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CASE STUDY ON APPLICATION OF WIRELESS ULTRA-WIDEBAND TECHNOLOGY FOR TRACKING EQUIPMENT ON A CONGESTED SITE

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EDITORS: Ruikar K. & Amor R.

Hassaan Siddiqui,
Concordia Institute for Information Systems Engineering (CIISE), Concordia University, Canada;
E-mail: **hassaan.a.s@gmail.com**

Faridaddin Vahdatikhaki, Assistant Professor,
Department of Construction Management and Engineering, University of Twente, the Netherlands;
E-mail: **f.vahdatikhaki@utwente.nl**

Amin Hammad, Professor,
Concordia Institute for Information Systems Engineering (CIISE), Concordia University, Canada;
E-mail: **hammad@ciise.concordia.ca**

SUMMARY: *Construction sites are well known for their dynamic and challenging working environment. Several researchers are investigating the application of various Real-time Location Systems (RTLSs) for improving the safety and productivity of construction projects. When integrated with real-time data analysis systems, RTLS can contribute to making the construction environment smarter and safer by identifying safety hazards and inefficient resource configurations. Previous research shows that the Ultra-Wideband (UWB) technology, an emerging type of RTLS, is suitable for the identification and tracking of construction resources. However, the prevalent form of UWB application requires a set of data cables for data communication and a set of timing cables that aids in the estimation of location. This requirement limits the use of the technology in construction sites, especially for outdoor tracking, since the cable connections can pose safety and logistical challenges. In the wireless application of UWB, the wireless bridges substitute the data cables and the timing cables are entirely removed. While the use of wireless UWB is investigated for indoor application in previous studies, the setting is not tested for the application in outdoor projects. This paper presents a case study on the application of the wireless UWB on an outdoor construction site. The case study was conducted for tracking the equipment on a building reconstruction project in downtown Vancouver. Special ready-to-install panels that contained all the required hardware components for a single sensor were designed to facilitate the installation of UWB on the site. The setting and installation of the wireless UWB is proven to be successful under the harsh construction site conditions. It is demonstrated that the designed UWB system configuration has a great potential for making the system logistically practical and user-friendly for outdoor tracking of construction equipment and assets. By highlighting the limitations of the system in the current set-up, the case study also helped pinpoint the areas of attention for further improvement of the system's performance in terms of accuracy and update rate.*

KEYWORDS: *Real-time locating systems, Equipment tracking, Construction sites.*

REFERENCE: *Hassaan Siddiqui, Faridaddin Vahdatikhaki & Amin Hammad (2019). Case study on application of wireless ultra-wideband technology for tracking equipment on a congested site. Journal of Information Technology in Construction (ITcon), Vol. 24, pg. 167-187, http://www.itcon.org/2019/10*

1. INTRODUCTION

Real-time information is the essence of smart decision making. In construction operations, real-time information about the equipment and workers can certainly assist in reinforcing the safety and improving the overall productivity. The advancements in Real-time Location Systems (RTLSs), such as Radio Frequency Identification (RFID) and Global Positioning System (GPS), have enabled researchers to investigate the applicability of these systems to automate the on-site data collection process. Ultra-Wideband (UWB) technology, a type of RTLS, has been investigated by several researchers for the identification, localization, and tracking of construction resources. The UWB technology has the potential to track and visualize construction resources on site and increase the awareness level of the construction staff in near real time. Previous research shows that the Ultra-Wideband (UWB) technology, an emerging type of RTLS, is suitable for the identification and tracking of construction resources (Rodriguez 2010, Maalek & Sadeghpour, 2013 Zhang et al. 2012, Vahdatikhaki & Hammad 2014, Vahdatikhaki et al. 2015). However, the prevalent form of UWB application, which promises higher accuracy, requires two sets of cables; one set of data cables to synchronize the sensors, and one set of timing cables that estimates the location using the Time Difference Of Arrival (TDOA) technology. These two sets of cables limit the use of the technology in construction sites, especially for outdoor tracking, since the cable connections can pose safety and logistical challenges. Another option for the application of the UWB system is in the wireless setup, in which data is transferred from the sensors to the server using the wireless bridges instead of data cables, and the timing cables are entirely removed thus compromising the TDOA technique's positioning accuracy. While the use of wireless UWB is investigated for indoor application in previous studies (Maalek & Sadeghpour, 2013, Siddiqui et al. 2014), the setting is not thoroughly tested for the application in outdoor projects. As a result, the main gap in the current state of the research is that there are no comprehensive investigations of the performance of wireless UWB for outdoor tracking. Given the importance of tracking equipment and personnel in outdoor environment for the improved safety and productivity, and also given the limitations of other tracking solutions (e.g., GPS) in condensed urban spaces, it is important to explore the performance of wireless UWB in outdoor settings.

Propelled by the abovementioned gap, this research aims to: (1) design a logistically practical and easy-to-install system configuration for wireless UWB for applications in outdoor settings, and (2) implement and test the performance of the designed configuration in an actual project. On this premise, the present paper reports on the first ever experiment, to the best of the authors' knowledge, with the wireless UWB in an outdoor environment in downtown Vancouver. It is believed that UWB technology has a high potential for tracking equipment and personnel in outdoor settings provided the logistical barriers are removed. Through a comprehensive case study and a thorough analysis of the performance of wireless UWB system, it is expected to (1) identify the potential and limitations of the systems, and (2) develop practical recommendations for the improved system setup and performances.

The structure of the paper is as follows: Section 2 presents the literature review on UWB and its application in construction industry. The setting of wireless UWB and the design of the experiment are explained in Sections 3 and 4, respectively. The analysis of the results is presented in Section 5. Finally, the conclusions are presented in Section 6.

2. LITERATURE REVIEW

Conventionally, the monitoring of construction projects and the measurement of Project Performance Indices (PPIs) are performed using manual methods of data collection, which are error-prone, time-consuming and costly (Navon and Sacks 2007; Azimi et al. 2011). The inadequacy of the traditional methods has led to the adoption of modern RTLS technologies, e.g., Radio Frequency Identification (RFID), *GPS*, Laser Detection and Ranging (LADAR), *UWB*, inertial based systems, video/audio capturing, etc., for the monitoring of construction sites (Peyret et al. 2000; Navon et al. 2004; Navon 2007; Navon and Sacks 2007; Alshibani and Moselhi 2007; Rebolj et al. 2008; Perkinson et al. 2010; Azimi et al. 2011; Golparvar-Fard et al. 2013, Akhavian and Behzadan 2013).

2.1 Real-time Location Systems in Construction

RTLS provides the real-time information about the location of assets. Malik (2009) describes RTLS as a system which enables users to manage and analyze the information regarding where assets or people are located. It is further explained that an RTLS consists of the following parts: (1) tags, which are attached to the assets; (2) sensors, which reads the tags' data; (3) location engine, which is a software used to localize the tags; (4) middleware, which connects the location engine data with a software application; and (5) end-user software application.

In recent years, RFID based RTLS has been used for construction equipment tracking. Montaser and Moselhi (2013) presented an RFID based automated methodology for tracking and estimating the productivity of scraper-pusher fleet operations. They used data from RFID sensors to calculate productivity of the scraper-pusher fleet and to report it to related personnel. Ding et al. (2013) proposed an RFID-based safety warning system in which personnel was tracked in underground cross passage construction sites. Although very promising, the average accuracy of RFID is still in the range of a few meters, which renders it suboptimal for safety-related applications.

GPS technology has also been used widely for tracking equipment on construction sites. For instance, Song and Eldin (2012) used the tracking information of construction equipment collected by GPS to perform near real-time simulation that can better predict the project's progress. Pradhananga and Teizer (2015) used GPS to track construction equipment and feed the simulation model for better productivity estimation and layout planning. Alshibani and Moselhi (2016) presented a method for estimating the productivity of earthmoving operations based on the integration of Geographical Information System (GIS) and GPS. GPS has commonly a better accuracy than RFID, although the accuracy greatly depends on the quality of the unit. High-end GPS units, which can provide sub-meter accuracy, are rather expensive to be used for tracking workers. Besides, the functionality of GPS relies on the clear line of sight to the sky, which may not be available in the dense urban environment.

Recent advancements in the field of computer vision have enabled researchers to explore the possibility of construction equipment tracking. Azar and McCabe (2012) proposed a computer vision based system for 3D pose estimation of excavators. Soltani et al. (2017) proposed an image processing based system for excavator pose estimation. Computer vision is very promising in terms of accuracy, versatility, and affordability. However, in the current state of the art, precision and accuracy of these systems are still not at the level required for robust safety-related systems.

2.2 Ultra-Wideband Real-Time Location System

UWB is a special type of RTLS which transmits and receives short duration pulse of Radio Frequency (RF) energy (Lee et al. 2009). Malik (2009) explains that UWB is a carrier-less radio technology that uses wide bandwidth (i.e. exceeding 500 MHz), and is normally used in short-range wireless applications. Malik (2009) also explained that UWB-based positioning has several advantages over other RTLS technologies, which include: high accuracy, better performance in challenging RF environments, no interference from other RF systems, and relative immunity to multipath fading. The immunity to multipath fading is because UWB pulses are narrow and occupy the entire UWB bandwidth. The early applications of UWB technology were primarily related to radar.

