can be found based on the calculated center points on the axis of the boom.

3.6.3 Post-processing location data

As described in Figure 3-3 post-processing location data can be used for purposes such as productivity, lean construction, quality and continuous improvement, key performance indicators measurement, ergonomic operations, decrease fatigue and claim resolution that lead improvement in the construction practices. The paths of objects, speed and time related with activities can be determined most of the time with a reasonable delay. The data sensed have to be processed and converted into useful information for medium to long-term improvement and it has not necessary to be done in real time. In the case of post-processing, synchronization, accuracy errors and missing points lead to the application of almost the same procedure described in the real-time data processing. The difference is that, in Step 3, missing data for each tag can be calculated based on the readings before and after using interpolation instead of extrapolation.

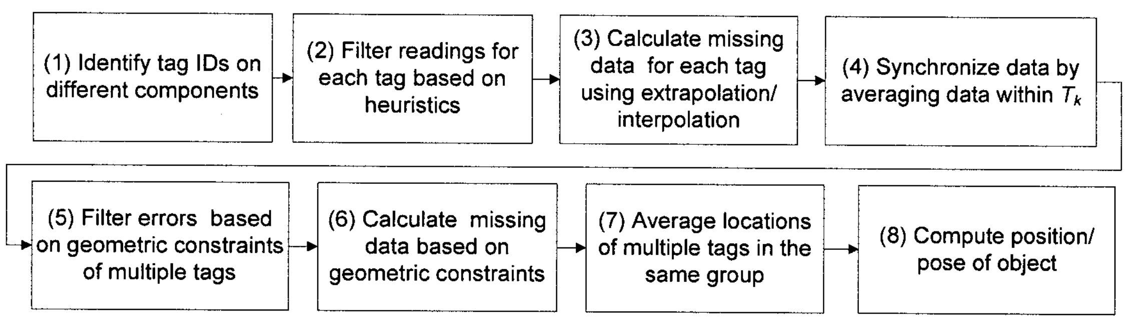


Figure 3-11 Steps of data analysis

3.7 Data visualization

The location data is recorded based on a coordinate system defined by the user. One of the principal aims of the RTLSs is to visualize the location of the assets. However, the visualization tools embedded in commercial RTLSs software are not designed to the specific requirements for tracking. In the case of Ubisense, the location information is displayed in the Location Engine in near real time, however it is not possible to record and re-play, which is one of the major purposes of tracking construction assets as described in this research. The Logger software which complements the Location Engine was used for recording purposes. However, the recorded data cannot be visualized in 4D. Then, the data has to be exported to a visualization tool such as Geographic Information System (GIS) software that allows the analysis for productivity and safety purposes. The steps to do this import process are described in Appendix E. It is important to notice that data from the UWB system must be translated into meaningful information as explained in Section 3.6.

3.8 Summary and conclusions

This chapter presented the proposed methodology which provides an approach of tracking construction resources with UWB RTLSs. The approach starts by defining the tracking purposes, then the assets to track and the requirements of the system to accomplish the tracking objectives. The approach covered the aspects to consider in the application of this technology in the construction industry for productivity purposes such as measuring the percentage of the wasted time in unnecessary movements, automating repetitive processes, optimizing the routes of workers in the building by using indoor navigation, standardizing the work by re-playing and analyzing the recorded activities, determining the progress of the project and reducing the conflict for resources. In addition, the safety purposes were identified such as identifying the poses of obstacles by using multiple tags attached to different components of equipment, checking the compliance with safety regulations and engineering constraints to prevent accidents, and achieving more advanced intelligent support by integrating path planning algorithms to generate a collision-free path. Furthermore, the specific purposes of tracking workers and equipment were identified.

The conclusions of this chapter are:

(1) An integral approach that includes the tracking purposes in near-real time and post processing location data, makes feasible the improvements of construction sites and construction practices by using UWB RTLS for productivity and safety.

(2) The requirements for the deployment of UWB in construction sites were identified as accuracy, visibility, scalability and real time, tag form factor, power, and networking requirements.

(3) Two scenarios were considered to design the application of the proposed methodology, one for tracking workers and equipment in the indoors and the other for outdoor construction sites. Those scenarios satisfy the identified requirements for the deployment of UWB in construction sites.

(4) The process of UWB near real-time data processing or post-processing was defined. This process has several steps including indentifying tag IDs on different components, filtering readings for each tag based on heuristics, calculating missing data for each tag using extrapolation or interpolation, synchronizing data by averaging data within each time period, filtering errors based on geometric constraints of multiple tags, calculating missing data based on geometric constraints, averaging locations of multiple tags in the same group, and computing the position or the pose of the object.

(5) Several visualization methods of location data from UWB RTLSs are necessary to convert the location information into meaningful information for construction projects.

CHAPTER 4 CASE STUDIES

4.1 Introduction

Three case studies are implemented to validate the proposed approach. In the first case study, the accuracy of the system is measured in the laboratory. In the second case study, UWB tags are used mainly to record the traces of workers and equipment in a real indoor construction site during the installation of a part of the HVAC system. In this case study the data is obtained by using the Ubisense Location Engine (Ubisense, 2009) and the information is recorded as text file for further analysis. The test was designed considering the requirements explained in Section 3.4. The workers were performing regular activities for installing HVAC ducts.

The third case study uses UWB technology to record the movements of a hydraulic crane in an outdoor simulated construction site. Attached UWB tags provide the possibility of determining the geometry of the monitored crane. Additionally, the test was designed to fulfill the requirements.

The first two tests were performed using the low cell update rate of 40 Hz. The system was upgraded to the high update rate of 160 Hz before the third test to better fit the requirements of the safety tracking.

4.2 Case study 1: Static test

The first case study was performed in a laboratory at the EV Building of Concordia University and aimed to verify the accuracy of the UWB system in controlled conditions.

The purpose of the test was to verify the accuracy of the system taking into account three variables: (1) Location and number of sensors (2 to 4), (2) UWB method, AOA only or combination with TDOA, and (3) the position of the tags within the sensor cell, the setting of the test is presented in Figure 4-1 and Figure 4-2 where five points were chosen to compare the accuracy. Tag A is centered, tag B is lower in height and tag C is closer to the walls. Tag D and tag E are near the walls where they are in proximity to metallic objects.

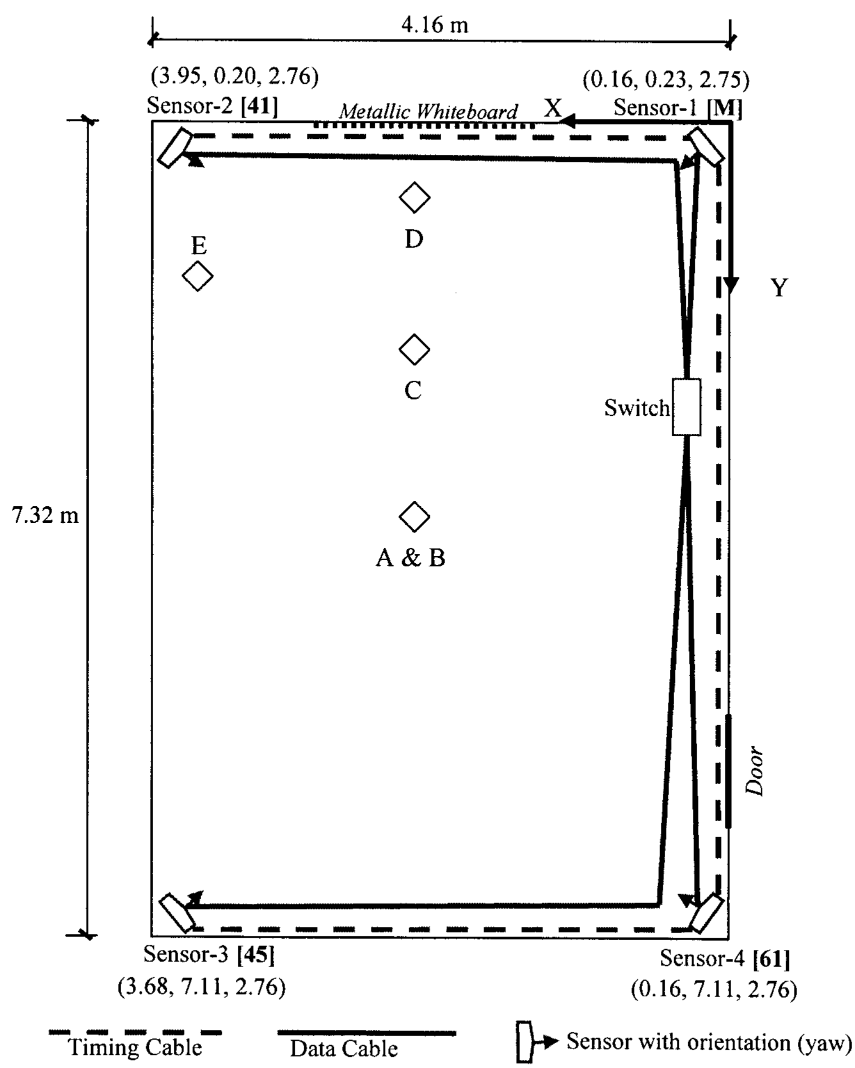


Figure 4-1 Laboratory setting in 2D

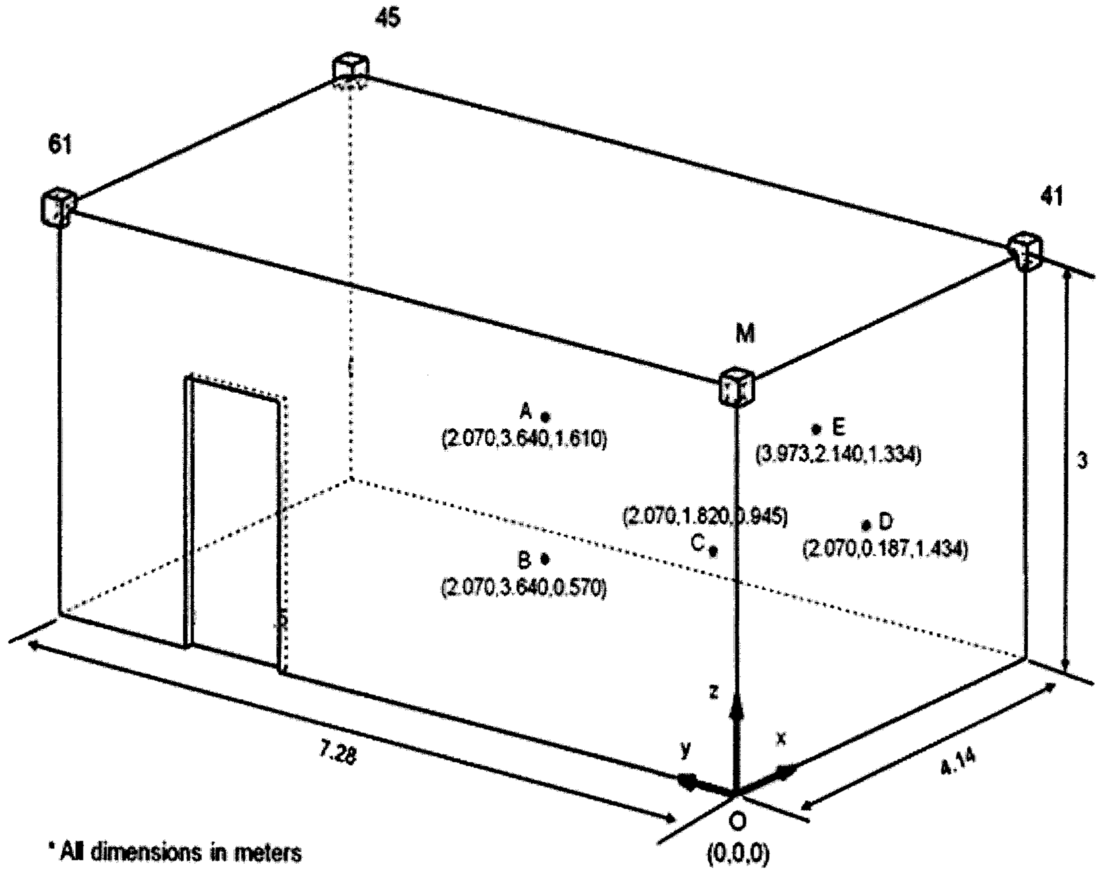


Figure 4-2 Laboratory setting in 3D (adapted from Kaushik, 2009)

The Ubisense software was already installed and the pre-test activation of sensors and cables was already completed. The calibration of sensors was done using a reference tag approximately at the center of the room. Tags were fixed at certain points by using camera tripods and their coordinates were measured using a laser meter. All the tags were leveled to face up in order to improve their visibility. It was assumed that while changing one of the variables of the test, all other variables remain constant throughout the test. The room configuration (position of furniture) was maintained throughout the tests in order to ensure consistency in the tests. Only the tag used in the test was kept in the room throughout the testing and the other tags were out of the range of the sensors.

4.2.1 Test results

The naming convention of the results is explained as follows: number of sensors, methods used, and sensors used. For example, 3S_AOA_TDOA_M_41_45 means that 3 sensors were used (3S), both AOA and TDOA were used (AOA_TDOA), and the used sensors are the master sensor, and sensor 41 and 45 (M_41_45). Figure 4-3 shows the accuracy for each combination and point sensed.

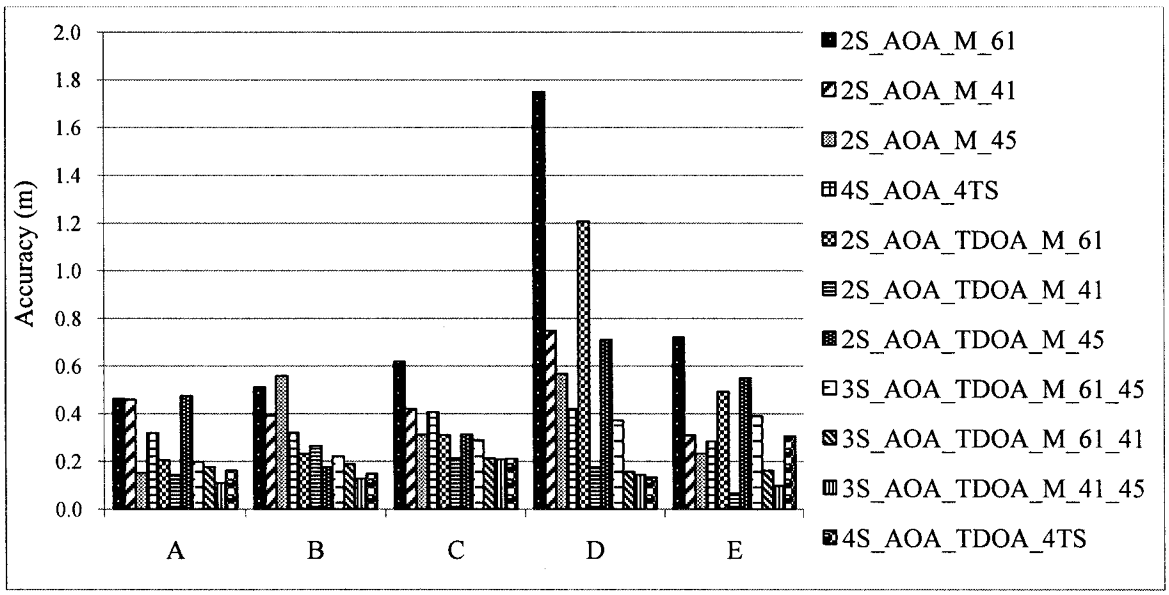


Figure 4-3 Accuracy comparison (Motamedi, 2010)

It was expected that with more sensors and by using both technologies (AOA and TDOA) the accuracy will be better. This was true for almost all the points sensed. Four sensors using the combination of AOA and TDOA give the best results for accuracy followed by three sensors and two sensors. These results show that more sensors and a combination of both methods must be used to obtain accurate results. Another analysis is related with the position of the tags; in most of the cases position detection of tag A is more accurate than tag B and tag C. The results for tag D are the worst because of the reflection of RF from the walls and metallic objects near this tag. This means that the cell design must consider the object to be monitored to be mostly in the center of the cell in order to obtain accurate results.

4.3 Case study 2: Indoor test

4.3.1 Test Setting

All the UWB system components were tested one week before the on-site test to verify if the system can run well out of the laboratory. The conditions were simulated in a large meeting room in the EV building of Concordia University. The cables were adjusted according to the conditions of the room where the test will be done to reduce the set-up time for the test.

The schedule of the work was coordinated with the help of Dessau that owns the construction company Verrault as the general contractor for the construction and Ventilabec as the sub-contractor for the HVAC system. The project director and superintendant collaborated actively in the development of the test providing information about the approximate schedule for the project and the resources to accomplish the test without disturbing the general operations on the construction site. However, because of the dynamic nature of the project, there were changes that did not affect the overall schedule.

