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FEASIBILITY INVESTIGATION AND ACCURACY ASSESSMENT FOR A NEW GENERATION UWB TRACKING SYSTEM

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Abstract: The applications of Real Time Location estimation Systems (RTLS) showed strong potential in automatically monitoring construction sites for safety and productivity management in the past decades. Ultra-Wide Band (UWB), as one of the RTLS systems, has demonstrated great suitability for construction site conditions due to its higher accuracy, lower dependency on the Line-Of-Site, less signal attenuation and multipath effect in comparison. Nonetheless, the difficulty of relocating and reconfiguring the readers, requirements for time cables between readers for time synchronization, as well as the large cost of the system, greatly decrease the practicality of its use on construction sites. In recent years, a new-generation UWB RTLS has emerged that seems to overcome all these shortcomings of previous systems. The objective of this study is to investigate the feasibility of using the new generation of UWB RTLS on construction sites and evaluate its accuracy compared with the previous generations. The specific subobjectives of this study are to (1) measure the location estimation accuracy of the new generation UWB RTLS in static mode; (2) investigate the impact of Line-Of-Site and signal blockage on its accuracy; (3) investigate the effect of speed on dynamic accuracy. Natural neighboring interpolation algorithm was utilized for error distribution. A robotic Total Station was synchronized with the UWB RTLS in the dynamic experiment to provide real-time actual locations. The results showed high static and dynamic accuracy, less signal attenuation, easy installation and less computation complexity, which concluded the great applicability of the new generation UWB RTLS in construction sites.

1 INTRODUCTION

Safety issues are an inherent concern in construction sites. Assuring a safer working environment is a never-ending endeavor in construction projects. The dynamic characteristics of construction sites increases the probability of injuries occurring and the complexity of monitoring the potential hazards (Shahi et al., 2012). The injury rates in Alberta have a general trend of decreasing in the past five years (OHS, 2017). Nevertheless, there is still a large number of people being injured every year in construction sites; only in 2017, a total amount of 9089 disabling injury claims concerning construction and construction trade services was officially documented by the government of Alberta (OHS, 2017). Thus, it could be concluded that solely depending on standard policies is insufficient to prevent potential injuries.

Studies in the past decades have shown Real Time Location estimation System (RTLS) has great potential industrial applications in reducing possible injuries caused by collisions between equipment and equipment, equipment and workers as well as a worker's reaching a certain perilous height or region (Zhang et al., 2012, Carbonari et al., 2011). Different tracking technologies including Global Position System (GPS), Radio Frequency Identification (RFID), Bluetooth, Wi-Fi and Ultra-Wide Band are typically used in RTLS. Ultra-Wide Band (UWB), among all the RTLS tracking systems, has demonstrated the best suitability for construction site conditions due to its higher accuracy, lower dependency on the Line-Of-Site, less signal attenuation and multipath effect (Cheng et al., 2011). However, traditional UWB RTLS required relatively complex configuration due to the requirements of reference tags for calibrations and cables between readers for time synchronization used for Time Difference Of Arrival (TDOA) (Li et al., 2016). In addition, the UWB systems are expensive, which greatly reduced the practicality of their application in construction sites (Li et al., 2016).

All aforementioned shortcomings of previous systems are overcome by a new-generation UWB RTLS. What need to investigate next is whether the new UWB RTLS can achieve the same or even better performance in other important properties including accuracy and blockage effect. Therefore, the following three objectives are the dominant factors for industry application: (1) measure the static mode location estimation accuracy of the new generation UWB RTLS; (2) investigate the impact of Non-Line Of Site (NOLS) and signal blockage on accuracy; (3) investigate the effect of speed on dynamic accuracy.

2 LITERATURE REVIEW

UWB RTLS operates with relatively very large bandwidth (spectrum>500 MHz), which translate to high accuracy, high signal penetration capability, as well as low-power consumption (Jiang et al., 2011). This is promising for applications especially in congested environments, where other RTLS tracking technologies like GPS, Wi-Fi and Bluetooth suffer from inaccuracy due to multipath and signal attenuation (Chehri et al., 2009). However, conventional UWB systems confront many difficulties in the practicality of using them in construction sites.

2.1 Location estimation method

In the previous studies, TDOA (Time Difference of Arrival) or the combination of AOA (Angle of Arrival) and TDOA (Time Difference of Arrival) are typically utilized by UWB RTLS for location estimation (Khoury et al. 2009, Shahi et al. 2012, Maalek and Sadeghpour, 2013, Zhang et al. 2012, Giretti et al. 2009, Carbonari et al. 2011, Saidi et al. 2011, Andolfo 2016, Cho et al. 2010, Cheng et al. 2011). The tags broadcast UWB signals to difference directions and the anchors record the exact time when signals arrive. All anchors are synchronized and thus the time difference of arrival could be calculated. With an assumed constant UWB signal transmission speed in the air, the anchor could calculate the distance difference between anchors. For an arbitrary tag location, its distance difference between two anchors are constant, which is the definition of hyperbolas. By applying at least three anchors, the three hyperbolas' intersection is the estimated location. TDOA algorithm could achieve approximately 8cm high accuracy (Saidi et al. 2011).