Each sensor gathers two types of information from the signal received from the tag: the angle of the signal, and the time when the signal is received (Maalek & Sadeghpour, 2013). The UWB system utilizes two positioning techniques to estimate the tag's position depending on the information received by the sensors, which are Angle of Arrival (AOA) and Time Difference of Arrival (TDOA). In the AOA technique, the angle of the arrived signal is measured at several sensors by routing the main lobe of a directional antenna or an adaptive antenna array. Each measurement forms a radial line from the sensor to the tag. For 2D localization, the location of the tag is defined at the intersection of two directional lines of bearing (Ghavami et al., 2004). In the TDOA technique, the difference in the arrived signal's time at two different sensors is calculated. Then, each time difference is converted to a hyperboloid with a constant distance difference between the two sensors, where the location of the tag is the intersection of the two corresponding hyperboloids (Ghavami et al., 2004). AOA has an advantage over the TDOA as it does not require synchronization of the sensors nor an accurate timing reference (Ghavami et al., 2004); however, TDOA requires more cabling for accurate timing reference.

2.3 Applications of UWB RTLS in Construction Management

Although UWB RTLS has several industrial applications, the focus of this section is to highlight the applications of UWB RTLS in construction management. As not much literature is available in this domain, the related literature is reviewed in detail.

Maalek & Sadeghpour (2013) conducted seven different experiments to assess the accuracy of location estimated by the UWB RTLS. For each experiment, they simulated various construction site scenarios which are related to: (1) the presence of metallic items within the monitored area, (2) UWB signal blockage, (3) metallic items tracking, (4) wireless mode of UWB system, (5) tracking multiple items, and (6) the effect of the number of UWB sensors (total of 8 sensors). They found that the phenomenon called Dilution of Precision (Langley, 1999; Mahfouz et al., 2008), which is related to the geometry of the cell, has a strong impact on the accuracy of the UWB system. They also found that the overall accuracy using only AOA measurements is less than 53 cm in 2D and less than 63 cm in 3D. As all the variables for these experiments were simulated in an indoor environment and all tracked items were in a static mode, the nature of real construction site, which is mostly outdoor and highly dynamic, can affect the UWB system's performance significantly.

Maalek & Sadeghpour (2016) conducted three sets of different experiments to assess the accuracy of the UWB RTLS in dynamic mode and to evaluate the effects of speed and heading on the accuracy of the estimated location of dynamic tags. They found that the accuracy is inversely proportional to the speed of tag, the number of tags and the complexity of tag's movement path. They also defined an approach of danger zones on construction sites through which they validated the feasibility of using static tags to define the boundaries of danger zones on construction sites. Their experiments showed that the UWB RTLS achieved an accuracy of less than 100 cm while tracking objects in a dynamic mode in indoor scenarios. Although the tracked items were in dynamic mode, all of the three experiments were conducted in an indoor environment and the wired UWB system was used for the experiments.

Saidi et al. (2011) also conducted several experiments to evaluate the static and dynamic performance of a UWB RTLS. Their focus was to design the testing of this type of RTLS for personnel applications in open-space and in realistic construction conditions. Moreover, they developed a mathematical static model for estimating position errors of this system. They also identified twenty three factors that influence the accuracy of the UWB system, which include the calibration error, hardware (antenna type, receiver orientation) and the tags' roll, pitch, and yaw angles. They suggested that the effect of the orientation (yaw angle) of the UWB tag is one of the most important factors. They found that the average 2D and 3D errors were 8.7 ± 1 cm and 46.6 ± 4 cm, respectively, where the averages of the standard error of the mean are represented by + or – intervals. As the 3D error is significantly larger than the 2D error, they suggested that several sensors must be mounted at different heights, at either equal or close to equal distance to each other, to minimize the 3D error. The system used by Saidi et al. (2011) was a UWB only based on TDOA and did not use AOA. They assumed the conditions to be ideal as they have minimal obstacles and reflections and have a good medium for RF signal propagation.

Cho et al. (2010) analysed the reliability of the wireless UWB system's data for tracking assets in indoor construction sites. They conducted static and dynamic tests in various building spaces. They also developed an error model to minimize the positioning errors of wireless UWB system using some statistical techniques including regression analysis, outlier detection, and Kalman filtering. While conducting these indoor tests, they kept at least one receiver in direct Line-of-Sight (LoS) from any location of the monitored area. They concluded that the accuracy of the UWB system is lower in dynamic and closed space situation than in static and open space situation. Furthermore, they validated that although the accuracy of the wireless UWB system is lower than the wired one, the wireless UWB system is still capable of tracking mobile assets in indoor construction sites with an accuracy of about 50 cm in a static condition and 65 cm in dynamic condition for a highly congested closed space. Although the wireless UWB system was used in this research, the analysis did not take into account the conditions of outdoor construction environment as the tests were conducted in indoor environments.

Zhang et al. (2012) proposed a post-processing method to improve data quality and transform the location data into useful information that can be used for near real-time decision support systems. Moreover, they tested the UWB system using the proposed method to estimate the pose of a crane and concluded that the pose of the crane boom can be estimated in near real-time using the UWB system. Although they performed a thorough analysis using the UWB system, they only used the wired UWB system.

Vahdatikhaki & Hammad (2014) proposed a framework based on the integration of UWB RTLS with a simulation model of construction operations in order to enhance the simulation model continuously by capturing motion information about a truck and an excavator. Their proposed framework provides a method for capturing, processing, analysing, filtering and visualizing the equipment states along with enhancing the accuracy of the equipment state-identification. The data processing is done by considering the equipment-specific geometric and operational constraints. Although their proposed framework is tracking-technology-independent and can work with various types of RTLS technologies, they used wired UWB system in an indoor environment to demonstrate the feasibility of their proposed framework.

Li et al. (2016) conducted a review of current applications of RTLS in construction. They studied 75 publications in total, out of which 17 were related to the use of UWB in construction. They found that the dependence of UWB system configuration on a wired local area network (LAN) is a limitation in construction environments considering the dynamic nature of construction sites and the presence of heavy equipment.

Azar & Kamat (2017) presented a review of technologies used for earthmoving equipment tracking. They classified earthmoving equipment automation into four main areas: (i) Equipment tracking and fleet management, (ii) Safety management, (iii) Equipment pose estimation and machine control technology, and (iv) Remote control and autonomous operation. They found that, for equipment tracking and fleet management, several latest research projects use UWB-based local positioning systems as they provide consistent and fairly accurate spatiotemporal data of the tagged equipment, but only within a limited range.

Teizer et al. (2008) evaluated the applicability of UWB technology for construction process automation. They found that UWB technology has the potential to improve logistics and safety at construction sites. They conducted indoor and outdoor experiments using a wired UWB system. From the indoor experiment, they found that the average absolute error for X and Y axes was 4.2 cm and 4.3 cm, respectively. Whereas, the maximum absolute error for X and Y axes was 21.1 cm and 13.5 cm, respectively. From the outdoor experiment, they concluded that UWB technology can be applied to construction operations, but the error was not estimated for the outdoor experiments.

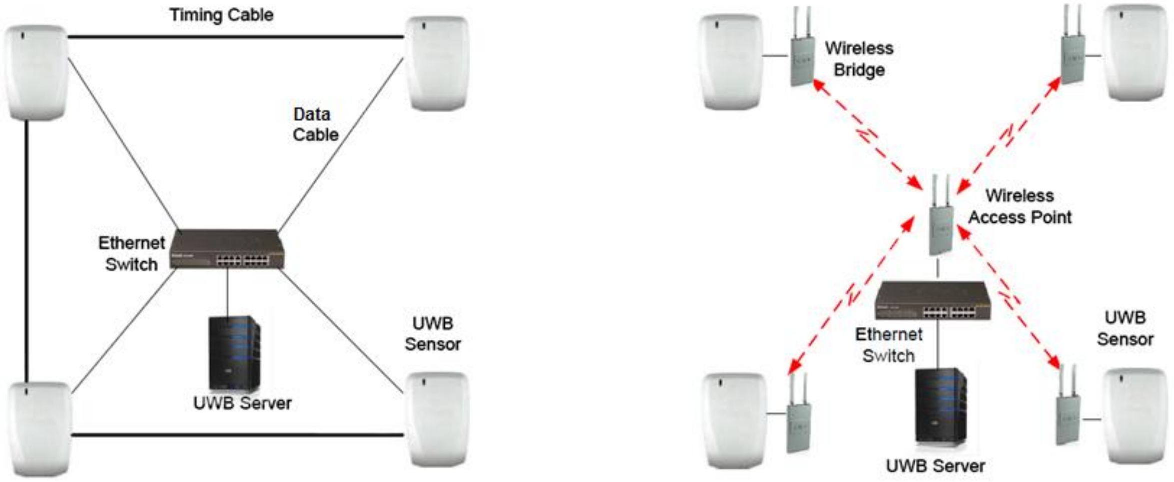
2.4 Data Enhancement Method

Vahdatikhaki & Hammad (2014) proposed a method to reduce the measurement errors in which sensory data is captured from the construction site and processed by the data processor. This Data Enhancement Method (DEM) focuses on adjusting the data according to the Geometric Constraints (GCs) and Operational Constraints (OCs), in which it is iteratively validated that a set of GCs and OCs are satisfied for each data point. The assumption of this method is that several UWB tags are installed on different parts of different pieces of the equipment and each tag has a unique ID.