On April 30, 2009, an indoor test was carried out on the 7th floor of the new John Molson School of Business (JMSB) building of Concordia University, where the installation process of HVAC ducts was undergoing. Figure 4-4 shows the schedule and specifically the distribution ducts that will be installed starting on April 27, and finishing on May 15, 2009. This figure shows the macro schedule (by weeks). However, for this project a micro schedule is needed. For that reason, the operations were monitored almost on a daily basis before the test was done to determine the sequence of operations and their timing and to adjust the test accordingly. The dimensions and the layout of the ducts are shown in Figure 4-5.

The UWB sensors were placed on place one day before conducting the test. All the system components were pre-tested. The sensor cell is designed as shown in Figure 4-6. Four sensors are fixed at four corners using tripods, and connected with data cables and timing cables. One of the challenges faced was that at the beginning it was planned to do the test covering the entire space shown in Figure 4-6. However, after a few days a wall was installed to divide the space into two rooms. Therefore, the scope of the test was limited to the room on the left side of Figure 4-6.

Figure 4-7 shows the angles of the sensors to consider during calibration. The orientation of the sensors was done considering the area of work to cover and the aspects discussed in Subsection 3.5.2.

Ten tags were attached to two workers and eight tags were attached to a scissor lift as shown in Figure 4-9 and described in Table 4-1. The table includes the description, position, identification number (ID) and the tag name. The tags were attached to the scissor lift at a height of about 160 cm when the scissor lift was down.

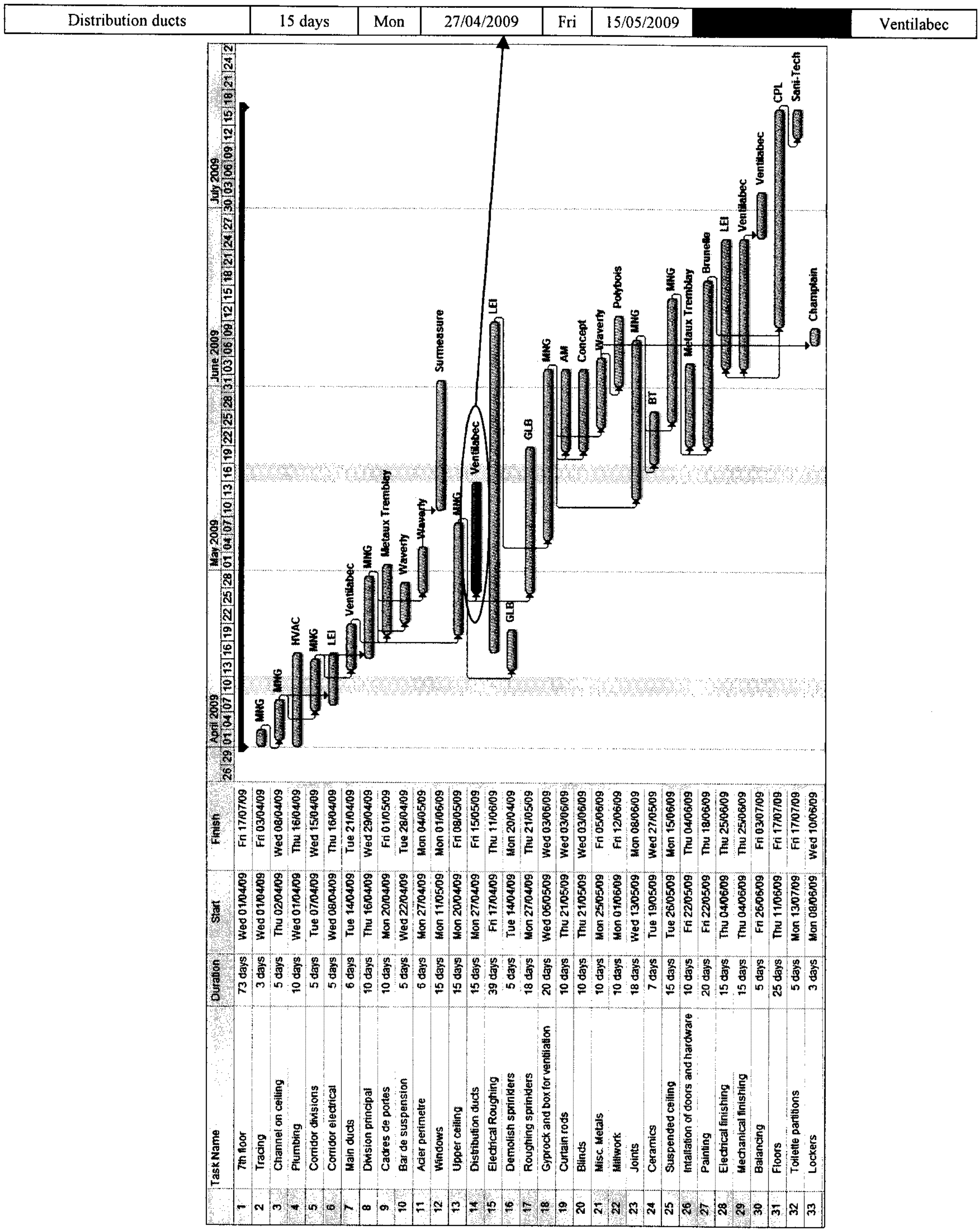


Figure 4-4 Part of the schedule of the 7th floor of JMSB building

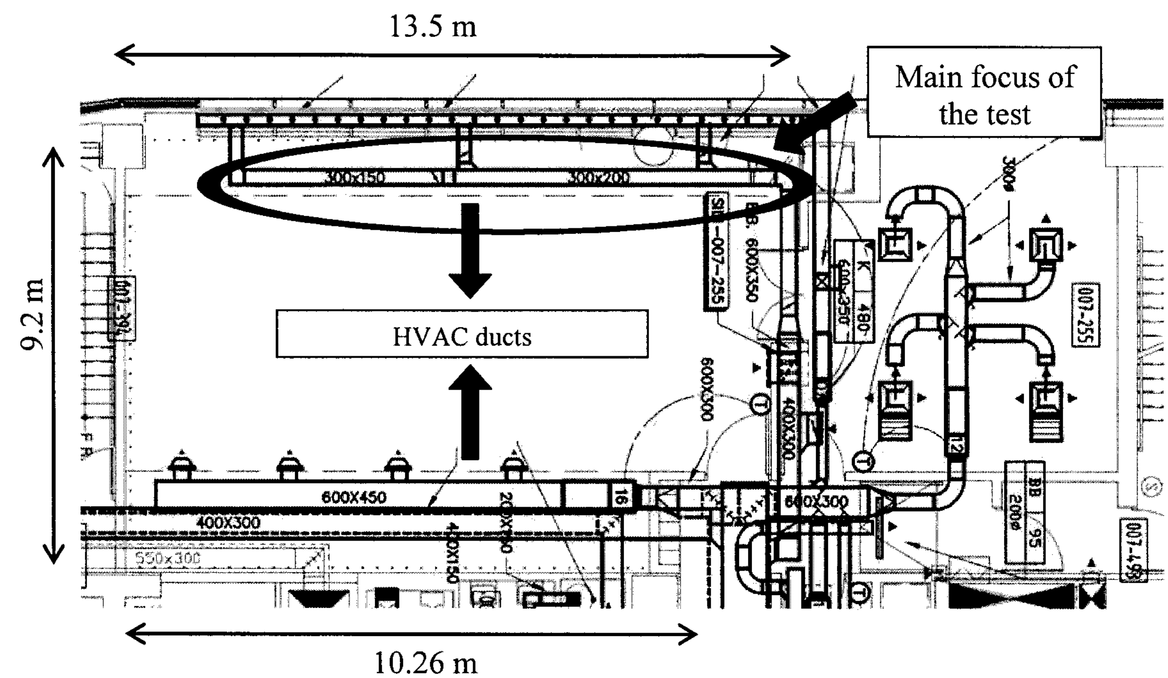


Figure 4-5 Dimensions of the room and ducts' location

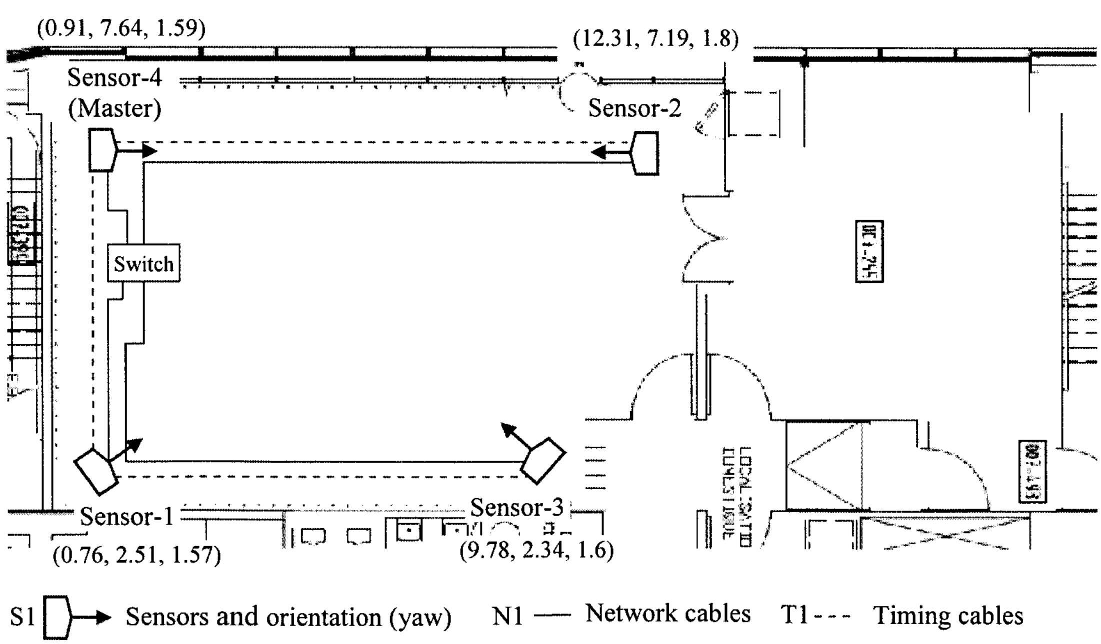


Figure 4-6 Placement of the sensors and cables

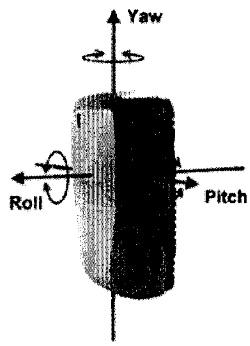
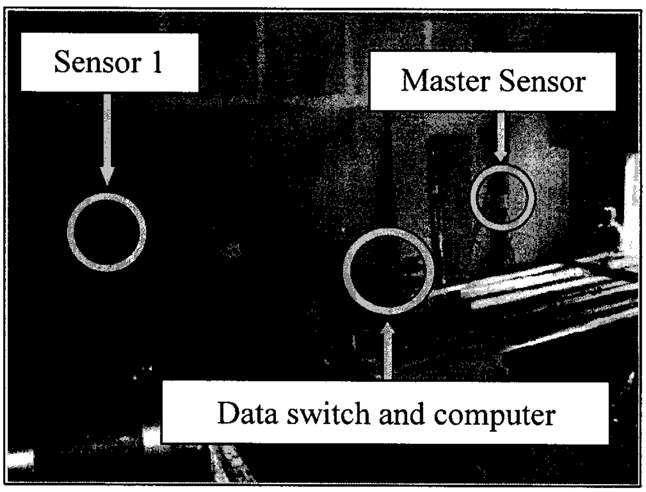
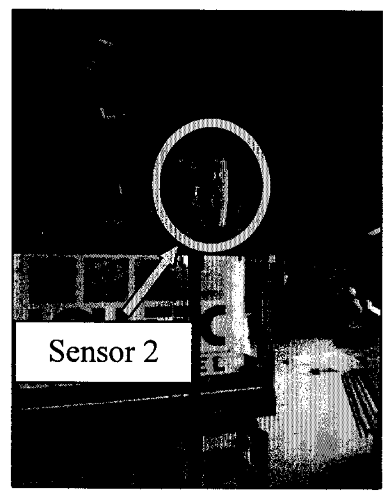


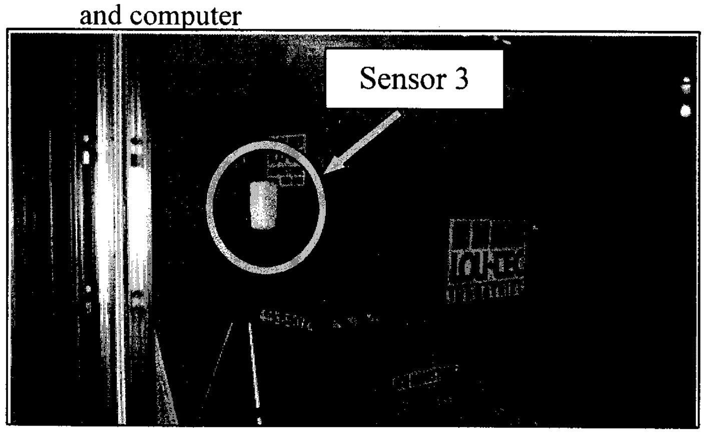
Figure 4-7 Yaw, roll and pitch of a sensor (Ubisense, 2009)



(a) Location of sensor 1, master sensor, data switch and computer



(b) Location of sensor 2



(c) Location of sensor 3

Figure 4-8 Location of sensors

On the day of the test, the calibration of the system started at 9:00 am and finished at 11:30 am. The calibration process includes measuring the x, y, z coordinates of each sensor and of a reference tag. Then the reference tag is used to calculate the yaw and pitch angles of the sensors. More details about the test setting process are given in Appendix B.

Table 4-1 Position of the tags

Description	Position		System Tag ID	Tag name
Worker-1	S^1	Hardhat – right	162	$W_1 - Tag_R^1$
		Hardhat – left	17	$W_1 - Tag_L^1$
	S^3	Right arm	75	$W_1 - Tag_R^3$
		Left arm	7	$W_1 - Tag_L^3$
	S^4	Belt – right	9	$W_1 - Tag_R^4$
		Belt – left	89	$W_1 - Tag_L^4$
Worker-2	S^1	Hardhat – right	85	$W_2 - Tag_R^1$
		Hardhat – left	77	$W_2 - Tag_L^1$
	S^2	Right shoulder	247	$W_2 - Tag_R^2$
		Left shoulder	98	$W_2 - Tag_L^2$
Scissor lift	S^1	Corner 1-1	82	$E_1 - Tag_1^1$
		Corner 1-2	70	$E_1 - Tag_2^1$
	S^2	Corner 2-1	29	$E_1 - Tag_1^2$
		Corner 2-2	78	$E_1 - Tag_2^2$
	S^3	Corner 3-1	15	$E_1 - Tag_1^3$
		Corner 3-2	14	$E_1 - Tag_2^3$
	S^4	Corner 4-1	87	$E_1 - Tag_1^4$
		Corner 4-2	10	$E_1 - Tag_2^4$

Appendix C presents the calibration data obtained. The differences between the angles of the master sensor in the three dual calibrations with the other sensors are less than 3°. The scheduling and filtering properties were configured equal for all the tags. The system used for this test is a 40 Hz system; the exact time slot length is 27.023 ms. The slot interval was fixed as 32 which means that the update interval is 865 ms for each tag.

For this test, the filter used was the default no filtering because this is the first test done in a real construction site and there is not information about the motion model to input in the information filtering algorithm. For this test only one cell is considered then the parameters for handover between cells do not apply for filtering in this test.