Nevertheless, anchors tend to have clock drift and result in inaccurate time difference calculation. Therefore, in order to achieve time synchronization, all the anchors are connected via a precise time cable. This could interfere the movements of equipment with a certain height like cranes and increases the difficulties of anchor configurations during dynamic construction sites. Besides, optimizing the anchor locations in three dimensions could achieve better Line Of Sight (LOF) and higher accuracy. The time cables limit the space for anchor locations including ceiling, ground, or columns.

2.2 Calibration

Many experiments in previous studies require the configuration of reference tag for calibration (Giretti et al., 2009, Saidi et al., 2011, Khoury et al., 2009, Cheng et al., 2011, Teizer et al. 2007). A reference tag is a tag with known locations. By using the reference tag and the tracking tag simultaneously, the subtraction of their time differences eliminates the transmission delay of RF frequency front end of the anchors (Wang et al., 2013). The reference tag must have clear Line-Of-Site (LOS) with the anchors for accurate calibration. However, in the dynamic construction sites, it is not always practical to find a such a LOS location. Therefore, the requirement of reference tag increased the complexity and requirement of field configurations.

2.3 Filtering method

Noise removal is vital for safety purpose real-time tracking accuracies. Many researchers used filtering methods including Kalman filter (Cho et al., 2010), maximum step velocity (Zhang et al. 2012) etc. to remove the outliers and enhance accuracy. These approaches could enhance the result to a degree within 20cm (Cho et al., 2010), but the filtering process needs to dispose all the data line by line, which greatly delays the real time data transmission and visualization.

Therefore, if is of great necessity to look for a UWB RTLS with the following advantages to achieve widespread industry application: (1) No time cables connected between readers or anchors. (2) No need of reference tag. (3) No need of filtering approaches to remove noise. (4) Less expensive and simple reconfiguration of the system. Based on the specification, the Ultra-Wide Band RTLS in this study is promising to overcome all these shortcomings of previous systems. Therefore, the objective of this study is to investigate the performance and feasibility of using the new generation of UWB RTLS on construction sites.

Table 1: Characteristics of existing UWB RTLS in previous literature.

Study	Method	Static	Dynamic	Average error (m)	Filtering method	Reference tag
Khoury et al. 2009	TDOA	√	×	0.5 (3D)	×	√
Shahi et al. 2012	AOA, TDOA	√	×	0.15 (2D)	×	×
Maalek and Sadeghpour, 2013	AOA, TDOA	√	×	0.16 (2D), 0.34 (3D)	×	×
Maalek and Sadeghpour, 2016	AOA, TDOA	×	√	0.31 (2D), 0.5 (3D)	×	×
Zhang et al. 2012	AOA, TDOA	×	√	×	Max velocity	×
Hwang 2012	AOA, TDOA	×	√	×	×	×
Teizer et al. 2007	TOF	×	√	Better than 1	×	√
Giretti et al. 2009	TDOA	×	√	×	Statistical filtering	√
Carbonari et al. 2011	TDOA	×	√	×	Aggressive model, Max step	×
Saidi et al. 2011	TDOA	√	√	0.087 (2D), 2.5 (Dynamic)	×	√
Andolfo 2016	AOA, TDOA	×	√	0.081 (2D) 0.2~0.25 (Dynamic)	×	×
Cho et al. 2010	TDOA	√	√	0.1~0.17 (2D) 1 (Dynamic)	Kalman filter Outlier removal	×
Cheng et al. 2011	TDOA	×	√	0.3~0.4 (Dynamic)	Kalman filter	√
Proposed UWB RTLS	*TOF*	√	√	*0.0753 (2D) 0.2 (3D) 0.15~0.25 (Dynamic)*	×	×

3 TIME OF FLIGHT LOCATION ESTIMATION ALGORITHM

A typical UWB RTLS is composed of anchors (readers) and tags (tracking objects). The anchor nodes fixed at a certain height implement a local network so that each tag could utilize Time of Flight (TOF) two way ranging to calculate their locations. During the two-way ranging estimation process, the initiator firstly sends an Ultra-Wide Band signal to the responder, then after a short reply time of the responder, it sends another Ultra-Wide Band message back to the initiator. Hence the TOF (Time of Flight) and range could be defined by the following equations (Eq.1, Eq.2) respectively:

[1] $\mathrm{TOF} = (t_2 - t_1 - t_{reply})/2$

[2] $\mathrm{range} = (t_2 - t_1 - t_{reply})/2 * \mathrm{v}$

where v is the transmission velocity of the UWB signal, t_1 is the time when the initiator sends the signal, t_2 is the time when the initiator receives the signal, t_{reply} is the responder's reaction time.