This method is implemented using the following steps: (1) The UWB tags are grouped according to their geometric relationships with respect to the equipment to which they are attached; (2) each tag's data are averaged over a short period of time (Δt), which refers to averaging a tag's location over several points in time; (3) if there are any missing data it will be calculated using interpolation, which means that new data is created for the missing data points; (4) the data are corrected based on the OCs and the GCs, which refers to the iterative adjustment of the tags' data to ensure that a set of OCs and GCs are satisfied at every given point in time. The OC is applied so that the difference between two consecutive tag data entries does not violate the maximum operational speed limit of the equipment whereas the GC is applied based upon a fixed geometric relation between any given two tags attached to a rigid body; and (5) the data is further enhanced by representing several tags at an intermediate point by averaging several tags' data which are attached to the same rigid body.

3. DESIGN AND PREPARATION OF WIRELESS UWB

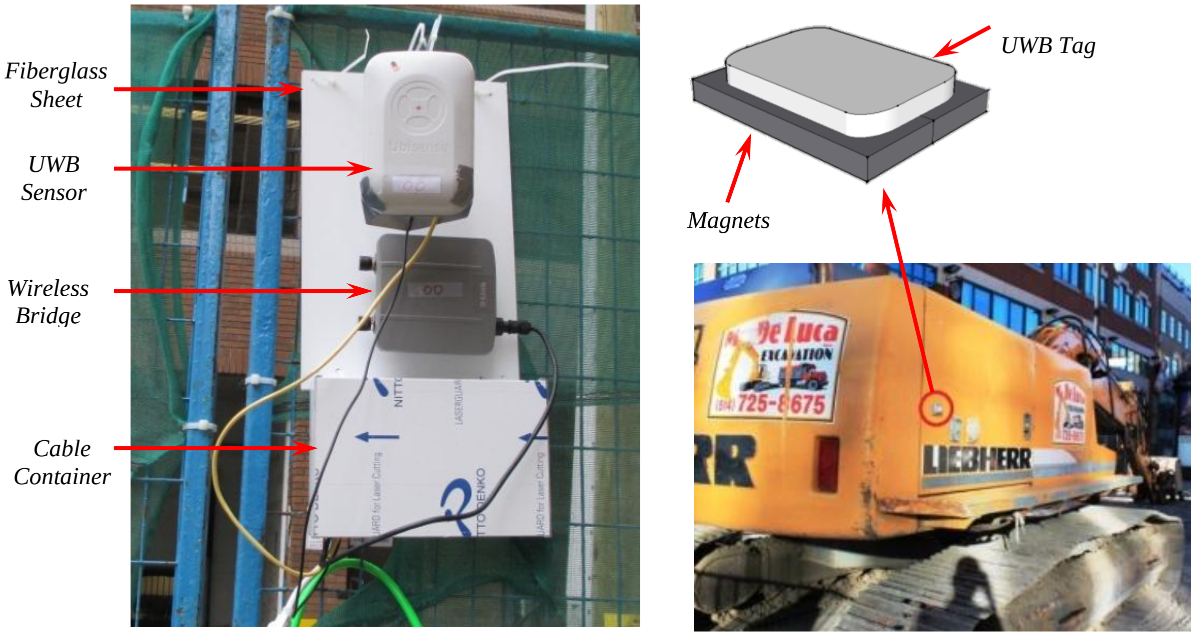
The UWB system used in this research is developed by Ubisense Group PLC (Ubisense, 2013a). This UWB system supports two modes, which are: the wired and the wireless. The settings of the wired and the wireless UWB systems are not similar, as shown in Figure 1. In the wired system (Figure 1(a)), all sensors are connected with each other through timing cables for the estimation of TDOA and are also connected to a network switch through data cables for the data communication of sensors with the server. Whereas in the wireless system (Figure 1(b)), each sensor is connected to the wireless bridge hence no timing or data cables are used.



(a) Wired System *(b) Wireless System*

FIG. 1: Schematic Diagrams of UWB Systems (adapted from Zhang et al., 2012b).

Setting up a UWB system requires several crucial steps including the placement of sensors and measuring their coordinates, configuration of the network connection, and configuration of various software components. For the purpose of faster, safer, and more efficient setup and application of wireless UWB, special ready-to-install sensor panels were designed, as shown in Figure 2(a). This design emerged out of the discussion with the site engineer who mentioned the safety concerns with regard to the installation of the wired UWB sensors within the site area. Each panel contains a UWB sensor, its corresponding wireless bridge and a cable container box that are securely bolted to a fiberglass sheet. These panels can be easily and securely attached to different surfaces such as concrete walls and fences.



(a) *(b)*

FIG. 2: (a) UWB Sensor Panel and (b) Tags with Magnets.

As shown in Figure 2(b), the UWB tags are prepared for attachment to the equipment by placing the tag on two pieces of magnets and binding them using heavy-duty duct tape. The previous works of the authors suggest that: (1) this arrangement is resilient enough to withstand the harsh construction working conditions without the risk of tags detachment or damages (Siddiqui et al. 2014) and (2) the magnets do not impact the accuracy of the UWB readings (Rodriguez 2010).

Several factors affect the performance of the UWB system, which are listed in Table 1. In terms of system settings, the wireless system is more critical than the wired system. As for the wireless system, appropriate settings of wireless bridges are essential because of the additional issues related to the stability of the communication between the sensors. The RF power and RF frequency of the wireless bridges should be selected according to the environment, as the RF frequency might have interference from the surrounding Wi-Fi networks, and the distance between the bridges and LoS requirement should be considered while designing the experiment. Previous work of the authors investigated the effect of wireless bridges in detail (Siddiqui et al. 2014).

TABLE 1: Factors affecting UWB System.

	Category	**Factor**
Connection-type-dependent	*Wired*	Cable connections
	Wireless	The line of sight between bridges
		RF frequency of bridges
		RF power of bridges
		Distance between bridges
Connection-type-independent	*Tag Type*	Compact
		Slim
	Tag Settings	Expected update rate vs. actual update rate
		Filtering algorithm and parameters
		Total number of tags used in the test
		Strategic placement of tags (elevated tag gives a better result)
	System Settings	Number of sensors
		Size and geometry of cell / Dilution of Precision
		Measurement of location and orientation of sensors
		Quality of calibration and measurement of the location of Tag
	Environment	RF Noise
		Object to be tagged (Metallic/Non-metallic/Humans)
		Objects present in the monitored area (Metallic/Liquid/Humans)
		The line of sight between sensors and tags

It is also important to select the right type of tags for each environment. The compact tags are suitable for tracking equipment, whereas for workers, slim tags are preferable. Furthermore, appropriate tag settings can improve the performance of the UWB system. The Expected Update Rate (EUR) of tags is critical and should be selected based on the total number of tags present in the UWB covered area. For the UWB system used in this research (Ubisense 2016), each second is divided into 153 time slots where the length of each time slot is 7.453 msec. The highest EUR which can be selected is 33.54 Hz which requires four time slots (Slot Interval = 4). To achieve this EUR, a maximum of four tags should be present in the UWB covered area. As the number of tags increases, the EUR will decrease in order to allow the system to log all tags' location. For example, if the EUR is set to maximum but eight tags are present in the UWB covered area, the EUR would automatically be decreased to 16 Hz. Another concern when setting the EUR is the moving velocity of the tagged objects. Objects with high velocity need more frequent updates to accurately track their traces. Therefore, it is essential to select a suitable number of tags with an appropriate EUR based upon their velocity (Zhang et al., 2012). Furthermore, strategic placement of tags is also very important, as elevated tags yield better performance (Maalek & Sadeghpour 2013, Saidi et al. 2011).