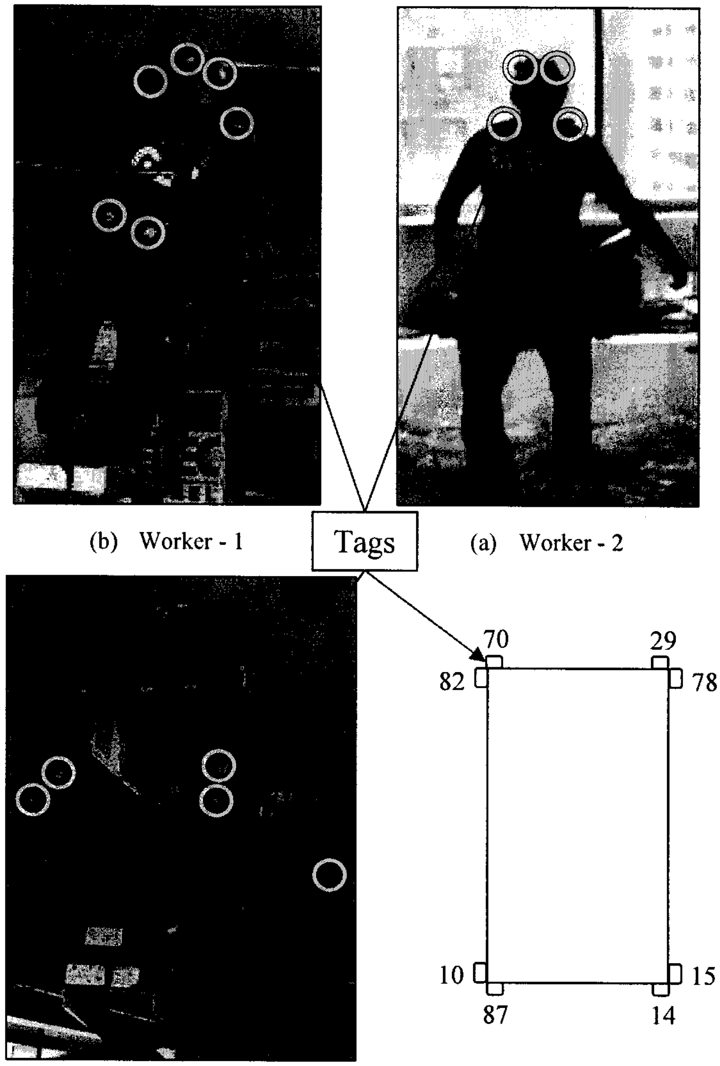
4.3.2 Data collection

The data was collected from 12:40 to 13:37 during four periods described in Table 4-2.

Table 4-2 Periods data recorded

Period	Start time	End Time	Duration
1	12:40:41	12:56:17	0:15:36
2	12:56:33	13:10:56	0:14:23
3	13:11:10	13:31:01	0:19:51
4	13:31:17	13:37:35	0:06:18

Some of the general tasks performed related while the workers were doing the installation of ducts for the HVAC system are described on Table 4-3 and Table 4-4 with the time.



(b) Worker - 1

(a) Worker - 2

(c) Scissor lift

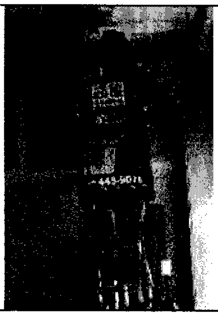
(d) Scissor lift

Figure 4-9 Locations of tags

Table 4-3 Worker-1 task record

Time	Worker-1 task	Picture
12:40	Measuring on the floor	
12:50	Went out to the other room	
13:00	Opening holes	
13:10	Went out of the room	
13:20	Cutting metal studs	
13:30	Installing the metal studs on the ceiling	
13:37	End of the test	

Table 4-4 Worker-2 task record

Time	Worker-2 task	Picture
12:40	Going up/down to measure	
12:50	Going up to make holes on the ceiling	
13:00	Opening holes	
13:10	Went out to take ducts out / Equipment belt on the floor	
13:20	Came back and took again the equipment belt	
13:30	Installing the duct near the corner out of range	
13:37	End of the test	

4.3.3 Data analysis

After collecting the information, the format in which the data was presented was comma separated values in a text file. That was translated into Microsoft Excel files, databases and ArcGIS maps to do the analysis. The data were compared with the pictures and video collected the day of the test. There were several limitations for analyzing the data translated into GIS information: (1) The used GIS tracking tool cannot support time data that include milliseconds; this made it difficult to check the update rate for the tags; (2) The GIS tracking tool shows traces related with time only in 2D; and (3) The process of import the data is itself a procedure that can take time depending on the volume of data to analyze. This process is described in Appendix E.

Another limitation is that one video camera cannot provide a view of each tracked worker/equipment each period of time, which makes the matching between the video and the traces more complicated than if a camera is recording only one entity during the entire test. Moreover, only a simple layout of the room could be shown in the GIS software. Future research should develop a method for integrating the UWB traces with BIM.

In this test, the slot interval was set to 32 time slots hence the update interval is 865 ms using the cell update rate of 40 Hz and the expected update rate of tags is 1.15 Hz. However, by reviewing the data, the interval fluctuates between 864 and 865 ms. For that reason, the time period t was created with a 864 ms interval in order to include only one reading by period. The actual measured tag updates are described in Table 4-5 for each period of time. Tag $E_1 - Tag_2^1$ was not sensed when the test was done. The measured update rate r' is calculated by dividing the number of updates of each period of each tag by the length of the period. Due to missing data, some tags have lower update rates than other tags.

Table 4-5 Tag updates

	Number of updates					Measured update rate r' (Hz)				
Tag name	**Period-1**	**Period-2**	**Period-3**	**Period-4**	**Total**	**Period-1**	**Period-2**	**Period-3**	**Period-4**	**Total**
$W_1 - Tag_R^1$	968	810	992	183	**2953**	1.03	0.94	0.83	0.48	**0.88**
$W_1 - Tag_L^1$	961	777	1048	183	**2969**	1.03	0.90	0.88	0.48	**0.88**
$W_1 - Tag_R^3$	866	712	895	150	**2623**	0.93	0.82	0.75	0.40	**0.78**
$W_1 - Tag_L^3$	838	716	906	114	**2574**	0.90	0.83	0.76	0.30	**0.76**
$W_1 - Tag_R^4$	774	704	933	128	**2539**	0.83	0.82	0.78	0.34	**0.75**
$W_1 - Tag_L^4$	856	721	862	120	**2559**	0.91	0.84	0.72	0.32	**0.76**
$W_2 - Tag_R^1$	1028	579	508	119	**2234**	1.10	0.67	0.43	0.31	**0.66**
$W_2 - Tag_L^1$	1048	577	507	122	**2254**	1.12	0.67	0.43	0.32	**0.67**
$W_2 - Tag_R^2$	1023	571	437	61	**2092**	1.09	0.66	0.37	0.16	**0.62**
$W_2 - Tag_L^2$	986	572	266	151	**1975**	1.05	0.66	0.22	0.40	**0.59**
$E_1 - Tag_1^1$	922	879	870	76	**2747**	0.99	1.02	0.73	0.20	**0.82**
$E_1 - Tag_2^1$	NA	NA	NA	NA	**NA**	NA	NA	NA	NA	**NA**
$E_1 - Tag_1^2$	1072	992	827	176	**3067**	1.15	1.15	0.69	0.47	**0.91**
$E_1 - Tag_2^2$	1078	989	786	35	**2888**	1.15	1.15	0.66	0.09	**0.86**
$E_1 - Tag_1^3$	1083	979	1110	225	**3397**	1.16	1.13	0.93	0.60	**1.01**
$E_1 - Tag_2^3$	1080	996	1305	316	**3697**	1.15	1.15	1.10	0.84	**1.10**
$E_1 - Tag_1^4$	1008	974	1351	433	**3766**	1.08	1.13	1.13	1.15	**1.12**
$E_1 - Tag_2^4$	915	711	992	279	**2897**	0.98	0.82	0.83	0.74	**0.86**

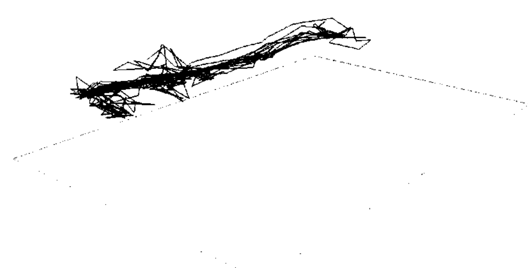
In order to improve the accuracy of the tags' location data, the data was post-processed following the steps defined in Figure 3-11. After filtering each tag individually, the average of the readings of the two tags on the hardhat of a worker or at a corner of the scissor lift was computed.

The readings that were sensed in the areas that were occupied by obstacles (like ducts in the middle of the room) or outside the room were removed by using the boundary coordinates of the room. For the tags attached to the workers, the points far from the previous point or the following point assuming walking speed (1.5 m/s) were removed and replaced by the interpolation of the two points before and after. This walking speed corresponds to two human strides per second and an average step length of 0.75 m (Ladetto et al., 2000). The macros created in VBA for this purpose are given in Appendix D.

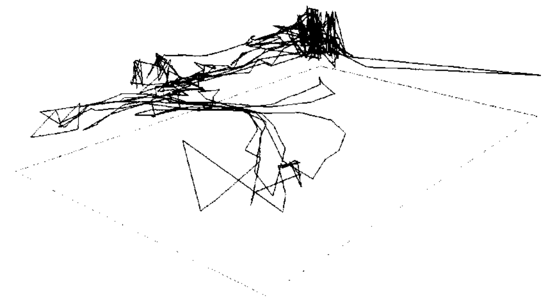
By analyzing the information obtained from the analysis, the following observations can be made:

(1) By comparing the traces of each worker over consecutive time periods, it is possible to understand the work zone used by that worker at each time period in 2D and 3D. For example Figure 4-10 shows the work zone of Worker-1 for each period in 3D by showing the location of $W_1 - Tag_L^1$.

(2) The work zones are in most of the cases non-overlapping, which means that although there is no pre-arrangement for using space, each worker reserves a certain area for a certain period of time. Figure 4-11 shows two main work zones for each worker during Period-3.

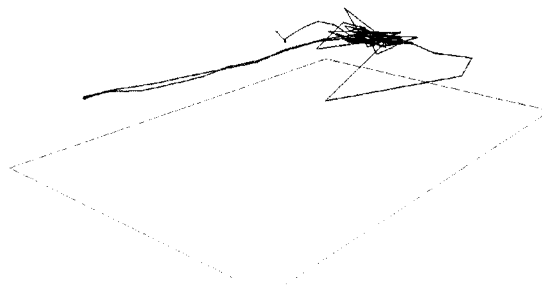


(a) Period-1



(b) Period-2

(c) Period-3



(d) Period-4

Figure 4-10 Location of $W_1 - Tag_L^1$

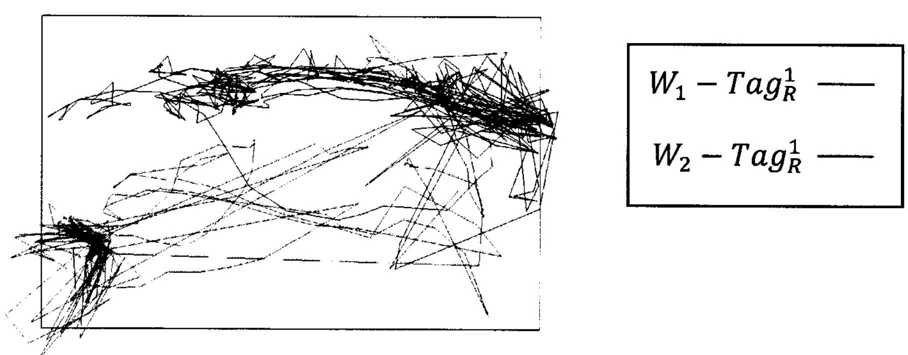
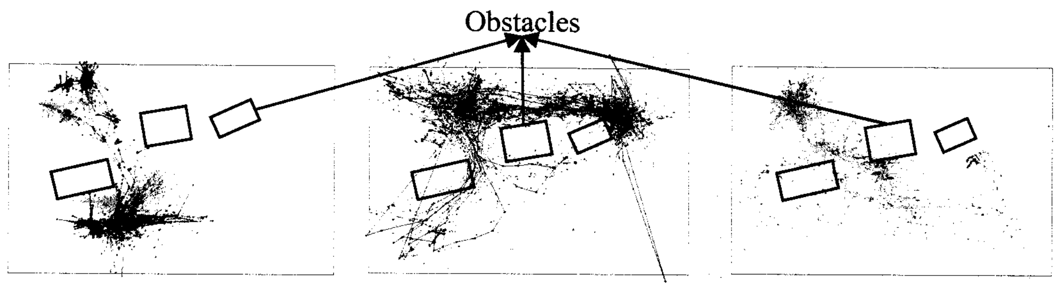


Figure 4-11 Work zones for each worker during Period-3

(3) The traces demonstrate that the room had many obstacles on the floor. In a construction environment, the objects and obstacles vary depending on the work that

is realized. Figure 4-12 shows how the traces of the tags on the scissor lift and on workers move around those obstacles during Period-2.



(a) Scissor lift – All tags (b) Worker-1 – All tags (c) Worker-2 – All tags

Figure 4-12 Identifying moving patterns around obstacles

(4) In order to better understand the relationship between the work zones used by the workers and their tasks, the traces are matched with the video recording. For example, in Period-1, Worker-1 was focusing on the marking on the floor while Worker-2 was measuring and opening holes in the ceiling as shown in Table 4-3 and Table 4-4.

(5) The traces also show that the workers move back and forth in the same work zone. For example, Worker-1, while doing the measurements and the marking on the floor, moved along a narrow work zone as shown in Figure 4-13 and related pictures extracted from the video. T_1 shows Worker-1 reviewing plans, T_2 shows when Worker-1 is on the scissor lift and working near the ceiling, T_3 shows when Worker-1 is measuring the distance to the wall and T_4 shows the moment when Worker-1 is going to the other room.

(6) Using the information of the paths, it is possible to measure the length of the path in 2D and 3D. For example

(7) Table 4-6 shows the length in 2D and 3D of the traces of the two tags attached to the hardhat of Worker-1 during each time period. These distances are calculated in

meters and the data is not yet filtered. The percentage is the difference of the lengths of the traces of the two tags over the smaller value of the traces' length.

(8) Table 4-6 also shows that Period-2 has more vertical movements because it has the biggest difference between the lengths in 2D and 3D.

(9) It is also possible to measure the speed of movement of each worker/equipment. This could be useful to check the compliance with safety regulations because in some jurisdictions workers are not allowed to move on the lift to a new position unless the lift is down. For example, the average speeds of the two tags positioned at one corner of the scissor lift are shown in Table 4-7.

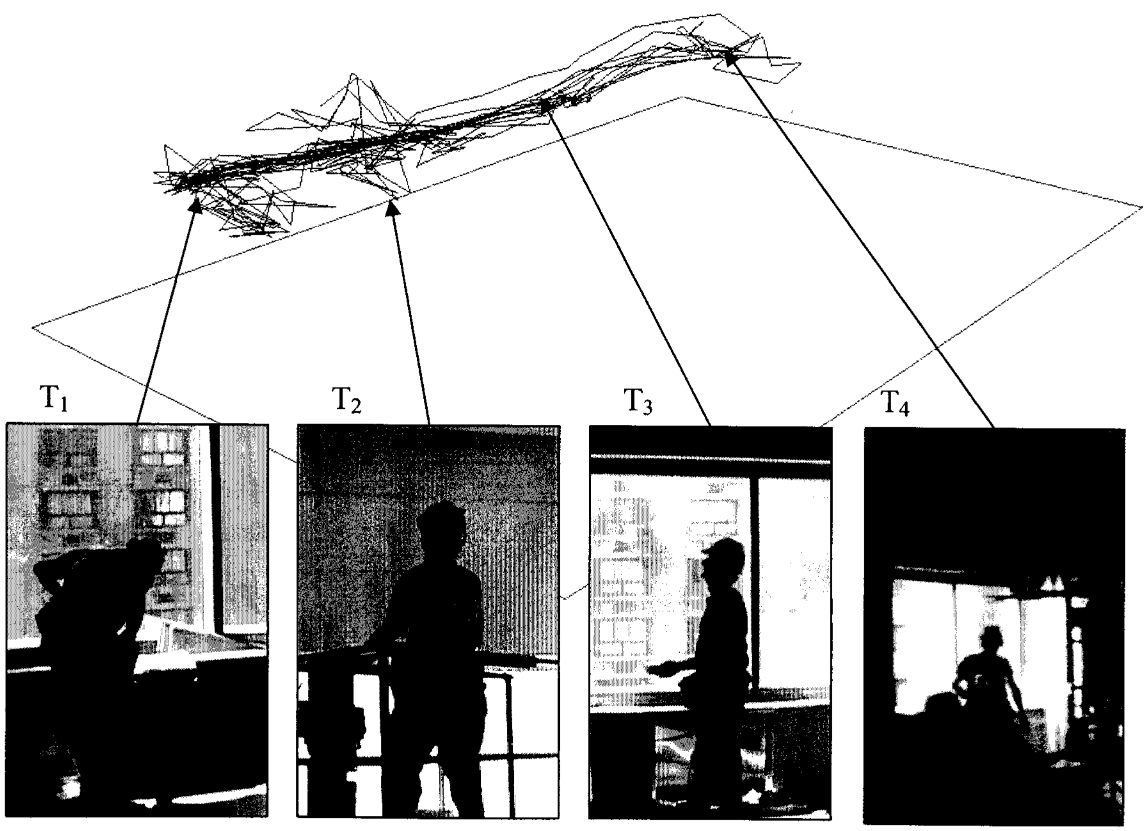


Figure 4-13 Work zone of $W_1 - Tag_R^1$ in Period-1

Table 4-6 Lengths of traces in 2D and 3D

		Period-1	Period-2	Period-3	Period-4	All periods
2D length (m)	$W_1 - Tag_L^1$	299.82	287.5	380.11	107.05	1074.48
	$W_1 - Tag_R^1$	304.47	300.26	389.02	74.91	1068.66
	Average	302.14	293.88	384.56	90.98	1071.57
	% Difference	1.55%	4.44%	2.34%	**42.90%**	0.54
3D lenght (m)	$W_1 - Tag_L^1$	316.38	358.5	428.74	111.62	1215.24
	$W_1 - Tag_R^1$	321.53	357.17	436.28	76.71	1191.68
	Average	318.96	357.84	432.51	94.17	1203.46
	% Difference	1.63%	0.37%	1.76%	**45.51%**	1.98%
Difference between 2D and 3D (m)		16.81	**63.96**	47.95	3.19	131.89

Table 4-7 Average speed in 2D

	Tag ID	Period-1	Period-2	Period-3	Period-4	Total
2D speed m/s	$E_1 - Tag_1^4$	0.05	0.27	0.35	0.45	0.24
	$E_1 - Tag_2^4$	0.05	0.10	0.09	0.18	0.09

(10) Based on analyzing the patterns of movement of workers and their work zones, it is possible to use this information to plan space usage for similar tasks and to improve the efficiency by placing the tools and materials at the most suitable locations based on the tasks. In current practice, most of the work is done on an ad-hoc basis.