After obtaining at least three ranges between a tag (initiator) and three different anchors (responder), the x, y and z coordinates of the tag could be determined based on the three ranges. The exact time t_1 t_2, as well as the duration t_{reply} are obtained from the clocks of the tags and anchors respectively. Those three parameters dominate the accuracy of this two-way ranging measurement. Nevertheless, the tag also could face clock drift issues which could lead to potential errors on the exact time t_1, t_2. The typical reason for clock drift is the frequencies of clock crystal can be deviated from the designed frequency, so the drifted clock of a certain tag is desynchronized with other clocks (Zanca et al., 2008). In order to prevent the influence of the clock drift, a more advanced compensation asymmetric TOF model named Poll-Response-Final (PRF) (Figure 1) is utilized. This PRF model calculate the TOF from several durations instead of exact time, which prevents the clock drift effect errors. The following equation (Eq. 3) is utilized to calculate the TOF (Dacawave, 2015):

[3] $\mathrm{TOF} = (T_{round\ 1} * T_{round\ 2} - T_{reply\ 1} * T_{reply\ 2})/(T_{round\ 1} + T_{round\ 2} + T_{reply\ 1} + T_{reply\ 2})$

where $T_{round\ 1}$ is the duration of round 1, $T_{round\ 2}$ is the duration of round 2, $T_{reply\ 1}$ is the duration for the responder to reply, and $T_{reply\ 2}$ is the duration for the initiator to reply.

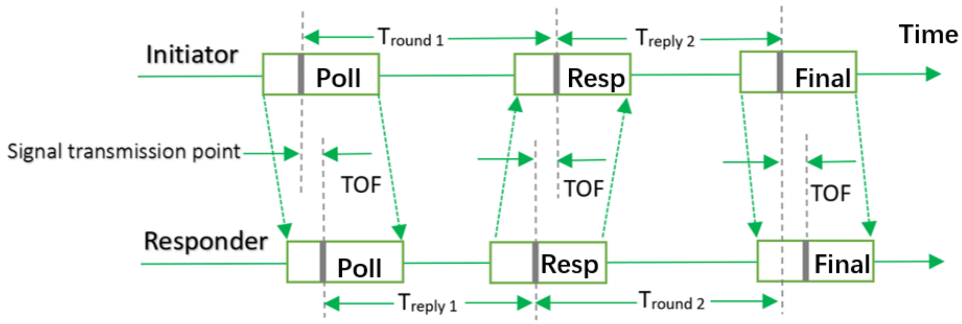

Figure 1: Poll-Response-Final approach

4 EXPERIMENT CONFIGURATIONS AND MODELLING ALGORITHMS

The UWB RTLS used in this study is Decawave DWM1001. Each module contains a location computing chip (Figure 2a), which is the functional component for ranging computation by applying TOF algorithms. The complete module (Figure 2b) includes the computing chip, battery, printed circuit board and protecting case. It can be interchangeably configured as an anchor (fixed at a certain height for network building) or a tag (nodes for location estimations). The module sends all the data in a format of a log file via Bluetooth to Android systems. Based on the equipment instruction, three anchors are the minimum requirement for the measurement, nevertheless, four anchors are configured at each corner of the room since one of the anchors could double check as an error reducer for higher accuracy.

(a) (b)

Figure 2: Dacawave UWB RTLS (a) UWB RTLS chip and (b) UWB RTLS tag/anchor

4.1 Static Experiment in Lab Environment

4.1.1 Experiment Configuration

For this experiment, an empty lab environment is configured to avoid obstacles. Blocks could result in Non-Line Of Site (NLOS) effect and interrupting the UWB signal during the signal transmission process. The actual location of the anchors and tags (Figure 3) are surveyed with a high accuracy total station (Leica TCR 803, 1.5mm at 1.5m). This will enable an accuracy comparison between the actual locations and the estimated location of the UWB RTLS.