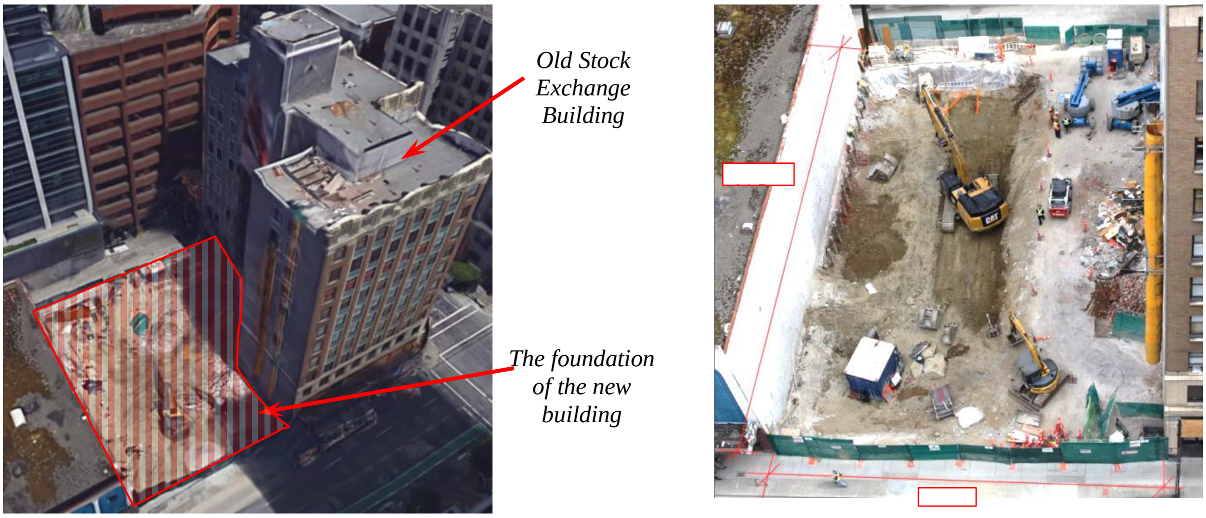
Another significant factor related to tag settings is filtering. The data from the UWB sensors are filtered to remove the noise and minimize the location errors. The UWB system, used in this research, supports four types of Information Filters (IF) which estimate a tag's current position by using its previous motion (Ubisense, 2016) and each variant of the IF has a number of parameters that control the behavior of the filter, out of which 12 parameters are common to all types of IF. One of the 12 common parameters is Minimum Reset Measurements (MRM) which represents the minimum number of supporting measurements required. A single measurement can be either an azimuth, an elevation, or a TDOA between two sensors (Ubisense, 2016). In the wired setting, if two sensors see a tag, there will be five measurements (azimuth and elevation from each sensor, plus a TDOA) whereas in the wireless setting, if two sensors see a tag, there will be four measurements (just the azimuth and elevation from each sensor), as there is no TDOA in the wireless setting.

Another important factor that affects the overall performance of the UWB system is the number of UWB sensors used to monitor the area. Moreover, the size and geometry of the sensor cell are very critical since the phenomenon of Dilution of Precision also has a strong impact on the location accuracy (Maalek & Sadeghpour 2013). It is preferable that the sensor cell would be in a square-like geometry. The performance of the UWB system is also sensitive to the orientation and the measurement of the locations of sensors and the location of the calibration tags.

Finally, it is essential to assess the environment where the UWB system would be used. The RF noise present in the environment could affect the accuracy of estimated locations. Furthermore, the materials of objects to be tagged and the objects present in the environment have an impact on the performance of the UWB system.

4. DESIGN OF EXPERIMENT

This test was conducted at a construction project in downtown Vancouver. In this project, a new high-rise building called The Exchange is to be built next to the already existing Vancouver's Old Stock Exchange building, as shown in Figure 3(a). At the time of the case study, the project was at the phase of excavating the foundation of the new building. The total area of the site is about 36.5 m x 24 m, and is surrounded by walls on two sides and by fences on the other two sides, as shown in Figure 3(b). This picture was provided by the site engineer before the site visit. As it can be seen in this figure, one large excavator and one small excavator were performing earthmoving operations. However, when the site was visited on Monday, June 23, 2014, two large excavators were present in the site area along with a large crane, as shown in Figure 4(a). At that time, these equipment were working on the demolition of a concrete chimney in the neighboring building rather than performing earthmoving operations. This was a setback for the UWB data collection process as the heavy-metallic body of the large crane was a significant source of radio noise for the wireless UWB system. The demolition process was carried out for two consecutive days and the crane left the site on the third day. The test was conducted for two days, i.e. from Wednesday, June 25, 2014, to Thursday, June 26, 2014. The site conditions on each day are shown in Figure 4.



(a) *(b)*

FIG. 3: (a) Side View of the Project from Google Earth, and (b) Top View of the Excavation Site (the picture is taken a month before the case study)

(a) Day 1 *(b) Day 2*

(c) Day 3 *(d) Day 4*

FIG. 4: Site Conditions for Each Day of the test period

For localizing the excavator using the wireless UWB system, four UWB sensor panels were initially attached to the fences covering an area of about 36.5 m x 22 m. The UWB workstation was set up on the second floor of the existing building to avoid the expected rainy weather. Two UWB sensors were powered by two separate power generators whereas the other two sensors were powered by cables extending from the existing building. The measurement of the sensors' position was done with the help of the surveying team, which used a total station. The surveying team provided the sensors' positions in the Easting and Northing Coordinate System (ENCS). The coordinates were transformed to a local coordinate system. After the installation of the sensor panels, the wireless UWB system was calibrated. At that time, the surveying team was not available; therefore, the calibration tag's position was measured using a measuring tape. This measurement was not easy as the excavators and the crane were performing the scheduled tasks. The calibration of the wireless UWB system was difficult because some of the UWB sensors were unable to detect the calibration tag. The reasons for this were the presence of a large excavator in the middle of the site which blocked the view of sensor S1 and a metallic storage room. Therefore, this sensor panel was relocated to another part of the fence and then the calibration was performed again. After this relocation, the UWB covered area became about 36.5 m x 20 m, as shown in Figure 5.

The positions of tags on the excavator are shown in Figure 6. The EUR of the tags was set to 4.19 Hz as almost 32 tags were present in the monitored area, and Static IF was used with all the default settings except MRM, which was set to 3. Furthermore, an Internet Protocol (IP) based camera was also installed on the site to have a complementary source of data for visual validation of the results of the UWB system. The data from both data sources were recorded for almost two days.

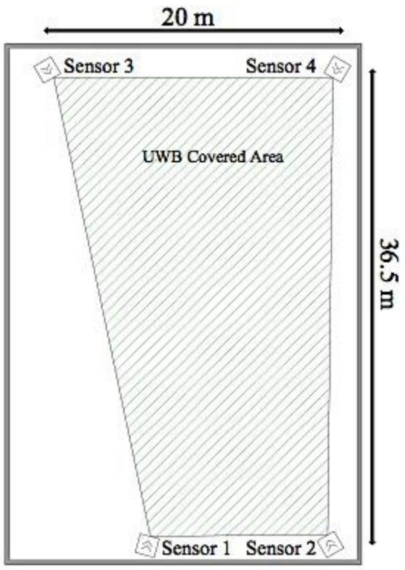
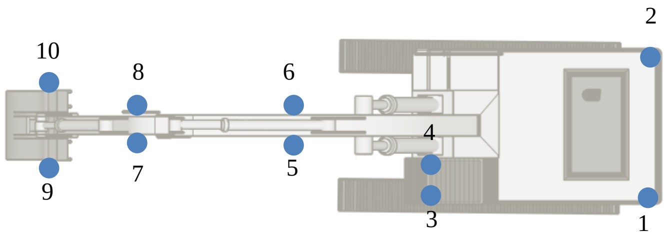
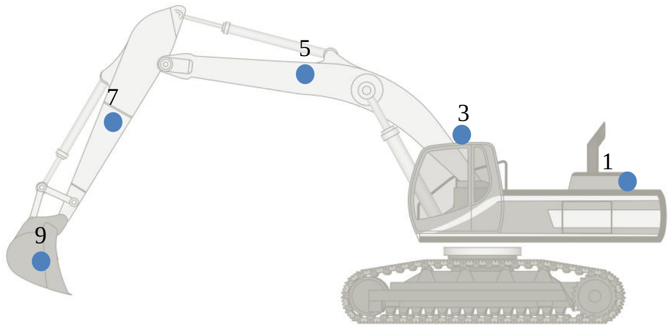


FIG. 5: The UWB Cell



(a) Top View



(b) Side View

FIG. 6: Position of Tags

5. RESULTS AND ANALYSIS

The data are analyzed in the 2D x-y plane. In order to demonstrate the analysis method, two separate three-minute periods of the test were analyzed. The first period was on Day 4 from 12:52 PM to 12:54 PM, when the excavator was stationary and not performing any operations; whereas the second period was also on Day 4 from 11:27 AM to 11:29 AM, when the excavator was not stationary and performing an operation.