(11) By comparing the different tags attached to the same worker/equipment and located near each other, it is clear that the data collected for different tags do not match in some cases. For example, Figure 4-14 shows two tags attached to one corner of the scissor lift. In one area the traces are not matching while in the other area the

traces are matching. This could be explained by the fact that some tags have large errors because of the lack of direct line of sight to the sensors (obstacles), the reflection from metallic ducts or because the tags were out of the field of view of most sensors.

Figure 4-15 shows the data matching of two sensors attached to two different corners of the scissor lift and the traces are showing the width of the scissor lift during Period-2.

(12) The traces related with time can be linked to pictures taken from the video as Table 4-8 shows. This comparison is based on the position of the scissor lift and the traces of $E_1 - Tag_2^4$ during Period-2 shown in ArcGIS tracking tool.

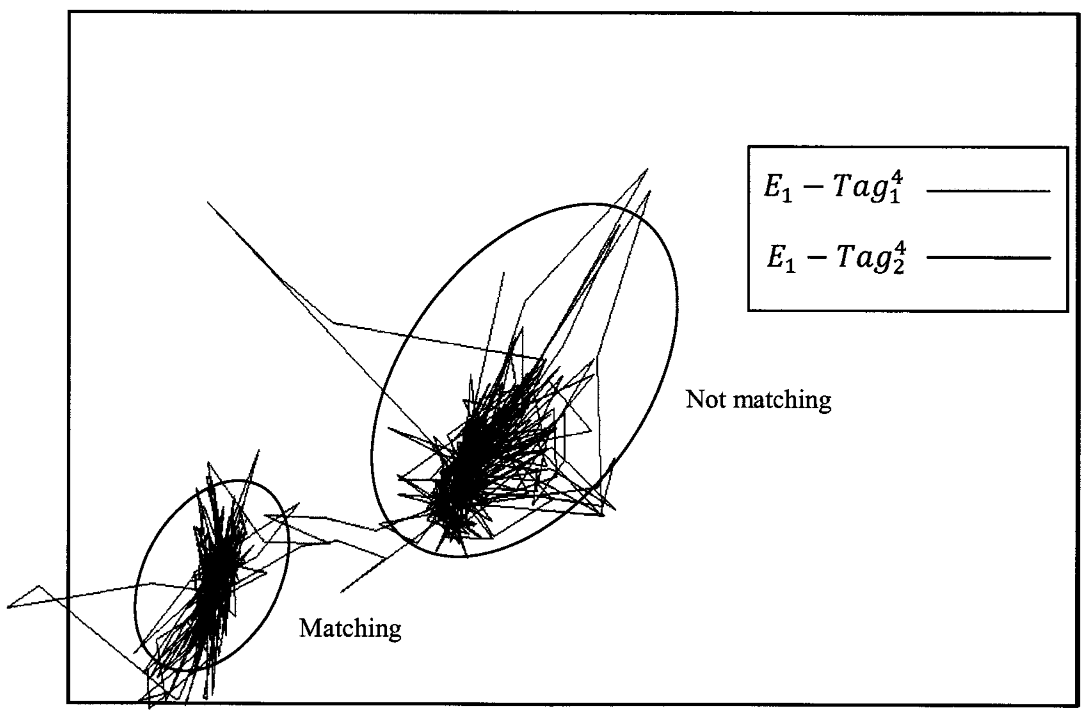
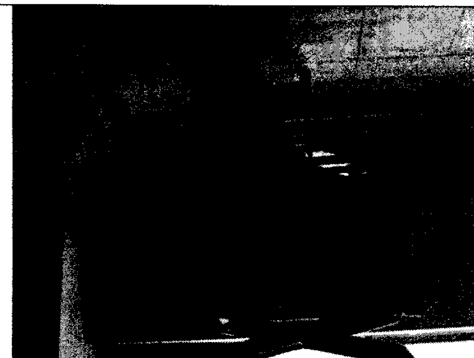
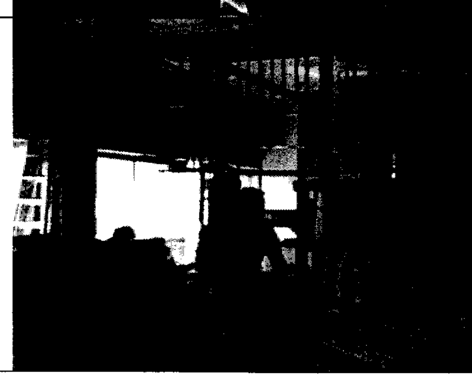


Figure 4-14 Traces for tag $E_1 - Tag_1^4$ and tag $E_1 - Tag_2^4$ in Period-3

Table 4-8 Comparison traces in GIS and pictures from video

Time	Traces GIS	Picture from video
12:57:33		
13:01:33		
13:02:33		
13:03:03		

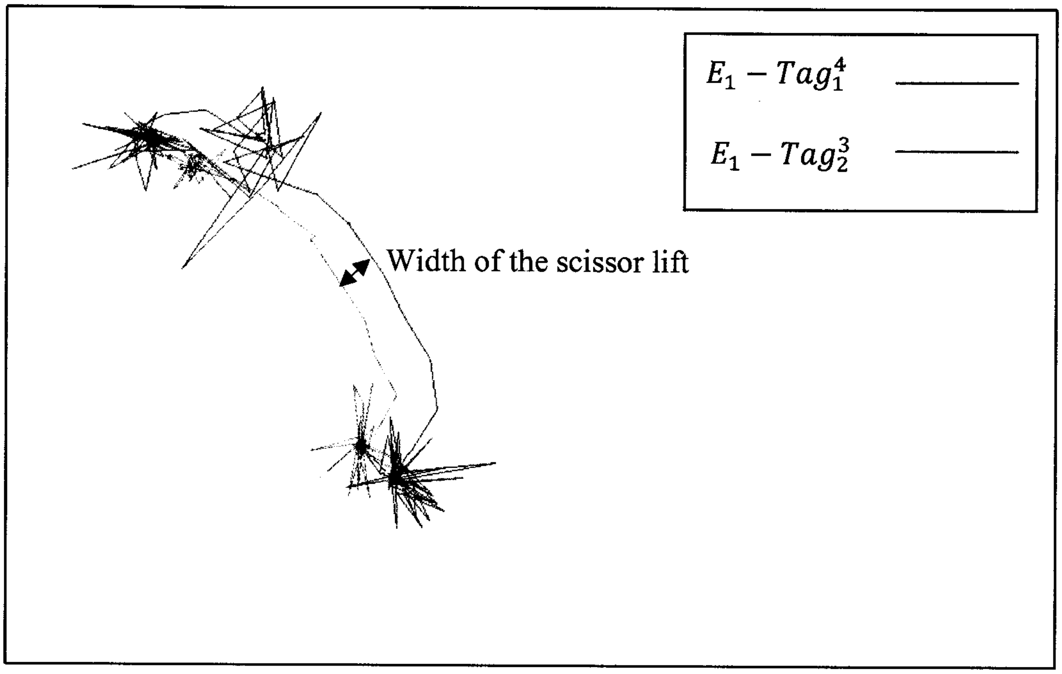


Figure 4-15 Traces for tag $E_1 - Tag_B^3$ and tag $E_1 - Tag_B^4$ during Period-2

4.4 Case study 3: Outdoor test

4.4.1 Test setting

The objective of the outdoor tests is to investigate the different aspects of the proposed methods for setting the UWB system as discussed in Section 3.5 , mainly the usage of multiple tags on a crane and the selection of the number of tags and their update rates to satisfy the requirements of accuracy, visibility, scalability and real-time tracking. A test was done on the yard of a crane company on December 4, 2009, using a TMS300 crane (GUAY, 2010). The UWB system was upgraded from low update rate (40 Hz) to high update rate (160 Hz) to better fit safety requirements. The test was designed in detail, including the sensors' locations, tags' locations, cables' connections, system calibration, data filtering, and task description. Furthermore, several indoor tests were done to test the stability of the UWB system, the influence of the magnetic attachment of the tags, etc.

In this outdoor test, where the focus is on the crane, only the pitch angles of the four sensors at the lower elevation were adjusted to about 25° to capture the boom movement and the yaw angles were adjusted to face the center of the area. Figure 4-16 shows the outdoor setting of the sensor cell with the timing and data cables and the locations and yaw orientations of the four sensors. Figure 4-17 shows part of the site with the crane and one sensor (Sensor-2). A car was positioned as an obstacle on the moving path of the crane. Twenty-two tags were attached to the crane body, with three sets of tags (12 tags) attached to the boom, as shown in Figure 3-7. Other tags were attached to outriggers, operator cab, hook, and lifted object. Moreover, four tags were attached on the hardhats of two workers (two tags on each hardhat) to track their movements on site. Figure 4-18 shows tags attached to different objects. Figure 4-19 shows the pictures of tags Tag_1^2, Tag_2^2, and Tag_4^2 near the end of the first part of the boom.

To test the scalability of the UWB system, which has a high cell update rate of 160 Hz, we kept 52 additional tags in the same area so that the total number of tags in the cell was 74 tags resulting in a tag update rate of about 2 Hz. Therefore, in this test, the synchronization of multiple tags will be based on t = 500 ms. An information data filter provided by Ubisense was used to improve accuracy with a motion model of position and Gaussian noise on position. According to the inequalities introduced in Section 3.4, the time slot interval was set to 128, where a nonimal update rate is 1.2 Hz to 2.4 Hz for each tag.

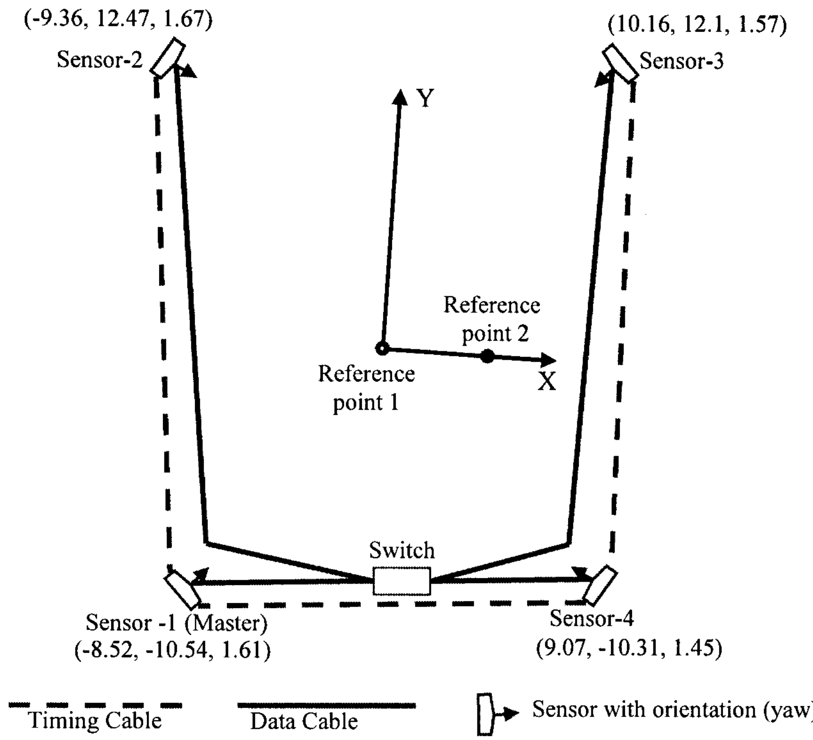


Figure 4-16 Outdoor setting of sensor cell

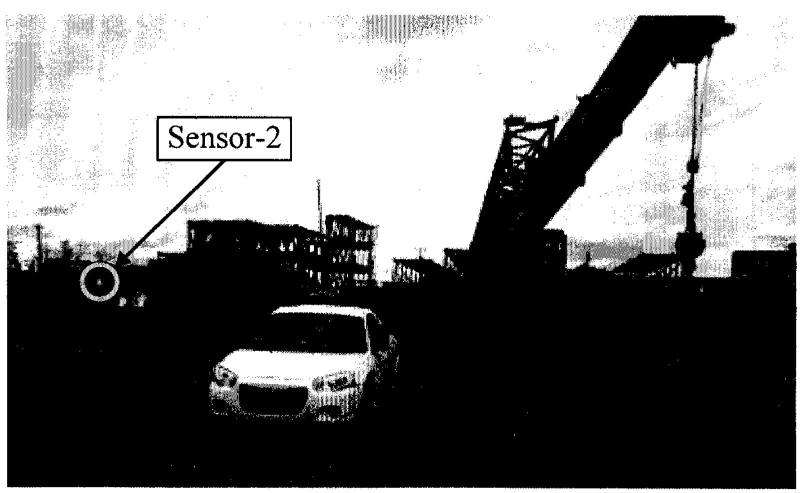
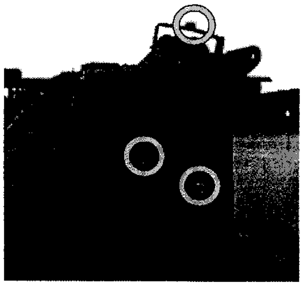
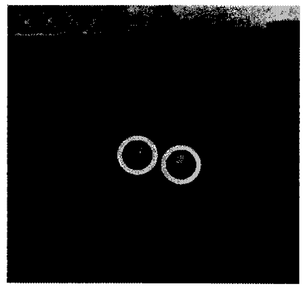


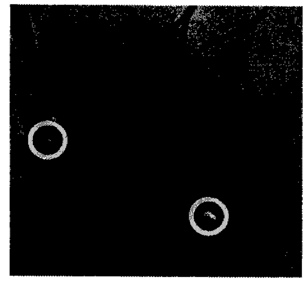
Figure 4-17 Crane with obstacle and one sensor



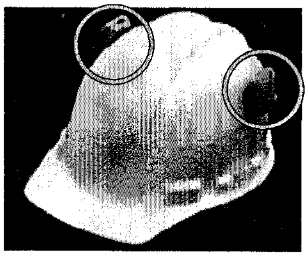
(a) Boom tip



(b) Hook



(c) Lifted object



(d) Hardhat

(e) Tag with magnetic attachment

Figure 4-18 Tags attached to different objects

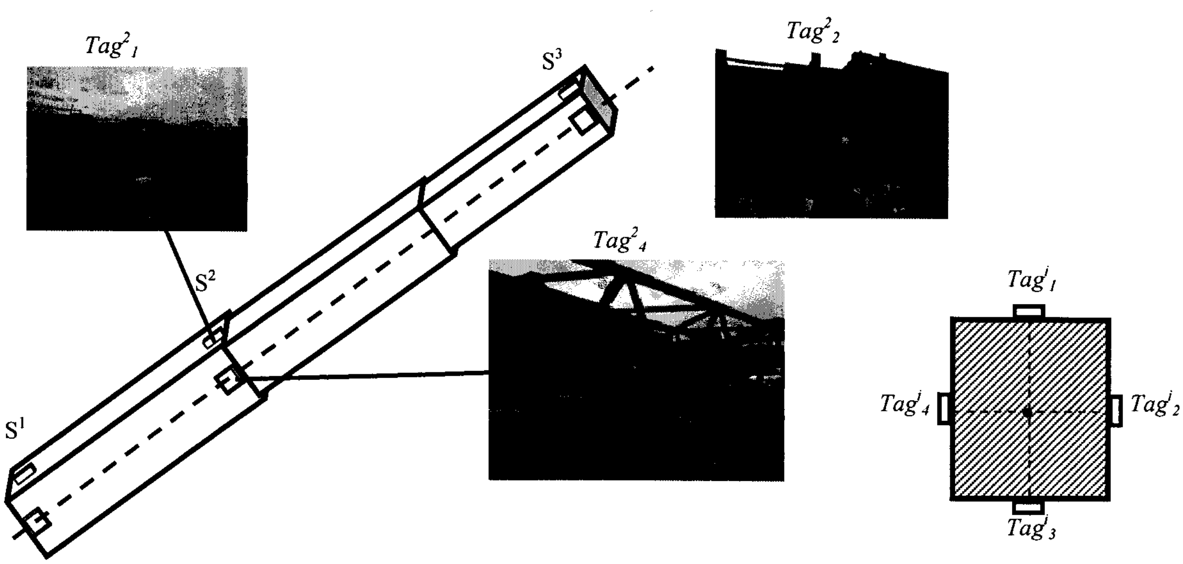
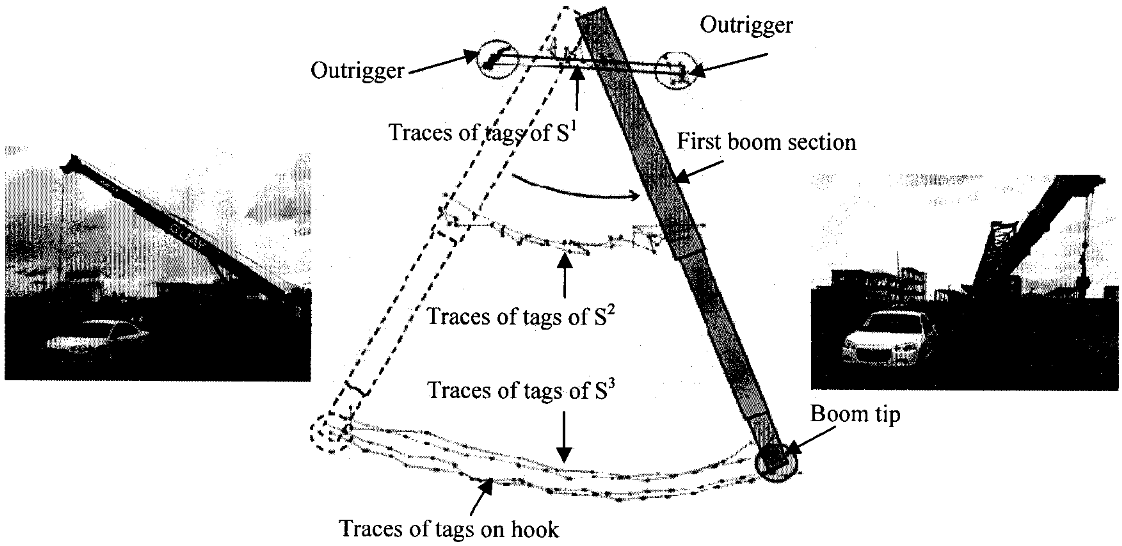


Figure 4-19 Tag position of cross section S^2 on the boom

The total duration for the outdoor test was about two hours, including system configuration, measurement, calibration, moving the crane into the monitored area, and collecting data during the crane operation. The task given to the crane operator was to lift an object from one place to another while avoiding an obstacle (a car) on the path by swinging and raising up the boom as shown in Figure 4-17. During the rotation of the boom, the length of the boom and the length of the cable were fixed. A part of the raw data collected in the test is shown as traces in Figure 4-20. The tags shown in three cross sections are Tag_4^1, Tag_1^2, Tag_3^2, Tag_1^3 and Tag_4^3. The tags attached to the top of the boom had very good visibility and better accuracy (less noisy data) compared with those attached to the bottom and the sides of the boom, which had a large number of missing points and noisy data. The raw UWB data were processed following the steps explained in Figure 3-11 in order to get the poses of the boom. However, because of the low update rate about (2 Hz) and the large amount of missing data, some steps were not always applicable (e.g., averaging or extrapolation at a certain time period). Nevertheless, the redundancy provided by having multiple tags on the boom made it possible to calculate the poses of the boom based on the traces as shown in Figure 4-26. The crane maximum boom length is 110 ft (33.5 m), and the minimum and maximum angle to the ground for the boom are 10° and 80°, respectively.



(a) Initial crane pose | (b) Crane poses based on raw data | (c) Final crane pose

Figure 4-20 Part of the raw data collected

4.4.2 Visibility analysis

As mentioned before, twenty-two tags were attached to the crane and four tags attached to the hardhats of workers. Within 36 seconds, tags obtained different numbers of updates, as shown in Table 4-9. The measured update rate r' is calculated by dividing the number of updates of each tag by 36 seconds. Due to missing data, some tags have lower update rates than other tags.

From the table, it can be seen that Tags on the upper and bottom sides of the boom had better visibility than the ones attached to the side surfaces. As shown in Figure 4-19, tags attached on the side that has a truss structure (i.e., Tag_4^1, Tag_4^2, and Tag_4^3) received less updates compared with other tags in the same cross section. This could be explained by radio signal reflections on the truss.

Table 4-9 Tag updates

Tag Location		Tag name	Number of updates in 36 seconds	Measured update rate r' (Hz)
Boom	S^1	Tag_1^1	61	1.7
		Tag_2^1	37	1.0
		Tag_3^1	73	2.0
		Tag_4^1	24	0.7
	S^2	Tag_1^2	74	2.1
		Tag_2^2	50	1.4
		Tag_3^2	70	1.9
		Tag_4^2	24	0.7
	S^3	Tag_1^3	74	2.1
		Tag_2^3	18	0.5
		Tag_3^3	42	1.2
		Tag_4^3	20	0.6
Cab		C_1	12	0.3
		C_2	39	1.1
Hook		H_1	74	2.1
		H_2	74	2.1
		H_3	73	2.0
		H_4	73	2.0
Lift		L_1	27	0.8
		L_2	20	0.6
Outrigger	Right	O_r	34	0.9
	Left	O_l	74	2.1
Hardhat-1		H^1_R	50	1.4
		H^1_L	24	0.7
Hardhat-2		H^2_R	72	2.0
		H^2_L	61	1.7

Tags attached to the cab also had bad visibility because the rotation of the cab cannot guarantee direct line-of-sight from two sensors. All the four tags attached to the hook had excellent visibility. Tags attached to the lift object had bad visibility that may be explained by the lack of direct line of sight. One tag attached to the left outrigger had good visibility.

4.4.3 Precision analysis

The location data of two static tags on the outriggers were analysed to see the precision of the system. Table 4-10 shows the standard deviations in three directions of these data. Furthermore, as introduced in Table 4-9, the tag on the left outrigger has more readings than the other (74 vs. 34), which contributed to improving the precision of the left tag as shown in Table 4-10.

Table 4-10 Standard deviation in three directions for static tags

Tag name	σ_x (m)	σ_y (m)	σ_z (m)	Average (m)
O_l	0.1630	0.1762	0.23	0.1897
O_r	0.1873	0.2545	0.1735	0.2051

For moving tags, the precision is calculated by measuring the distance between two tags attached to the same component, such as the four tags on the same cross section of the crane boom. Table 4-11 shows the standard deviation of the distance between the two tags attached to the upper and lower sides of the three cross sections (Tag_1^i and Tag_3^i).

The reason for large deviation of tags' distance in S^3 is caused by a large error at the end of the trace of Tag_3^3. After removing these wrong data, the stand deviation was improved 0.253 m.

Table 4-11 Standard deviation in three directions for moving tags

Distance between Tag_1^i and Tag_3^i	σ_{3D} (m)
S^1	0.513
S^2	0.219
S^3	0.771

4.4.4 Removing errors and filling the missing data

Example of filtering readings of tags based on heuristics

Based on the steps defined in Figure 3-11, errors are identified and eliminated in real-time. After identifying tag IDs on different crane components, the heuristic of the maximum expected velocity (v_{max}) could be set for specific tags. Based on our observation, the average velocity of tags in cross section S^2 of the boom is about 0.5 m/s. By adding the UWB system error, which is about ±30 cm in all readings, v_{max} used to filter the UWB readings in real time for tags in S^2 is set to 1.5 m/s. Taking Tag_3^2 as an example, there is a sudden movement in the Z direction at t_{24}, as shown in Table 4-12 and Figure 4-21, and the velocity of Tag_3^2 is calculated as 4.53 m/s, which by far exceeds v_{max}. Therefore, the reading at t_{24} is rejected and replaced by a location calculated based on extrapolation according to the Δ value in each dimension (X, Y, and Z). The purpose of calculating the difference in each dimension individually is that the accuracies in these three dimensions are different, and based on our observation, the accuracy in Z dimension is lower than those in X and Y dimensions. Average Δ value (μ_Δ) and standard deviation (σ_Δ) are calculated based on previous data history during the last 5 sec. Only the point with a Δ in any of the X, Y, Z dimensions that is out of the range of [μ_Δ - $2\sigma_\Delta$, μ_Δ +

$2\sigma_{\Delta}$] is corrected in those specific dimensions using extrapolation from two previous points. As shown in Table 4-12, the Δ values in Y and Z dimensions are out of range at t_{24}, where Δ_y= 0.21 m, Δ_z= 2.13 m, and out of the ranges of [-0.073 m, 0.059 m] and [-0.184 m, 0.220 m], respectively, where $\mu_{\Delta y}$= -0.007 m, $\mu_{\Delta z}$= 0.018 m, $\sigma_{\Delta y}$= 0.033 m, $\sigma_{\Delta z}$= 0.101 m (these values are at t_{23}). Extrapolation is done based on the location data at t_{22} and t_{23} for those two dimensions (Y and Z). It should be noticed that the information filter used for all the tags in the Ubisense system always predict location data based on previous readings; therefore, the data collected for the next time periods (from t_{25} to t_{31}) are all affected by the prediction based on errors, and they have to be recalculated by extrapolation similar to the point at t_{24} to avoid exceeding v_{max}. This extrapolation results in creating new data as shown in the highlighted part in Table 4-12. The results are shown in Figure 4-21, where the raw data and the processed data are plotted. The big jump in the Z dimension is eliminated.

It should be clarified that by chance the movement of Tag_3^2 during the period between t_{24} and t_{33} is almost parallel to the X axis and to the X-Y plane, as can be seen in Figure 4-26; therefore, after correction, the Δ_y and Δ_z values are close to 0. A flowchart is shown in Figure 4-22 to summarize the real-time data processing for single tags.

Table 4-12 Data processed for Tag_3^2 in real time

Raw data of Tag_3^2													
time	x (m)	y (m)	z (m)	v (m/s)	Δ			Average Δ (μ_Δ)			Std. deviation (σ_Δ)		
					Δx	Δy	Δz	Δx	Δy	Δz	Δx	Δy	Δz
t_{23}	0.40	5.43	3.75	0.047	0.02	0.00	0.01	0.08	-0.01	0.02	0.170	0.033	0.101
t_{24}	0.70	5.64	5.88	4.531	0.30	0.21	2.13	0.09	-0.02	0.04	0.180	0.080	0.669
t_{25}	0.71	5.64	5.87	0.030	0.01	0.00	-0.01	0.12	0.002	0.25	0.183	0.079	0.673
t_{26}	1.04	5.22	5.63	1.228	0.33	-0.4	-0.24	0.1	0.005	0.22	0.193	0.156	0.685
t_{27}	1.06	5.23	5.6	0.078	0.02	0.01	-0.03	0.14	-0.04	0.19	0.193	0.157	0.686
t_{28}	1.28	5.38	5.15	1.096	0.22	0.15	-0.45	0.14	-0.03	0.19	0.192	0.167	0.714
t_{29}	1.29	5.38	5.14	0.030	0.01	0.00	-0.01	0.15	-0.02	0.14	0.194	0.167	0.714
t_{30}	1.32	5.37	5.1	0.107	0.03	-0	-0.04	0.15	-0.02	0.14	0.132	0.164	0.716
t_{31}	1.69	5.19	4.46	1.595	0.37	-0.2	-0.64	0.1	-0.01	0.14	0.153	0.173	0.757
t_{32}	1.69	5.19	4.45	0.021	0.00	0.00	-0.01	0.13	-0.02	0.07	0.154	0.173	0.757
t_{33}	1.71	5.18	4.43	0.063	0.02	-0	-0.02	0.13	-0.02	0.07	0.154	0.173	0.757

Processed data of Tag_3^2													
time	x_n (m)	y_n (m)	z_n (m)	v (m/s)	Δ			Average Δ (μ_Δ)			Std. deviation (σ_Δ)		
					Δx	Δy	Δz	Δx	Δy	Δz	Δx	Δy	Δz
t_{23}	0.40	5.43	3.75	0.047	0.02	0.00	0.01	0.15	-0.05	0.063	0.250	0.033	0.101
t_{24}	0.70	5.43	3.76	0.629	0.30	0.00	0.01	0.15	-0.02	0.035	0.180	0.033	0.100
t_{25}	0.71	5.43	3.77	0.030	0.01	0.00	0.01	0.12	-0.02	0.036	0.183	0.034	0.010
t_{26}	1.04	5.43	3.78	0.694	0.33	0.00	0.01	0.1	-0.02	0.005	0.193	0.034	0.008
t_{27}	1.06	5.43	3.79	0.047	0.02	0.00	0.01	0.14	-0.02	0.007	0.193	0.034	0.006
t_{28}	1.28	5.43	3.8	0.462	0.22	0.00	0.01	0.14	-0.01	0.009	0.192	0.034	0.006
t_{29}	1.29	5.38	3.81	0.109	0.01	-0.05	0.01	0.15	-0.01	0.009	0.194	0.036	0.005
t_{30}	1.32	5.37	3.82	0.070	0.03	-0.01	0.01	0.15	-0.02	0.010	0.132	0.016	0.003
t_{31}	1.69	5.36	3.83	0.776	0.37	-0.01	0.01	0.1	-0.01	0.009	0.153	0.016	0.000
t_{32}	1.69	5.19	4.45	1.348	0.00	-0.17	0.62	0.13	-0.01	0.010	0.154	0.054	0.193
t_{33}	1.71	5.18	4.43	0.063	0.02	-0.01	-0	0.13	-0.02	0.071	0.154	0.053	0.194

Example of calculating missing data based on geometric constraints

The same procedure is applied for Tag_1^2 as shown in Figure 4-23. However, in some cases, missing data are occurring in more than two consecutive times because of radio interference, for example, between t_{41} and t_{57}, as shown in Figure 4-23. In these cases, repeating extrapolation based on the history of the tag itself may increase the error, which could be detected by checking geometric constraints. As described in step 5 in Section 3.6, multiple tags are used to filter error and fill the missing data based on geometric constraints of the object. The distance between Tag_1^2 and Tag_3^2 at each time t is calculated to check if it is within the range of $[D_{ii'} - 2\varepsilon, D_{ii'} + 2\varepsilon]$, where $D_{ii'}$ is 1.6 m and ε is 30 cm, resulting in a range of [1.0 m, 2.2 m]. This step has been applied starting from t_{42}, where extrapolation is applied for four times in a row to fill the missing data of Tag_1^2. However, at t_{46}, the distance between Tag_1^2 and Tag_3^2 is 2.44 m, which is out of range. Therefore, the location of Tag_1^2 calculated based on extrapolation is not acceptable. In this case, according to step 6, data of Tag_1^3 and Tag_1^1 are used to calculate the missing data of Tag_1^2 between t_{46} and t_{57} based on the known distances between the three tags, Tag_1^1, Tag_1^2 and Tag_1^3, (3.9 m and 8.4 m, respectively) as shown in Figure 4-26. Figure 4-23 shows the extrapolation based on the history of Tag_1^2 from t_{42} to t_{44} and the interpolation based on geometry according to the other two tags (Tag_1^3 and Tag_1^1) from t_{46} to t_{56}. From t_{57} the system is able to capture the data for Tag_1^2 again.