5.1 First Period Analysis

Initially, the Actual Update Rate (AUR) and Missing Data Rate (MDR) of each tag are analyzed and presented in Table 2. It can be observed that, for some tags, the AURs are very low compared with the EUR, whereas for some tags, the AUR is less but satisfactory. Moreover, out of 10 tags, the MDR for 5 tags (Tag 1, 6, 8, 9 and 10) is more than 90% and for these tags, the AUR is less than 1 Hz. However, for the remaining 5 tags (Tag 2, 3, 4, 5 and 7), the AUR is more than 1 Hz and the MDR is also acceptable. The best performance is of Tag 3 with an AUR of 3.20 Hz and an MDR of 23.55%. One explanation for this inconsistency between tags' performance can be that during this period the excavator was near to sensors S1 and S2 and its side, where the tags with the higher AUR were attached, was facing these two sensors providing more visibility. For further analysis, the five tags with satisfactory performance, in terms of AUR and MDR, are considered. As during this three-minute period the excavator was stationary, its tags' coordinates are expected to be at the same point for the whole duration. Therefore, statistical analysis was applied to the data from these five tags. Table 3 presents the mean position and the standard deviation of the tags' x and y coordinates. From this table, it can be noted that the standard deviation for Tag 2 is high, i.e. an error of more than a meter in the x-direction and an error of almost a meter in the y-direction; whereas for Tags 3, 4, and 5, the standard deviation is satisfactory. Furthermore, the standard deviation for Tag 7 corresponds to an error of about 0.5 meter in both directions. The same information can be shown by visually inspecting the data points from these tags, as shown in Figure 7. From this figure, it can be observed that the data points for Tag 2 are very scattered, whereas the data points for Tags 3, 4, and 5 are more concentrated. Lastly, the data points for Tag 7 are also scattered but not as scattered as the data points of Tag 2.

TABLE 2: AUR & MDR Analysis for Period 1

Tag	AUR (Hz)	MDR (%)
1	0.16	96.29
2	1.28	69.53
3	3.20	23.55
4	2.09	50.18
5	2.38	43.56
6	0.20	95.10
7	1.84	56.28
8	0.33	92.58
9	0.16	96.95
10	0.07	98.15

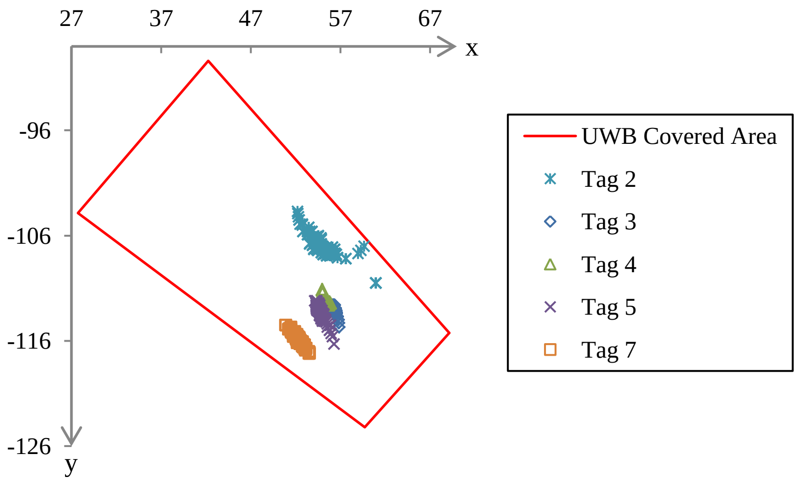


FIG. 7: Data Analysis of Five Tags for Period 1

After this analysis, the orientation of the excavator was estimated for this three-minute duration using the data from the wireless UWB system. The data from the same five tags (i.e. Tag 2, 3, 4, 5 and 7) were processed. As the AUR for each of these tags is more than 1 Hz, each tag's data were averaged over a period of 1 second for the whole duration of 3 minutes. Tags 3 and 4 were in close vicinity and Tags 5 and 7 were on a line parallel to the boom; therefore the data from these two pairs were averaged. This processing resulted in three different data points for each second, which are the positions for Tag 2 ($\boldsymbol{p_2}$), Tags 3 & 4 ($\boldsymbol{p_{3\text{-}4}}$), and Tags 5 & 7 ($\boldsymbol{p_{5\text{-}7}}$). The expected orientation based upon these three positions is shown in Figure 8. In order to estimate the orientation of the excavator, a scatter plot of these data points was drawn for each second. Figure 9 shows the scatter plots for the first 3 seconds and the last 3 seconds of the whole three-minute duration. Based on the visual comparison with the video, it was observed that the orientation estimated by the wireless UWB system is almost the same as the expected orientation. It can be further noted that the data of Tag 2 ($\boldsymbol{p_2}$) are scattered over a larger area, which is also clear from the standard deviation shown in Table 3.

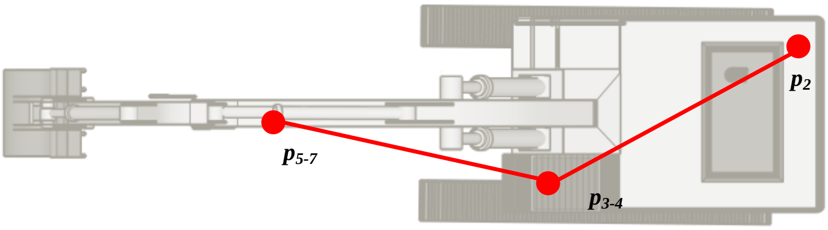


FIG. 8: Schematic View of Orientation of Excavator (Excavator image is taken from Google, 2014)

TABLE 3: Mean and Standard Deviation Analysis for Period 1

Tag	**Mean Position (m)**		**Standard Deviation (m)**	
	x	**y**	**x**	**y**
2	55.14	-107.06	1.37	0.92
3	56.24	-112.87	0.13	0.18
4	55.57	-112.33	0.13	0.17
5	54.81	-113.33	0.28	0.49
7	52.32	-115.84	0.52	0.55

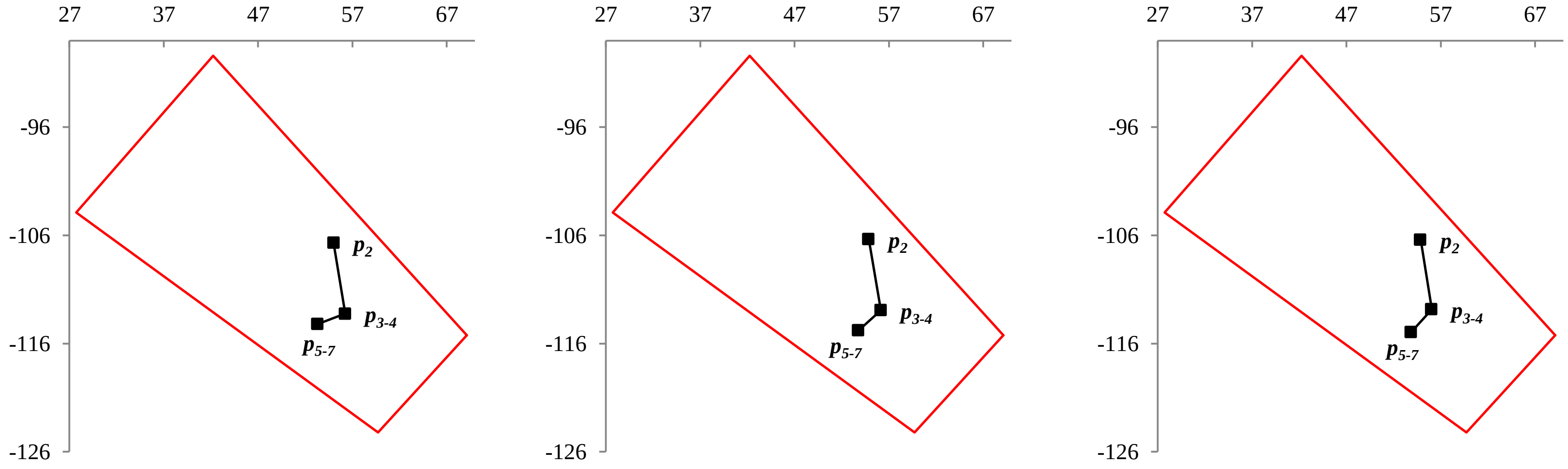
In addition to this visual analysis, a statistical analysis was conducted based on the angle between the lines formed by joining Tags 2 and 3 and Tags 5 and 7, as shown in Figure 10. The distance between Tag 1 & Tag 2 (d_{12}), and Tag 1 & Tag 3 (d_{13}) were measured using a measuring tape at the time of installation of tags on the excavator as 2.63 m and 3.65 m, respectively.

The expected angle (θ_e) between lines l_{23} and l_{13} is calculated using Equation 1, which resulted in an angle of 35.78°.