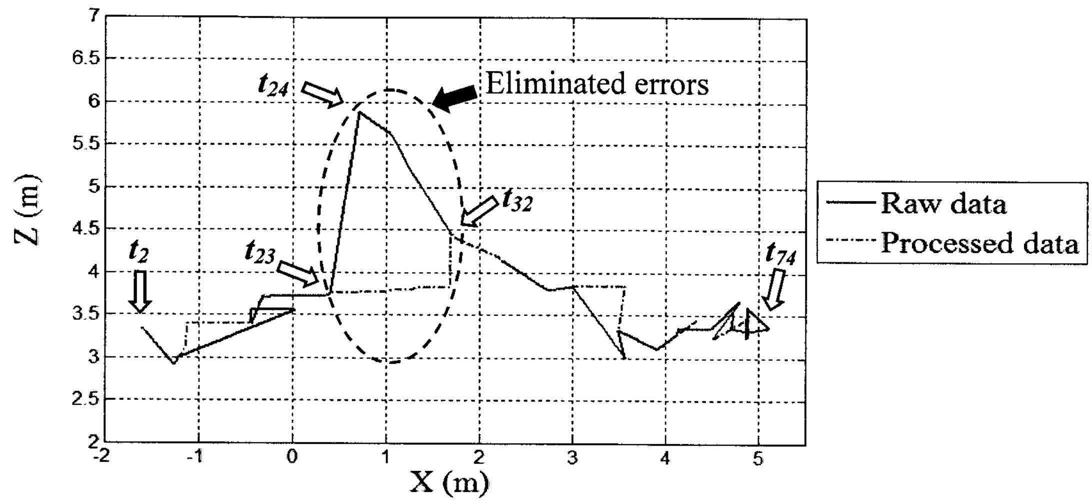


Figure 4-21 Comparison of traces of Tag_3^2 in X-Z plane before and after correction

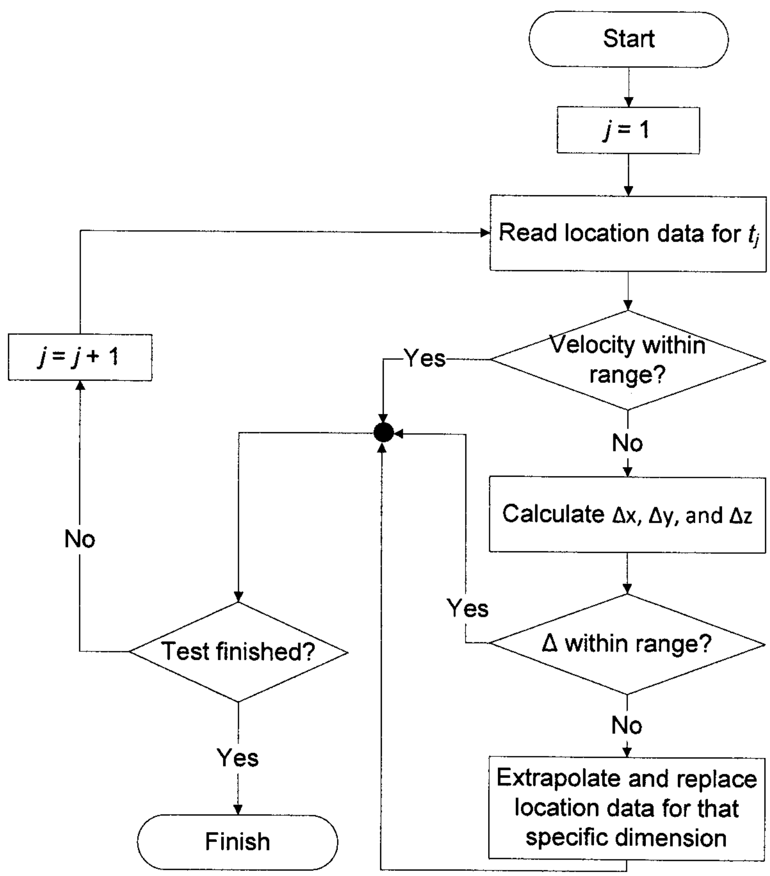


Figure 4-22 Flowchart of real-time data processing for single tags

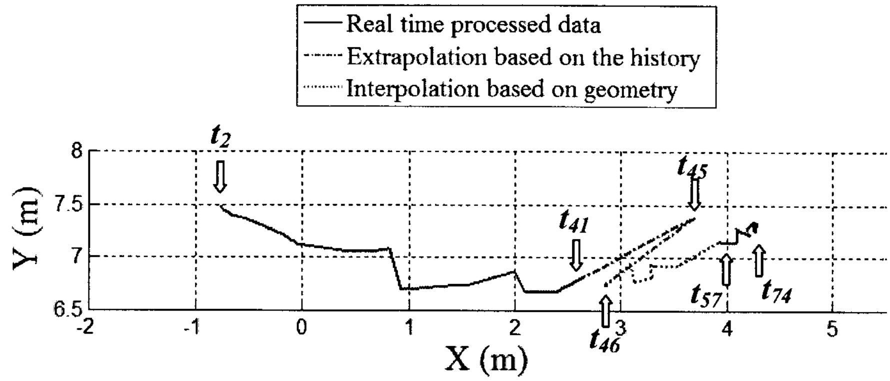


Figure 4-23 Trace of Tag_1^2 based on extrapolation of its history and extrapolation of other two tags

It should be noticed that in extrapolation based on geometry using two tags on the boom, although the data of all tags are assumed to be almost synchronized (step 4 in Figure 3-11), the small time gaps between different tags when the update rate of tags is not high enough may cause problems. For example, in this test, for tags attached to the upper side of the boom, which are Tag_1^1, Tag_1^2 and Tag_1^3, in each t, based on the automatic scheduling of the Ubisense system, the data of Tag_1^3, Tag_1^1, and Tag_1^2 were captured in that order with fixed time difference of 119 ms and 74 ms, respectively. As shown in Figure 4-24(a), a point with large error was captured for Tag_1^1; therefore, extrapolation based on Tag_1^2 and Tag_1^3 is applied to calculate the position of Tag_1^1. The black circles are the location data captured by the system, while the solid white circles are the real locations of the tags, and the dotted circles are the ones calculated based on extrapolation. Because of the small time gap and the relatively big distance between Tag_1^1 and Tag_1^3 (about 12.3 m) during the lifting task, a big offset of the location of Tag_1^1 is expected when applying extrapolation. Moreover, due to the static information filter of the Ubisense system used in this test (with Gaussian noise on position), when the movement of a tag is small, this movement is ignored when predicting the next location of the tag by the system, which results in a cluster of almost overlapping points. If these data are used for extrapolation, this may result in a backward movement of Tag_1^1, as shown in Figure 4-24(b). This figure shows the traces of Tag_1^1, Tag_1^2 and Tag_1^3 and the boom poses based on extrapolation explained above.

As an illustration of this problem, the trace for Tag_1^1 is shown in Figure 4-25, which is the data processed in near real time. Figure 4-25(b) focuses on the zigzag shape of the trace and the crossing of the boom poses at times t_5 and t_{10}, and at times t_{20} and t_{25}. Based on this observation, continuous extrapolation for Tag_1^1 based on the other two tags may increase errors.

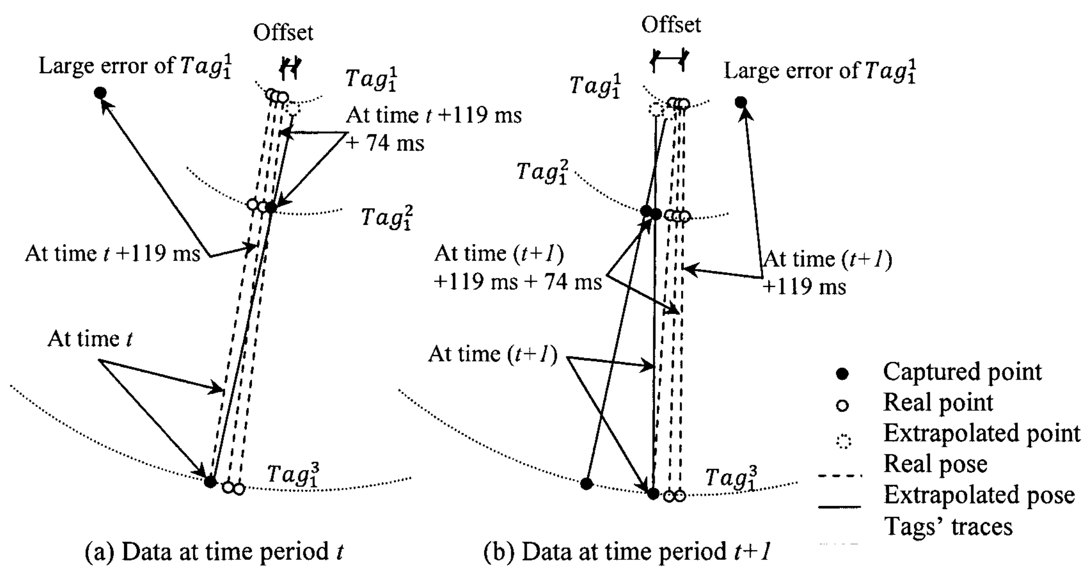


Figure 4-24 Conceptual figure of extrapolation errors

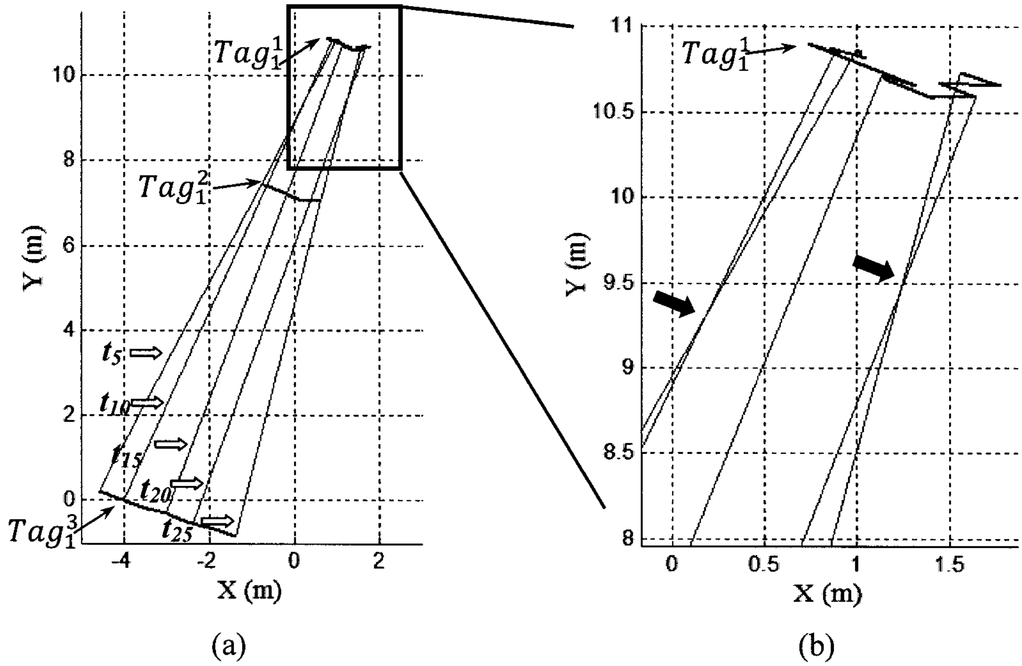


Figure 4-25 Data processed in real time showing the traces of three tags at different time

4.4.5 Calculating the poses of the boom

Real-time analysis

As described in step 7 in Section 3.6, averaging data of multiple tags in the same cross section should be applied to get the center points of these sections, which will define the axis of the boom. A bounding shape (e.g., a cylinder) to cover these three points at each time step can be created with a suitable buffer according to the cross section dimensions of the boom.

This method assumes that the quality of data of each tag is equal; however, based on the actual collected data, the method of calculating the pose of the boom should be adapted so that to preserve data of high quality. Based on our observation, tags on the top side of the boom have better quality; therefore, the traces of these tags (Tag_1^i) are used to create the pose of the boom. As shown in Figure 4-26, the three traces show the poses of the boom at different times.

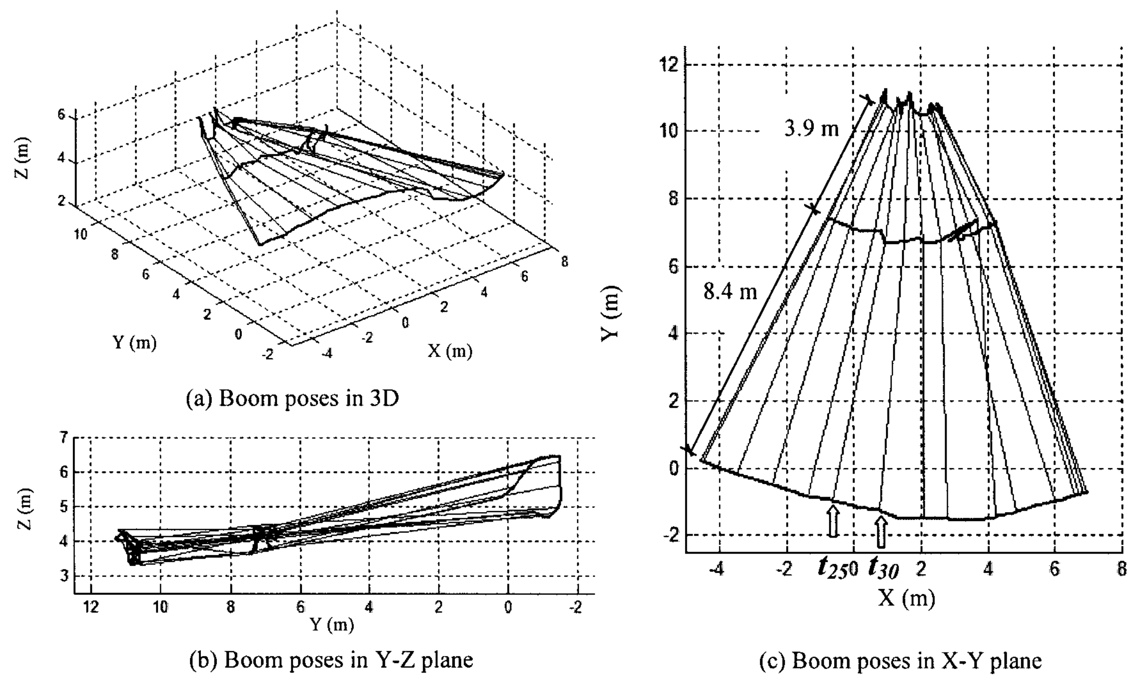


Figure 4-26 Boom poses at different time periods

Post processing analysis

Although real-time data processing is applied to remove errors and fill missing data, in order to investigate the quality of the UWB data, post processing has been applied to take advantage of the whole data set where interpolation can be used to produce data with better quality. Figure 4-27 shows an example of correcting errors of Tag_1^1, which has more errors because it is attached at the base of the boom where there are more radio reflection problems. In the X-Y plane, the trace of Tag_1^1 should follow a curve according to the movement of the boom; however, the raw data relatively large errors. An improvement can be seen after removing errors by applying interpolation based on history and extrapolation based on Tag_1^2 and Tag_1^3. In addition, the trace of Tag_1^2 is post processed to remove the jaggedness due to the missing data. Although this post processing of Tag_1^2 is unnecessary because the pose of the boom can be directly drawn based on Tag_1^1 and Tag_1^3, the purpose of applying post processing is to compare the poses based on real-time processing and post processing. Figure 4-28 shows the traces and the boom poses after post processing.