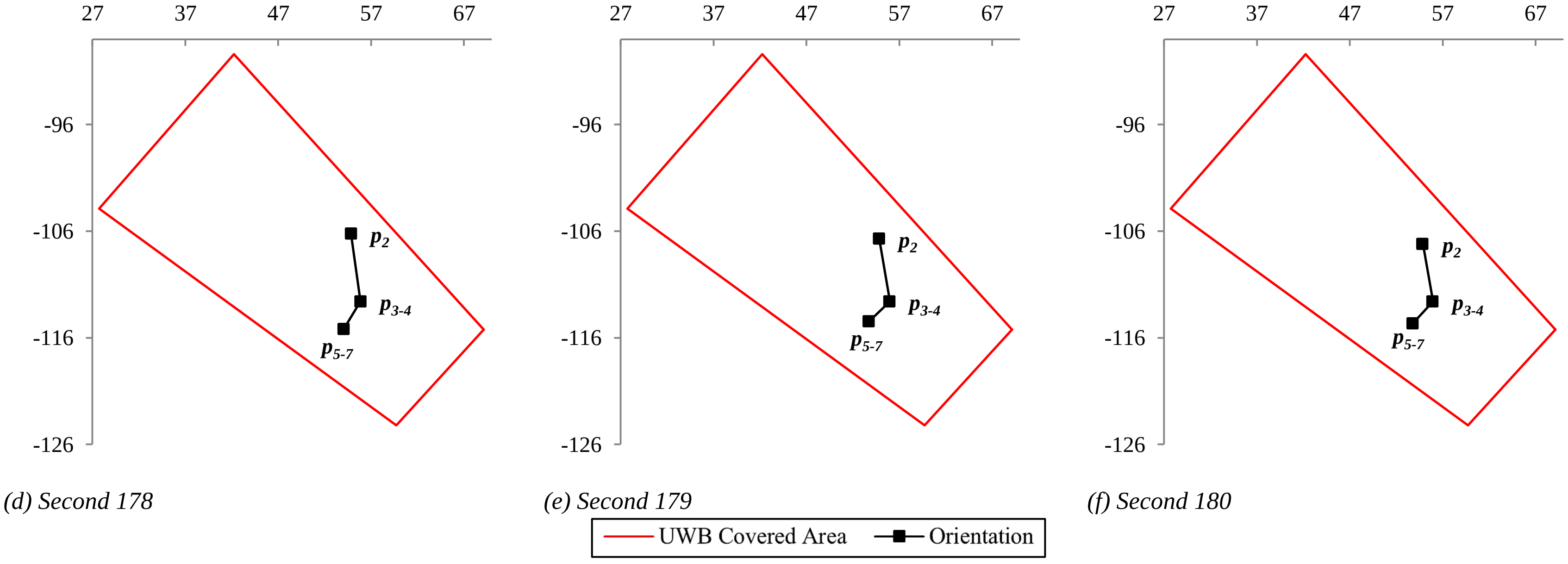
$$\theta_e = tan^{-1}\frac{d_{12}}{d_{13}} \qquad \text{Equation 1}$$

As the data from Tag 5 and Tag 7 are better than the data from Tag 1 and Tag 3, the angle between lines l_{23} and l_{57} is considered as the actual angle (θ_a), see Figure 11, and is compared with θ_e. The calculation of θ_a was performed in three steps using the individual UWB tag's data which were averaged over a period of 1 sec for the whole three-minute period. These steps are: (1) calculate the angle of l_{23} (α) with the local x-axis; (2) calculate the angle of l_{57} (β) with the local x-axis; (3) calculate $\theta_a = \alpha - \beta$.

Finally, the mean and the standard deviation of the error (ε) between θ_e and θ_a ($\varepsilon = \theta_a - \theta_e$) were calculated, which were found to be 19.83° and 17.88° respectively. Additionally, the error distribution for this accuracy assessment was investigated, as shown in Figure 12. From Figure 12, it can be observed that 85.5% of the error is distributed within the range of -5° to 40°.



(a) Second 1 *(b) Second 2* *(c) Second 3*



(d) Second 178 *(e) Second 179* *(f) Second 180*

FIG. 9: Scatter Plots for Orientation of Excavator – Period 1

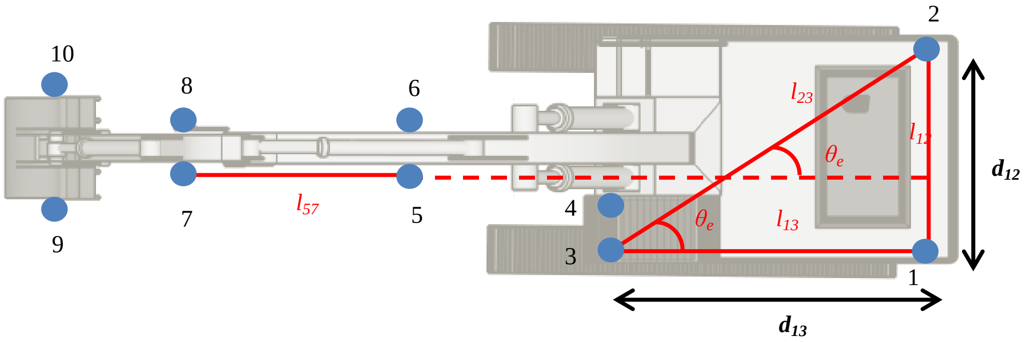


FIG. 10: Angle Calculation for Accuracy Assessment (Excavator image is taken from Google, 2014)

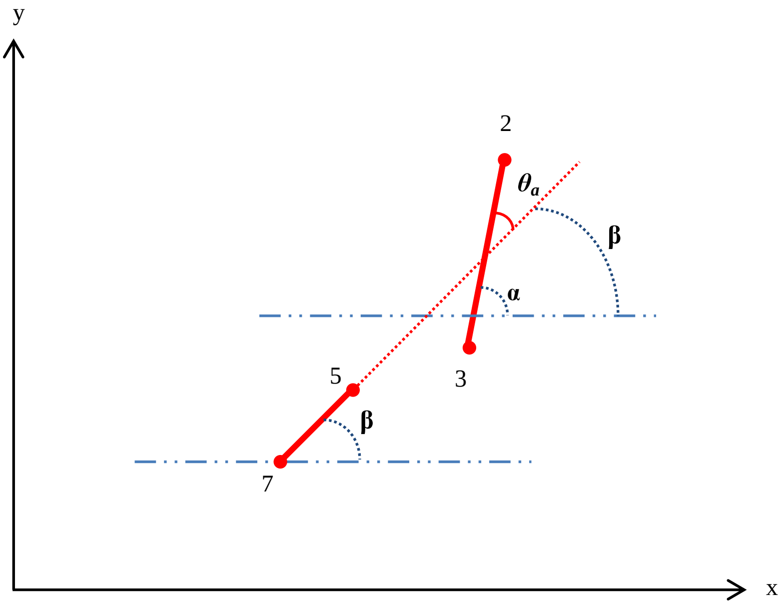


FIG. 11: Actual Angle (θa) Calculation for Accuracy Assessment

5.2 Second Period Analysis

During the second three-minute period, the excavator moved a piece of pipe from one place to another. During the first minute, the excavator moved forward and then waited there while a worker attached the pipe to its boom. During the second minute, the excavator moved backward and then swung its boom by almost 180°. Finally, during the last minute, the excavator was stationary while a worker was detaching the pipe from its boom.

Initially, the AUR and MDR of each tag are analyzed and presented in Table 4. It can be observed that out of 10 tags, the MDR for 5 tags is more than 80% and the AUR is less than 1 Hz. However, for the remaining 5 tags (Tag 1, 2, 3, 4 and 5), the AUR is more than 1 Hz and the MDR is also acceptable. The best performance is of Tag 4 with an AUR of 1.19 Hz and an MDR of 71.65%. For further analysis, the data of the five tags with better performance are considered. The tracked movement of the excavator, during the three-minute period, was analyzed as shown in Figure 13. For this analysis, one location was extracted from the data of the five tags with an AUR of more than 1 Hz; by first averaging each tag's data over a period of 1 sec and then averaging all five tags' data. From Figure 13, the working area of the excavator can clearly be identified and it can also be observed that it was not stationary.

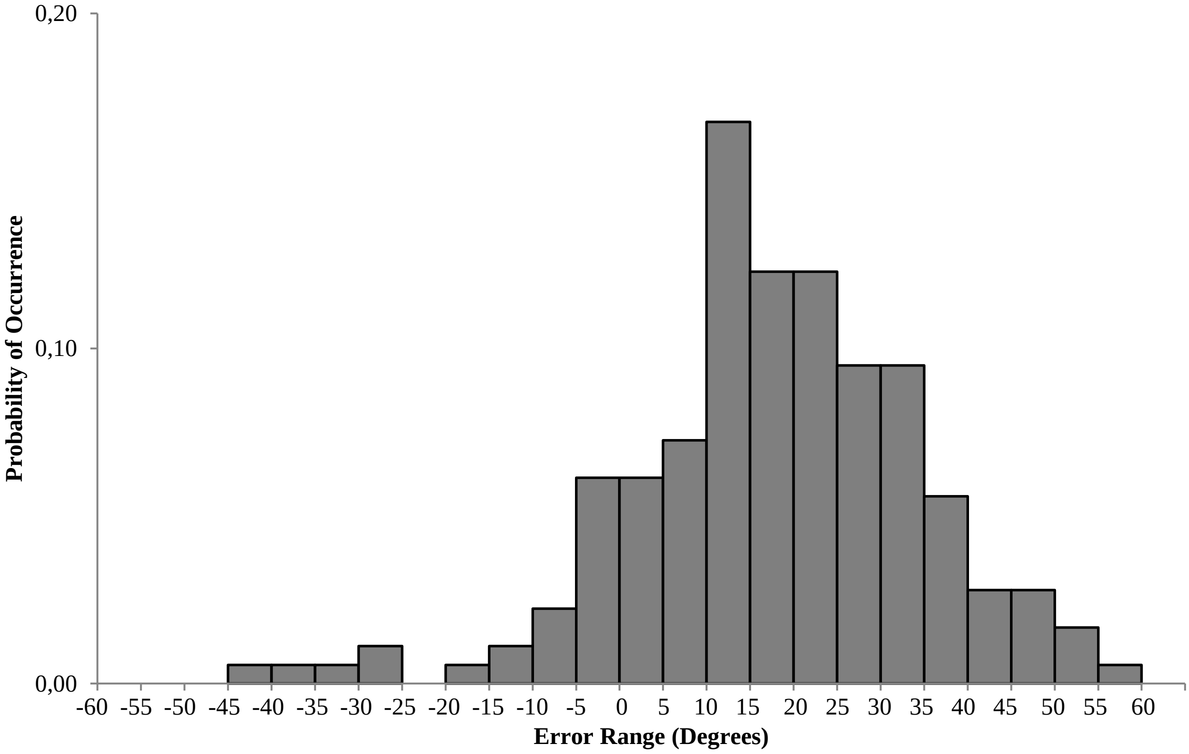


FIG. 12: Error Distribution for Orientation Accuracy Assessment – Period 1

TABLE 4: AUR & MDR Analysis for Period 2

Tag	**AUR (Hz)**	**MDR (%)**
1	1.07	74.56
2	1.15	72.71
3	1.14	72.84
4	1.19	71.65
5	1.07	74.43
6	0.14	96.82
7	0.76	82.11
8	0.23	94.57
9	0.83	80.26
10	0.29	93.24

Furthermore, the orientation of the excavator estimated by the wireless UWB system was analyzed using the data from Tags 1, 2 and 3. As for each of these tags, the AUR is more than 1 Hz, the data were averaged over a period of 1 second. The expected orientation, based upon these three positions, is shown in Figure 14. The scatter plot for these data points was drawn for each second. Figure 15 shows the scatter plots for 3 seconds from the first minute and 3 seconds from the last minute. As the excavator was not stationary during this three-minute period, the actual positions of the excavator during the first minute and the last minute are not the same. These actual positions are shown in Figure 16. Based on the visual comparison with the video, it was observed that the orientation estimated by the wireless UWB system is almost the same for the first minute as the expected orientation; however, for the last minute, the estimated orientation is not similar. One reason for this error in the UWB data can be that during the last minute the excavator was at the edge of the UWB covered area.

Moreover, to assess the orientation accuracy of the wireless UWB system, further analysis was conducted based on the angle between the lines formed by joining Tags 1 and 2 and Tags 1 and 3, as shown in Figure 14. The expected angle (θ_e) between these two lines is 90°. The actual angle (θ_a) was calculated using the individual UWB tag's data which were averaged over a period of 1 sec. The mean and the standard deviation of the error (ε) between θ_e and θ_a ($\varepsilon = \theta_a - \theta_e$) were calculated, which were found to be 8.09° and 34.8° respectively. Additionally, the error distribution for this accuracy assessment was investigated, as shown in Figure 17. From Figure 17, it can be observed that 57% of the error is distributed within the range of -25° to 25°.

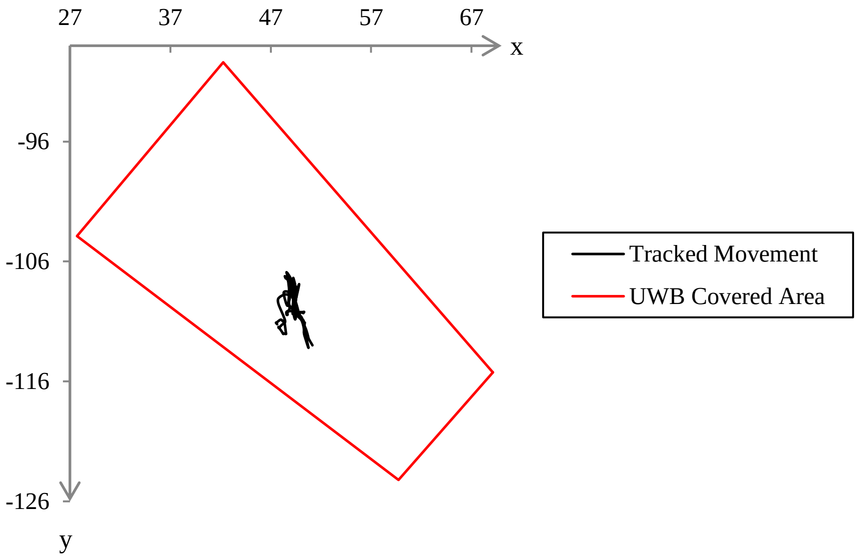


FIG. 13: Tracked Movement of Excavator for Period 2

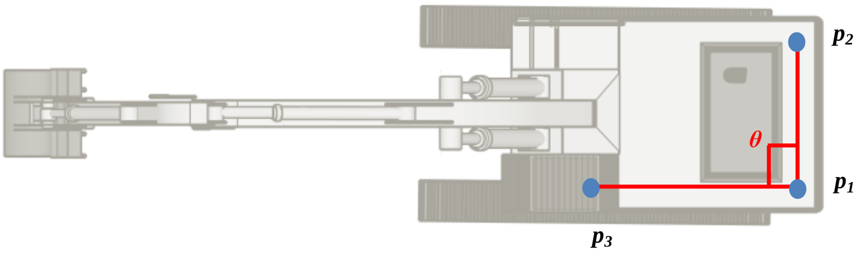
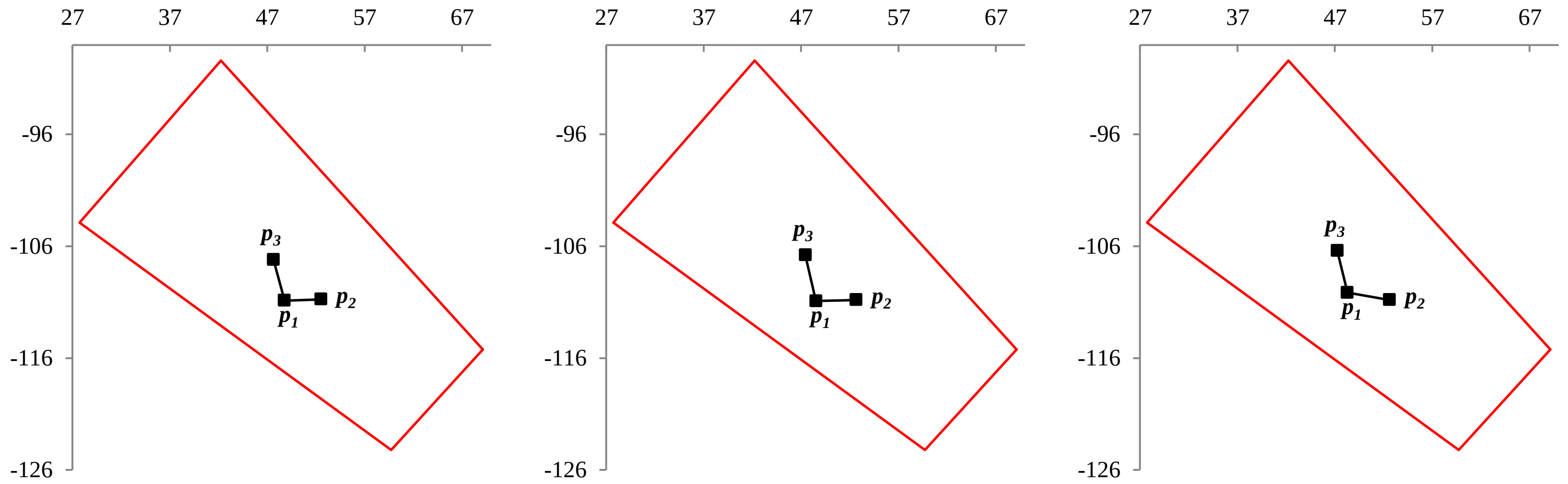