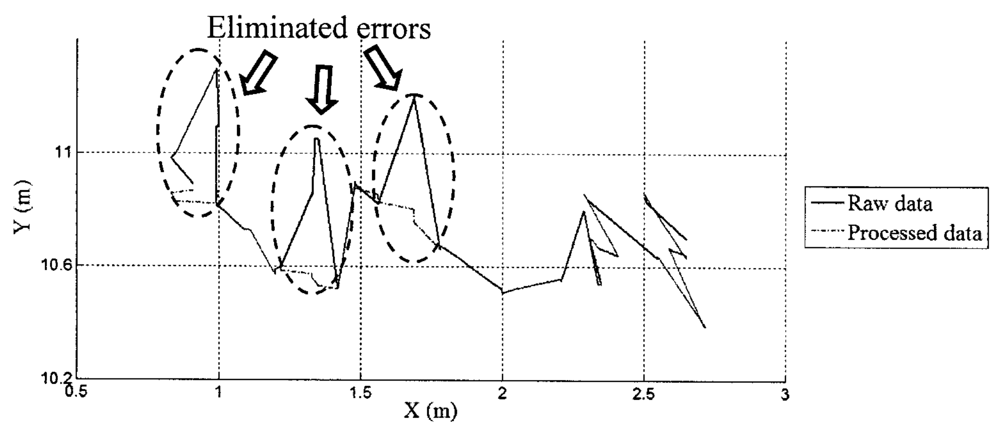
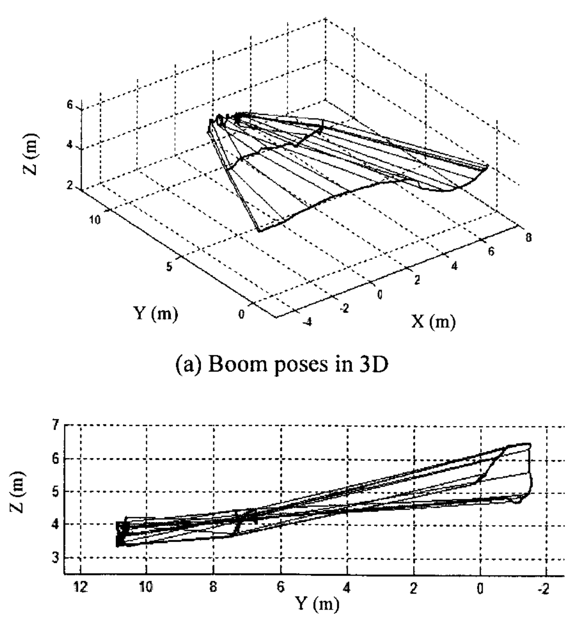
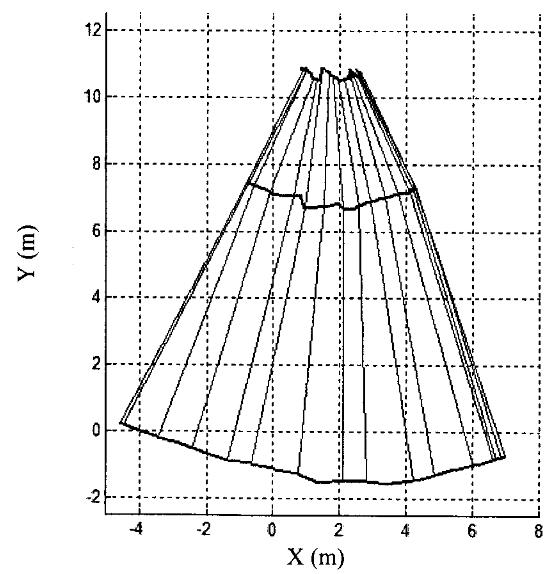


Figure 4-27 Comparison of traces of Tag_1^1 in X-Y plane before and after correction using post processing



(a) Boom poses in 3D

(b) Boom poses in Y-Z plane



(c) Boom poses in X-Y plane

Figure 4-28 Boom poses at different time periods after post processing

4.5 Summary and conclusions

In this chapter we discuss the use of UWB RTLS in construction sites and three case studies to show the applicability of the proposed approach. System setting for satisfying the requirements defined in Section 3.4 is discussed in detail. Indoor and outdoor tests were applied to evaluate system performance. Data collected from the tests were analyzed in detail to investigate how to improve the system's usability when applying in construction, especially for improving productivity and safety.

A laboratory test showed that by using the combination of AOA and TDOA methods and by designing a sensor cell with four sensors, accurate results for position are obtained. Proximity to metallic objects showed less accurate results such as the case of point D. From these results, it is concluded that the cell design must be done in a way that the objects to be monitored are mostly near the center of the cell to obtain accurate results. In addition, an indoor construction test was conducted during the installation of HVAC components. Multiple tags were attached to workers and equipment for the first time in a real construction site. After processing and importing the data into GIS software, it was possible to determine the traces of workers and equipment in 2D, 3D and 4D. This test shows that several applications of UWB technology are possible, such as comparison of the traces of the workers and equipment, identifying obstacles, calculating the length of the path, and the speed of the resource tracked. In this test, four periods of time were analyzed and Period 2 was identified as the one with more vertical movements because it has the biggest difference between the path lengths in 2D and 3D. Furthermore, the speed of two tags positioned at one corner of the scissor lift was measured. However, in this test embedded filters of the UWB system were not applied and the data have large errors which suggest that filtering algorithms must be applied to obtain accurate results.

Furthermore, an outdoor test was applied on a crane with tags attached to different components. Twenty two tags were attached to the crane body and the total number of tags in the cell was 74 tags resulting in a tag update rate of about 2 Hz. Based on the scalability test, the number of tags in the monitored area should be kept in a reasonable range; otherwise, not only more sensors, but also more cells should be used to achieve better update rate by dividing the area into small cells sensed by different groups of sensors. Regarding the visibility, tags should be attached to the upper and bottom sides of the boom to obtain better visibility and accuracy. One tag is enough to be attached to the hook. More tags should be attached to the lift object in case of metallic obstruction of radio signals, and it is better to attach the tags onto the top surface of the object. Tags should be attached onto the top of the operator's cab to get better visibility. Better visibility and scalability result in better accuracy. In addition to the settings of the test considering the requirements, embedded filters of the UWB system were applied and the results were much better that in the indoor test which makes it possible to determine the pose of the crane and realize the analysis of data in real time and post-processing.

The results of the tests show a good potential to use UWB system on construction sites for reducing safety risks and improve productivity. However, there are some limitations to implement UWB in construction sites such as the installation requirements (cables have to be placed in a way that safety conditions are not compromised), the difficulty of tracking objects with high velocity, which cannot be detected by the actual update rate of tags, and accuracy problems that can be minimized by using the appropriate filters in near real time (embedded or designed) and post-processing.

The accuracy problems that were found in these tests by using UWB technology can be attributed to one or a combination of the following reasons: (1) In some cases there is not enough visibility of the tags due to the placement of the tag at a certain time (e.g., objects blocking or interfering the signals; (2) The multipath problem of signals; (3) Metallic objects can produce noise; (4) Other radio frequencies can interfere with the UWB signals.

CHAPTER 5 CONCLUSIONS AND FUTURE WORK

5.1 Summary of research

The research investigates the feasibility of using UWB RTLSs for improving productivity and safety in construction sites. In the literature review it was identified that UWB technology can be used to identify and track construction resources to better manage projects. However, the requirements of the location data were not specifically defined and were the motivation of this research.

The proposed methodology provides an approach of tracking construction resources with UWB RTLSs. The approach starts by defining the tracking purposes, then the assets to track and the requirements of the system to accomplish the tracking objectives. An investigation of the requirements for the deployment of UWB in construction site was done. They were identified as accuracy, visibility, scalability and real time, tag form factor, power and networking requirements. Two scenarios were considered to design the application of the proposed methodology, one for tracking workers and equipment in an indoor and the other for outdoor construction sites. Moreover, real-time processing, post-processing and visualization of location data methods from UWB RTLSs were discussed. Furthermore, the processes to analyze data in near real time and post-processing were defined and discussed.

Three case studies demonstrated the applicability of the proposed approach of using UWB RTLS in construction sites. System setting for satisfying the requirements were defined and discussed in detail. Indoor and outdoor tests were applied to evaluate system performance. Data collected from the tests were analyzed in detail to investigate how to improve the system's usability when applying in construction, especially for improving productivity and safety.

A laboratory test showed that by using the combination of AOA and TDOA methods and by designing a sensor cell with four sensors, accurate results for position are obtained. In addition, an indoor construction test was conducted during the installation of HVAC components. Tags were attached to workers and equipment in a real construction site. After processing and importing the data into GIS software, it was possible to determine the traces of workers and equipment in 2D, 3D and 4D. This test shows that several applications of UWB technology are possible, such as comparison of the traces of the workers and equipment, identifying obstacles, calculating the length of the path, and the speed of the resource tracked. However, in this test embedded filters of the UWB system were not applied and the data have large errors which suggest that filtering algorithms must be applied to obtain accurate results.

Furthermore, an outdoor test was applied on a crane with tags attached to different components. Based on the scalability test, number of tags in the monitored area should be kept in a reasonable range; otherwise, not only more sensors, but also more cells should be used to achieve better update rate by dividing the area into small cells sensed by different group of sensors. Regarding the visibility, tags should be attached to the upper and bottom sides of the boom to obtain better visibility and quality. One tag is enough to be attached to the hook. More tags should be attached to the lift object in case of metallic obstruction of radio signals, and it is better to attach the tags onto the top surface of the object. Tags should be attached onto the top of the operator's cab to get better visibility.

Better visibility and scalability result in better accuracy. In addition to the settings of the test considering the requirements, embedded filters of the UWB system were applied and the results were much better that in the indoor test which makes it possible to determine the pose of the crane and realize the analysis of data in real time and post-processing.

5.2 Research contributions and conclusions

UWB is an effective tool for monitoring construction resources, such as workers and equipment, because it provides accurate information in real time. The contributions of this research are:

(1) An integral approach that includes the tracking purposes in near-real time and post processing location data, makes feasible the improvements of construction sites and construction practices by using UWB RTLS for productivity and safety. An investigation of applications of this technology was done such as measuring the percentage of the wasted time in unnecessary movements, automating repetitive processes, optimizing the routes of workers in the building by using indoor navigation, standardizing the work by re-playing and analyzing the recorded activities, determining the progress of the project and reducing the conflict for resources. In addition, the safety purposes were identified such as identifying geometry of obstacles by using multiple tags attached to different components of equipment, checking the compliance with safety regulations and engineering constraints to prevent accidents and achieving more advanced intelligent support. Furthermore, the specific purposes of tracking workers and equipment were identified.

(2) The requirements for the deployment of UWB in construction sites were identified as accuracy, visibility, scalability and real time, tag form factor, power, and networking requirements.

(3) Two scenarios were considered to design the application of the proposed methodology, one for tracking workers and equipment in the indoors and the other for outdoor construction sites. Those scenarios satisfy the identified requirements for the deployment of UWB in construction sites.

(4) The process of UWB near real-time data processing or post-processing was defined. This process has several steps including indentifying tag IDs on different components, filtering readings for each tag based on heuristics, calculating missing data for each tag using extrapolation or interpolation, synchronizing data by averaging data within each time period, filtering errors based on geometric constraints of multiple tags, calculating missing data based on geometric constraints, averaging locations of multiple tags in the same group, and computing the position or the pose of the object.

(5) Several visualization methods of location data from UWB RTLSs are necessary to convert the location information into meaningful information for construction projects.

(6) A laboratory test showed that by using the combination of AOA and TDOA methods and by designing a sensor cell with four sensors, accurate results for position are obtained. Proximity to metallic objects showed less accurate results such as the case of point D. From these results, it is concluded that the cell design must be done in a

way that the objects to be monitored are mostly near the center of the cell to obtain accurate results.

(7) An indoor construction test was conducted during the installation of HVAC components. Multiple tags were attached to workers and equipment for the first time in a real construction site. After processing and importing the data into GIS software, it was possible to determine the traces of workers and equipment in 2D, 3D and 4D. This test shows that several applications of UWB technology are possible, such as comparison of the traces of the workers and equipment, identifying obstacles, calculating the length of the path, and the speed of the resource tracked. In this test, four periods of time were analyzed and Period 2 was identified as the one with more vertical movements because it has the biggest difference between the path lengths in 2D and 3D. Furthermore, the speed of two tags positioned at one corner of the scissor lift was measured. However, in this test embedded filters of the UWB system were not applied and the data have large errors which suggest that filtering algorithms must be applied to obtain accurate results.

(8) An outdoor test was applied on a crane with tags attached to different components. Twenty two tags were attached to the crane body and the total number of tags in the cell was 74 tags resulting in a tag update rate of about 2 Hz. Based on the scalability test, the number of tags in the monitored area should be kept in a reasonable range; otherwise, not only more sensors, but also more cells should be used to achieve better update rate by dividing the area into small cells sensed by different groups of sensors. Regarding the visibility, tags should be attached to the upper and bottom sides of the boom to obtain better visibility and accuracy. One tag is enough to be

attached to the hook. More tags should be attached to the lift object in case of metallic obstruction of radio signals, and it is better to attach the tags onto the top surface of the object. Tags should be attached onto the top of the operator's cab to get better visibility. Better visibility and scalability result in better accuracy. In addition to the settings of the test considering the requirements, embedded filters of the UWB system were applied and the results were much better that in the indoor test which makes it possible to determine the pose of the crane and realize the analysis of data in real time and post-processing.

(9) The results of the tests show a good potential to use UWB system on construction sites for reducing safety risks and improve productivity. However, there are some limitations to implement UWB in construction sites such as the installation requirements (cables have to be placed in a way that safety conditions are not compromised), the difficulty of tracking objects with high velocity, which cannot be detected by the actual update rate of tags, and accuracy problems that can be minimized by using the appropriate filters in near real time (embedded or designed) and post-processing.

5.3 Future work

The following steps are necessary for fully realizing the proposed approach: (1) The data obtained from UWB RTLSs need to be integrated with other project management systems to convert location data to information that can be used for management purposes; (2) In the near real-time data processing, the linear interpolation and extrapolation is based on two points only and may not fit the accuracy requirement.

Future improvement can be done using curve fitting or other methods while taking more points into account. The filter embedded in the system is not easy to control and Kalman filter combined with geometric constraints (Arras et al., 2003) is a better solution to explore in the future; (3) Advanced applications that combine location data with other data sources such as 3D models need to be developed; and (4) UWB RTLSs for tracking workers and equipment can be integrated with other technologies such as RFID for tracking construction components.

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Appendix A Timeslot length

Table A-1 Timeslot length for a 40 Hz system (Ubisense, 2009)

Slot interval	Update interval (seconds)	Listen interval (seconds)	Reschedule response time
4	0.109	0.109	fast
8	0.216	0.216	fast
16	0.432	0.432	fast
32	0.865	0.865	fast
64	1.73	1.73	fast
128	3.46	1.73	fast
256	6.91	1.73	fast
512	13.8	1.73	fast
1024	27.7	1.73	fast
2048	55.3	55.3	slow
4096	111	111	slow
8192	221	221	slow
16384	221	221	slow
32768	221	221	slow

Table A-2 Timeslot length for a 160 Hz system (Ubisense, 2009)

Slot interval	Update interval (seconds)	Listen interval (seconds)	Reschedule response time
4	0.026	0.026	fast
8	0.052	0.052	fast
16	0.104	0.104	fast
32	0.208	0.208	fast
64	0.416	0.416	fast
128	0.832	0.832	fast
256	1.66	0.832	fast
512	3.32	0.832	fast
1024	6.66	0.832	fast
2048	13.3	0.832	fast
4096	26.6	26.6	slow
8192	53.2	53.2	slow
16384	106	106	slow
32768	106	106	slow

Appendix B Instructions for field testing

(1) Needed equipments:

Sensors
Mounting equipments
Cables (4 regular network cables and 3 thick timing cable)
Computer
Software: Ubisense package, DHCP server, solver
Switch and power: POE switch plus its power cables, power generator for outdoor scenario
Level
Cutter

(2) Layout design steps

Conceptual connectivity design (daisy chain, star, extended start)
Decide on where to put the sensors in the yard

1. Decide on where to put one tag for calibrating the sensors
2. Decide on two ,easy to measure, points on the yard
3. Decide on how to run the cables and protect them
4. Decide on where to put the switch
5. Draw the connectivity map
6. Decide on the reference point (0,0,0)
7. Fill out table (Calibration tag ID info, Sensors: x,y,z and mac)

(3) Site preparation

Note: activities with letter "P" could be done in parallel

P1: Fix the sensors on the mounting device on the designated place
P1: Put the switch on its designated place and attach to the power
P1: Run the network cables from switch to sensors and fix the cables
P1: Run the timing cables based on the connectivity map (most often between the sensors)

(4) Measurements

P2-0: Measure the "area" : W,L,H
P2-1: Measure x,y,z of the sensors (one by one or using the solver)

-Decide on two points and measure the x,y of them , (preferably we set the (0,0) on the corner of two walls in the area)
-Measure the distance from the points to the sensors
-Enter them in the solver

-Get the xyz of the sensors

P2-2: Measure the reference point for calibration (x y z) (could be the same points in the last step)

(5) Basic configuration

Note: sensors are now turned off because they are not attached to the switch
All cables should be connected properly (check if they are loos/ timing cables are connected to upper left)

1. Restart the pc (switch is powered, sensors are not connected, pc is connected to switch)
2. Attach the computer to the switch
3. Start DHCP server
4. Open platform control
5. Make sure the services are running (no prefix, not in standalone mode)
6. Open location engine
7. Open log tab
8. Connect the sensor cables
9. Looking at logs to see if we receive logs
10. Move sensors to cell
11. Define master (checkboxes,....)
12. Look at the LEDs

(6) Software configuration

Note: So far the sensor MAC addresses should be under "available sensors"

1. Open "site manager"
2. Area tab
3. Open note pad
4. Type the coordinates of the area the file (P2-0)
5. Save in .dat file
6. Create walls in the area tab >load walls> load .dat
7. Go to the cell tab and load the area
8. Extend the cell
9. Open location engine
10. Load area and cell
11. Drag the sensors to the area
12. Select the master and check: "master", "timing source" and "disable sleep"
13. Check the RF power of the cell (must be 250)
14. Check the LEDs (should be solid green)
15. Enter XYZ of the sensors (using P2-1)
16. Put the tag on the calibration point (using P2-2)
17. Do the dual calibration

(7) Assign tags to objects

1. Open "Site Manager"
2. Go to tab "Objects"
3. Click "Objects" on the menu, and select "New"
4. Create new object and type
5. Open "Location Engine Config"
6. Go to tab "Owners"
7. Click "Ownership" on the menu, and select "New" and assign tags to objects

(8) Set update time slots

1. Open "Location Engine Config"
2. Go to tab "tags"
3. Double click on lines, and select the Slower QOS, the Faster QOS, and the Threshold.