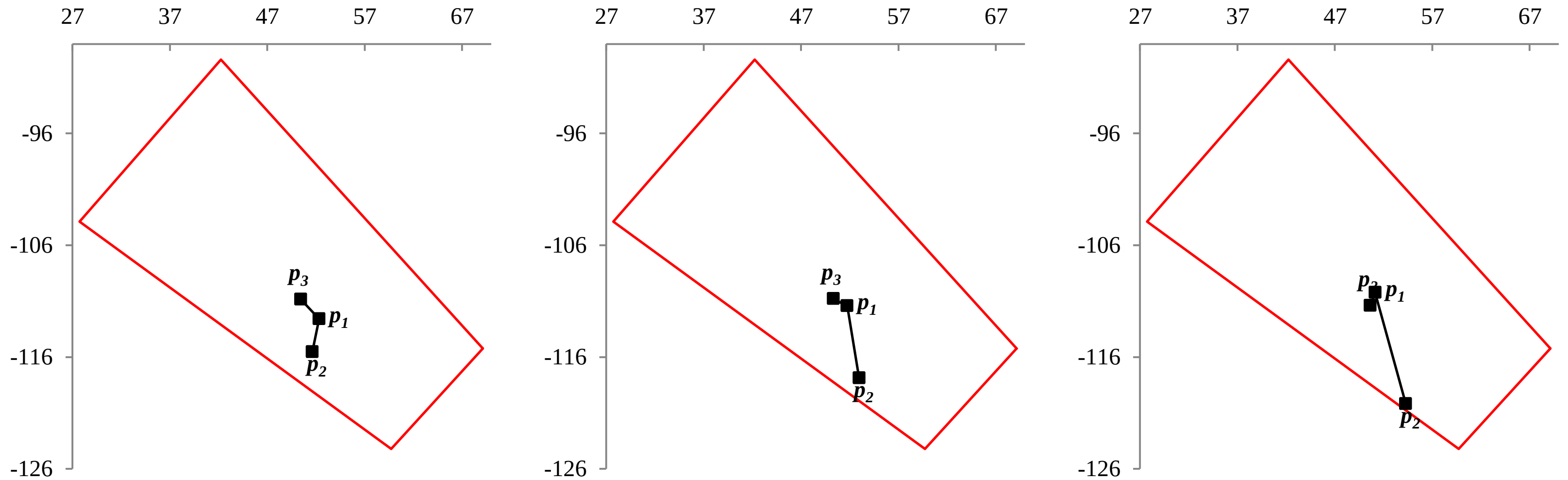
FIG. 14: Schematic View of Orientation of Excavator for Period 2 (Excavator image is taken from Google, 2014)



(a) Second 30

(b) Second 31

(c) Second 32



(d) Second 166

(e) Second 167

(f) Second 168

FIG. 15: Scatter Plots for Orientation of Excavator – Period 2

(a) First Minute *(b) Last Minute*

FIG. 16: Excavator Position

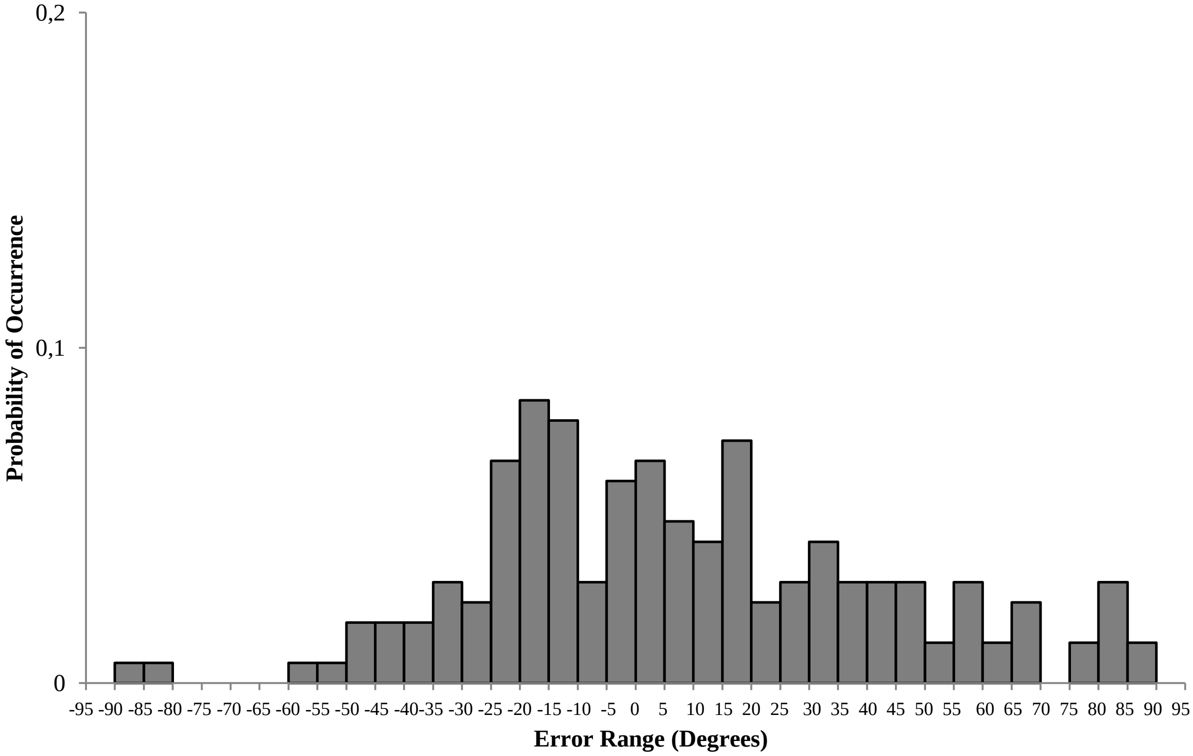


FIG. 17: Error Distribution for Orientation Accuracy Assessment – Period 2

6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This research reports on the application of the wireless UWB RTLS for localizing construction equipment on a congested construction site for a high-rise building project in downtown Vancouver. Special ready-to-install panels were designed to package all the hardware components of wireless UWB in such a way that the installation can be done with minimal disruption of the project. The performance of the wireless UWB system was analyzed using pose estimation methods. The setting and installation of the wireless UWB are proven to be successful under the harsh construction site conditions. It is demonstrated that the designed UWB system configuration has a great potential for making the system logistically practical and user-friendly for outdoor tracking of construction equipment and assets. Given that the wireless setting of the UWB for outdoor application was tested for the first time, a side-by-side comparison with the results of other research is not feasible. However, by looking at the results obtained by Teizer et al. (2008) and Maalek and Sadeghpour (2016), it can be concluded that the accuracy obtained in this research is marginally lower. This can, to a great extent, be attributed to the planning and set up of the system, which was hampered by ongoing activities on the site. The case study revealed some other limitations of the wireless UWB in the context of construction sites. Some of these limitations are inherent to the general use of the technology:

- The installation of the system requires thorough preparation; and therefore it is necessary to consider the application of the UWB in the planning phase of the project;
- Although it is not rigorously tested in this study, the presence of large metallic objects in the vicinity of the tags is believed to introduce some noise into the data. The application of robust noise reduction techniques can be considered to contain the detrimental effect of metallic objects.

There are also a few observations about the wireless setting of UWB in outdoor applications:

- The wireless setting of UWB reduced the installation time of the system considerably, but still, it requires some space in the schedule of the project.
- The data from the wireless UWB system should be enhanced using a suitable data enhancement method in order to accurately track the movement of the tagged object. However, high MDR limits the benefits of data enhancement methods and degrades the data.
- The wireless UWB system has high MDR compared to the wired system. The reason is that it uses only AOA estimation technique which reduces the number of readings which are required for the filter to calculate the location. Additionally, the wireless bridges are a vital component of the wireless UWB system and their correct configuration is essential.
- The calibration process is less controllable in construction sites, and small angular errors in calibration can result in larger positioning errors due to the large scale of construction sites.

In the lights of the above observations, the following lessons are learnt:

- Using more tags on each piece of equipment can provide more data so that if some tags have high MDR, the other tags' data can be used for positioning that piece of equipment. Nevertheless, it must be considered that the increase in the number of tags covered by a cell of UWB sensors reduces the EUR. One method to keep the balance between the number of tags and the EUR is to cover more tags in smaller cells. For example, rather than making one cell containing 8 sensors, two cells each containing 4 sensors can solve the problem of the limited EUR.
- Using more UWB sensors can provide more visibility, and therefore more readings to the filter for accurately calculating the locations.
- The timely availability of the surveying team is very important for accurate system calibration, which requires effective coordination with the site team and management.
- In addition, to overcome the limitations imposed on the performance of the wireless UWB system by the harsh environment of construction sites, it is anticipated that fusing data from a complimentary sensory data source, e.g. video, can further enhance the localization of the construction equipment.

The above lessons can be used by researchers and practitioners to further improve the performance of wireless UWB for tracking equipment on congested construction sites. The future efforts can be directed towards: (1) using more UWB sensors in a cellular architecture to monitor large construction sites; and (2) using another sensory source to capture equipment's location (e.g. video recording and computer vision techniques) and fusing data from both sensory sources (i.e. UWB and Computer Vision) under the Multi-Sensor Data Fusion model to improve the location accuracy.

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