(9) Using Logger to record data

1. Run "\ubisense\joshua Materials\Logger\V4\bin\Debug\UbisenseLogger.exe"
2. Click "Record/Playback file…"
3. Create a new file with ".txt" under a specified folder
4. Select objects need to be monitored
5. Go to tab "Record" and click on the red button
6. Captured events will be shown in the frame

Appendix C Calibration data of indoor and outdoor tests

Table C-1 Calibration data indoor test

Sensor name		Sensor-1	Sensor-2	Sensor-3	Sensor-4 (Master)
MAC address		00:11:CE:00:1C:3F	00:11:CE:00:1C:41	00:11:CE:01:1C:45	00:11:CE:01:1C:61
Sensor position	X	0.76	12.31	9.78	0.91
	Y	2.51	7.19	2.34	7.64
	Z	1.57	1.8	1.6	1.59
Ref. tag name		020-000-059-000			
Ref. tag position	X	5.15			
	Y	4.63			
	Z	1.49			
Angle calibrated	Yaw	9.90837	16.701	9.07993	6.00979
	Pitch	39.4838	-186.524	127.715	-0.163048
Angle Master	Yaw	6.00979	4.77851	6.46879	
	Pitch	-0.163048	-1.07736	0.20181	

Table C-2 Calibration data outdoor test

Sensor name		Sensor-1	Sensor-2	Sensor-3	Sensor-4 (Master)
MAC address		00:11:CE:00:1C:3F	00:11:CE:00:1C:41	00:11:CE:01:1C:45	00:11:CE:01:1C:61
Sensor position	X	-8.52	-9.36	10.16	9.07
	Y	-10.54	12.47	12.1	-10.31
	Z	1.61	1.67	1.57	1.45
Ref. tag name		020-000-059-089			
Ref. tag position	X	0			
	Y	0			
	Z	2.46			
Angle calibrated	Yaw	45.8939	-52.1697	-135.879	134.174
	Pitch	22.5174	20.5125	26.6233	22.5969
Angle Master	Yaw	0	0	0	0
	Pitch	45.8939	-52.1697	-135.879	134.174

Appendix D Macros in VBA

CODE	COMMENTS

```
Sub Macro1()                                          'This macro make timestamp for the data collected

Range("X2").Select                                    'Select the first cell containing timestamps

   ActiveSheet.Range("X2").Activate
   totalms = ActiveCell.Value
   intdif = 864                                       'Interval 864 ms
   mscountlow = 60041658                              'Starting time in ms
   mscountup = mscountlow + intdif
   interval = 1

Do While totalms > 0
   totalms = ActiveCell.Value
   If totalms < mscountup And totalms <> 0 Then       'Write the timestamp
   ActiveCell.Offset(0, 5) = interval                 'Go to the next cell
   ActiveCell.Offset(1, 0).Activate
  Else
   mscountlow = mscountlow + intdif                   'Increment in 1 the counting of timestamp
   mscountup = mscountlow + intdif
   interval = interval + 1
     End If
 Loop

End Sub

Sub Macro2()                                          'This macro fill the timestamp missing with NA

Dim dir As String
   Range("AC2").Select
   ActiveSheet.Range("AC2").Activate
   ts = ActiveCell.Value
 Do While ts > 0
   ts = ActiveCell.Value                              'Verify which rows have valid time stamps
   tsn = ActiveCell.Value + 1
   tsc = ActiveCell.Offset(1, 0).Value
   If tsn = tsc Or tsc = 0 Then
   ActiveCell.Offset(1, 0).Activate
   Else
   dir = ActiveCell.Offset(1, 0).Address
   Range(dir).Select
   Selection.EntireRow.Insert
   Range(dir).Activate
   ActiveCell = tsn
   ActiveCell.Offset(0, 1) = "NA"
   End If
 Loop

End Sub
```

CODE	COMMENTS
Sub Macro3()	
	'If difference between one point to the last point 1.5 then fill with NA
Range("AC2").Select	
ActiveSheet.Range("AC2").Activate	'Activate the first cell with timestamp
ts = ActiveCell.Value	
Do While ts > 0	
difer = ActiveCell.Offset(0, -15).Value	'Calculate the difference
file = ActiveCell.Offset(0, -28).Value	
If difer > 1.5 Or file = 0 Then	'To verify if the value is bigger than the one fixed
ActiveCell.Offset(0, 1) = "NA"	'Fill with NA
End If	
ActiveCell.Offset(1, 0).Activate	
ts = ActiveCell.Value	'Go to the next cell
Loop	
End Sub	
Sub Macro4()	
	'This macro create new points based on two tags
Range("AC2").Select	
ActiveSheet.Range("AC2").Activate	'Activate the first cell with timestamp
ts = ActiveCell.Value	
Do While ts > 0	
ta = ActiveCell.Offset(0, 1).Value	'Take the variables for each point
tb = ActiveCell.Offset(0, 33).Value	
xa = ActiveCell.Offset(0, -18).Value	
ya = ActiveCell.Offset(0, -17).Value	
za = ActiveCell.Offset(0, -16).Value	
xb = ActiveCell.Offset(0, 14).Value	
yb = ActiveCell.Offset(0, 15).Value	
zb = ActiveCell.Offset(0, 16).Value	
If ta = 0 And tb = 0 Then	
xf = (xa + xb) / 2	'Calculate the average
yf = (ya + yb) / 2	
zf = (za + zb) / 2	
ActiveCell.Offset(0, 36) = xf	'Create the new points
ActiveCell.Offset(0, 37) = yf	
ActiveCell.Offset(0, 38) = zf	
End If	
If ta = 0 And tb = "NA" Then	'If one value or the other is 0 or NA then, the other point is used
ActiveCell.Offset(0, 36) = xa	
ActiveCell.Offset(0, 37) = ya	
ActiveCell.Offset(0, 38) = za	
End If	
If ta = "NA" And tb = 0 Then	
ActiveCell.Offset(0, 36) = xb	
ActiveCell.Offset(0, 37) = yb	
ActiveCell.Offset(0, 38) = zb	
End If	
ActiveCell.Offset(1, 0).Activate	
ts = ActiveCell.Value	
Loop	
End Sub	

CODE	COMMENTS
Sub Macro5()	'If difference between one point to the last point and to the next point > 1.5 then fill with NA
Range("AC2").Select ActiveSheet.Range("AC2").Activate	'Activate the first cell with timestamp
ts = ActiveCell.Value	
Do While ts > 0	
difer = ActiveCell.Offset(0, -15).Value file = ActiveCell.Offset(0, -28).Value diferp = ActiveCell.Offset(1, -15).Value	'Comparison with the last and next point
If difer > 1.5 And diferp > 1.5 Or file = 0 Then	'If the difference is bigger that the value for comparison
ActiveCell.Offset(0, 1) = "NA"	
End If	
ActiveCell.Offset(1, 0).Activate ts = ActiveCell.Value	'Activate next cell
Loop	
End Sub	
Sub Macro15()	'This macro interpolate the points for missing data
Range("P2").Select ActiveSheet.Range("P2").Activate	'P is the column with timestamp
ts = ActiveCell.Value np = 0	'Initialize the counting of missing points
stepx = 0 stepy = 0 stepz = 0 Do While ts > 0	
ac = ActiveCell.Offset(0, 1).Value	'This search if the timestamp has NA value
If ts > 1 Then	
x1 = ActiveCell.Offset(-1, -13).Value y1 = ActiveCell.Offset(-1, -12).Value z1 = ActiveCell.Offset(-1, -11).Value	'Take the values
Else x1 = 0 y1 = 0 z1 = 0	
End If	
dir1 = ActiveCell.Address	'Take the cell address
Do While ac = "NA"	'Count the number of missing rows

CODE	COMMENTS
ActiveCell.Offset(1, 0).Activate	
ac = ActiveCell.Offset(0, 1).Value	
np = np + 1	
x2 = ActiveCell.Offset(0, -13).Value	
y2 = ActiveCell.Offset(0, -12).Value	
z2 = ActiveCell.Offset(0, -11).Value	
stepx = (x2 - x1) / (np + 1)	'Calculate the interpolation value
stepy = (y2 - y1) / (np + 1)	
stepz = (z2 - z1) / (np + 1)	
Loop	
If np > 0 Then	
Range(dir1).Activate	'Returns to the first empty cell
stp1 = 0	
xtemp = x1 + stepx	
ytemp = y1 + stepy	
ztemp = z1 + stepz	
Do Until stp1 = np	'Write for each empty cell the interpolated value
antx = ActiveCell.Offset(0, -13).Value	
anty = ActiveCell.Offset(0, -12).Value	
antz = ActiveCell.Offset(0, -11).Value	
ActiveCell.Offset(0, -13).Value = xtemp	
ActiveCell.Offset(0, -12).Value = ytemp	
ActiveCell.Offset(0, -11).Value = ztemp	
xtemp = xtemp + stepx	
ytemp = ytemp + stepy	
ztemp = ztemp + stepz	
If antx = Empty Or anty = Empty Or antz = Empty Then	
ActiveCell.Offset(0, 3) = "NEW"	'Identify which cells are null and which cells are replaced
Else	
ActiveCell.Offset(0, 3) = "REP"	
End If	
ActiveCell.Offset(1, 0).Activate	
stp1 = stp1 + 1	
Loop	
np = 0	
End If	
ac = 0	
ActiveCell.Offset(1, 0).Activate	
ts = ActiveCell.Value	
Loop	
End Sub	

Appendix E Steps to import data from Logger in GIS

Note: In GIS is very important to maintain the same names for folders, if the names are changed the files must be created again. To avoid that is better not to change the folders' names.

1. Create Excel file based on the Data
    a. Open Excel
    b. Save the file with the name related to the text file to analyze
    c. On the menu Data click Get external data From text
    d. Select the text data file extension: .txt that it is going to be analyzed
    e. On the new window select Delimited -> Next
    f. Select Comma and Space as Delimiters -> Next
    g. Select Do not import columns (skip) for the columns that are not needed and keep the General data format for all the other columns -> Finish
    h. Put the data on the existing worksheet
    i. Sort data based on tag ID and then based on time
    j. That sheet can be named as "fromtxt" and will contain the original data imported from the text file
    k. Create a copy of the "fromtxt" sheet and now work on this sheet that can be labelled as "attributes"
    l. Add a new column and put ID for all the data
    m. Remove C from the tag ID: Select the column that contain the tag ID, then click Data -> Text to Columns -> Fixed width ->Next , Divide the data after the C -> Next, Do not import (skip) the column that contains the C -> Finish
    n. Remove milliseconds from the time: Select the column that contain the time, then click Data -> Text to Columns -> Fixed width ->Next , Divide the data before the milliseconds -> Next, Do not import (skip) the column that contains the milliseconds-> Finish
    o. In a new column change format data of date using formula =TEXT(cell,"mm/dd/yyyy")
    p. In a new column change format data of hour using formula =TEXT(cell,"HH:mm:ss")
    q. In a new column mix the new columns created with the formula =cell1&" "&cell2
    r. Copy that column and paste special -> select only values in a new column (this produce a new column with the date as required in GIS, the columns with formulas cannot be imported in the database)
2. Create text files for points and lines
    a. Make a copy of the attributes table and label as Mapdata
    b. On the sheet Mapdata remove all the columns that include date and time leave the columns ID, x,y,z values and Tag ID (in this strict order)
    c. With formula join all the values into one cell using =cell& " "&cell
    d. Copy that column and paste special -> as values in two new sheets
    e. Label the new sheets as Points and Lines each one

f. On the Points sheet insert a new row at the top of all the data and write "Point" in the first cell and "End" at the end of all the data
g. On the Lines sheet insert a new row at the top of all the data and write "Polyline" in the first cell and "End" "End" at the end of all the data
h. On the lines sheet insert a new row before each set of data for the tags and write in the first cell the tag id, an space and then zero "0"
i. Save the excel file (important, if not the data can be lost)
j. Save the sheet Points as other formats -> MS DOS .txt format (don't use Unicode) label the new file with a name related with the data analyzed Answer OK and YES to the dialogue boxes
k. Close Excel and answer NO to the dialogue box
l. Open again the excel file that contain the information
m. Save the sheet Lines as other formats -> MS DOS .txt format (don't use Unicode) label the new file with a name related with the data analyzed Answer OK and YES to the dialogue boxes
n. Close Excel and answer NO to the dialogue box

3. Create Attribute database
   a. Open Access
   b. Create a new blank database with a name related with the analysis
   c. Click External data -> import Excel
   d. Browse the excel file that contains the data, click import in new table and click ok
   e. Select the attributes sheet -> Next
   f. If access ask for give automatically names to the fields click OK
   g. Deselect first row contains columns headings -> Next
   h. For each column save the data as follows

Field Name	Data type	Indexed
ID	Long Integer	Yes (Duplicates ok)
TagID	Long Integer	No
Datetime	Text	

   ->Next
   i. No primary key added by access
   j. Save the file
   k. Save the database as .dbf: click External data -> export -> more -> .dbf
   l. Close access
4. Translate points and lines to shapes in ARCGIS
   a. Open ARC Map and go to window /Command Line
   b. Write : CreateFeaturesFromTextFile 'originfile.txt'. 'destinfile.shp' #
   c. Click Enter

Example points:
CreateFeaturesFromTextFile '\\infra-plus.ciise.concordia.ca\ubisense\JMSB test 29 and 30 April 2009\LearningGIS\1240points.txt' . '\\infra-plus.ciise.concordia.ca\ubisense\JMSB test 29 and 30 April 2009\LearningGIS\1240points.shp' #

Example lines:
CreateFeaturesFromTextFile '\\infra-plus.ciise.concordia.ca\ubisense\JMSB test 29 and 30 April 2009\LearningGIS\1240lines.txt' . '\\infra-plus.ciise.concordia.ca\ubisense\JMSB test 29 and 30 April

2009\LearningGIS\1240lines.shp' #

    d. Save Arcmap file
5. Joint table of attributes from shape extension .shp and access database and create final shape file extension .shp
6. Joint table of attributes to points
    a. Open Arcmap
    b. Select the layer -> right click -> joints and relates -> join
    c. Join will be based on : File_ID
    d. Load the table from disk: choose the location of the attributes database extension = > .dbf
    e. The field on the table to base the join on: ID
    f. If a message indicating indexing appears give OK
7. Copy the tagid and timedate
    a. Select the layer points
    b. Open the table
    c. The information will not appear but the data can be copied from the attributes table joint before
    d. Click options -> add field
    e. Name -> td (time-date) type: Text
    f. Select the new field created (counting the positions of the columns and verifying by right click – properties)
    g. Right click the field calculator -> 1240points.td=1240data.datetime
    h. Click options -> add field
    i. Name -> tagid type: Long integer
    j. Select the new field created (counting the positions of the columns and verifying by right click – properties)
    k. Right click the field calculator -> 1240points.tagid=1240data.TagID
8. Remove joints
    a. Select the layer -> right click -> joints and relates -> remove all joins
    b. Verify if timedate information and tagid are now part of the table for the points layer
9. Add temporal data
    a. Choose 1: a feature class or shapefile…
    b. Choose 2: pointshape
    c. Choose 3: td (or the column that contains date and time)
    d. Choose 4: If your data can be… belongs to -> tagID (or the column that contains the tag ID)
    e. Choose 5 English (United States)
MM/dd/yyyy HH:mm:ss -> finish
    f. Save the file

Appendix F List of related publications

Journal papers

Hammad, A., Zhang, C., AlBahnassi, H., and Rodriguez, S. (Submitted, 2010). Motion Planning of Cranes using UWB Real-Time Location System. *Automation in Construction.*

Hammad, A., Zhang, C., Rodriguez, S., and Motamedi, A. (To be submitted, 2010). Feasibility of Location Tracking of Construction Resources Using UWB. *Journal of Construction Engineering and Management.*

Conference papers

Rodriguez, S., Zhang, C., and Hammad, A. (2010). Feasibility of Location Tracking of Construction Resources Using UWB for Better Productivity and Safety. *International Conference on Computing in Civil and Building engineering (ICCCBE). Nottingham, United Kingdom*

Colloquiums

Rodriguez, S., and Hammad, A. (2009). Location tracking of construction resources using UWB. *Presented in the 1st Canadian Graduate Student Colloquium on Computer-Assisted Construction Technologies (CCT). National Research Council Canada. London ON, Canada*