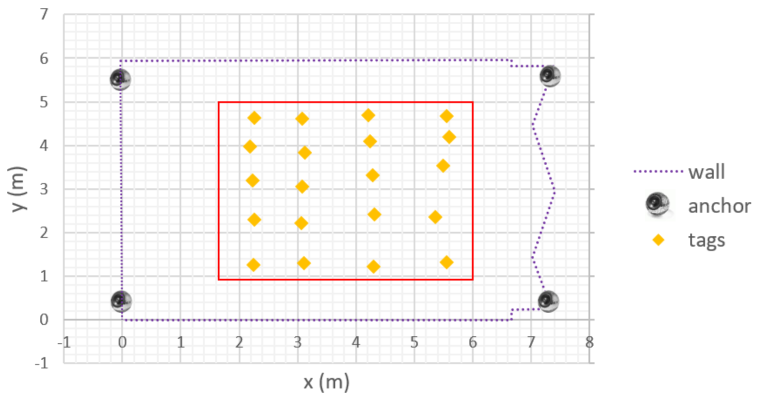

Figure 3: Lab experiment configuration

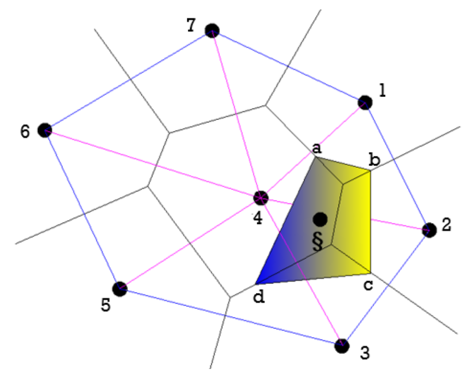

Figure 4: Voronoi diagram

4.1.2 Error Modelling Algorithm

To observe accuracy distributions within the continuous space of lab, a statistic mathematical model named Natural Neighbor Interpolation is utilized as it provides smoother approximation. In this model, the location of each tag is defined as a node and the Voronoi diagram is defined based on that. Consider a series of two-dimensional nodes N= $\{n_1, n_2, \dots n_m\}$ as shown in Figure 4. T_i is all the locations that has a shorter distance from node n_i compared with any other nodes. Hence the Voronoi cell can be defined in the following expression (Eq.4) (Sukumar et al., 2000):

[4] $T_i = \{\S \in R^2 : d(\S, \S_i) < d(\S, \S_k)\ \forall k \neq i\}$

where § is the point for value estimation and d is the distance from the point § to the node i.

After obtaining the primary Voronoi cells, the natural neighbor nodes need to be determined. When the point of interest § locates within the circumcircle of the triangle formed by any arbitrary neighbor nodes $\{n_i, n_j, n_k\}$ of point §, these nodes are defined as natural neighbor nodes. As is shown in Figure 4, nodes 1,2,3,4 are the natural neighbor nodes of the point §.

Using the perpendicular bisectors of the lines between point § and its each natural neighbor nodes, a closed polygon-the tertiary Voronoi cell abcd (quadrilateral in the case of Figure 4) is formed. The tertiary Voronoi cell abcd in Figure 4 are divided by the edge of the primary Voronoi cells into four small polygons. The area of each small polygon is further utilized for an area weighting method (Eq.5) (Sukumar et al., 2000):

[5] $\phi_i(\S) = A_i(\S)/A(\S)$

where $A_i(\S)$ is the overlapped area of the primary Voronoi cell T_i and the tertiary Voronoi cell, $A(\S)$ is the area of the tertiary Voronoi cell.

Ultimately, any weighted value $\mathcal{E}$ at an arbitrary location could be calculated by applying Eq.6(Sukumar et al., 2000):

[6] $\mathcal{E}(\S) = \sum_{i=1}^{n} \phi_i(\S)\, \mathcal{E}_i$

where $\mathcal{E}_i$ is the parameter $\mathcal{E}$ at node n_i. In the case of this study, $\mathcal{E}$ represents the DRMS and MRSE accuracy.

4.1.3 DRMS and MRSE

One dimensional accuracy analysis for industry utilization is obviously not enough, since the construction sites even without considering danger of the certain height also require at least 2D accuracy. Hence DRMS (Distance Root Mean Squared) and MRSE (Mean Radial Spherical Error), both of which are combinations of precision and offset (Leick, 2004), are currently the most representative approaches for two-dimensional and three-dimensional accuracy analysis. The formulas of DRMS (Eq.7) and MRSE (Eq.8) are shown in the following expressions:

$$[7]\ \mathrm{DRMS} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x_{Actual})^2}{n} + \frac{\sum_{i=1}^{n}(y_i - y_{Actual})^2}{n}}$$

$$[8]\ \mathrm{MRSE} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x_{Actual})^2}{n} + \frac{\sum_{i=1}^{n}(y_i - y_{Actual})^2}{n} + \frac{\sum_{i=1}^{n}(z_i - z_{Actual})^2}{n}}$$

4.2 Static Experiment in Construction Site

A contrast experiment is performed in the Concrete Construction Laboratory. In this laboratory, there are many types of blocks including metal collars, cranes, concretes. Among these blocks, a metal crane located close to the position A4 and a huge concrete block are considered as two major obstacles for the signal transportation process. The tags are put directly on the ground to create the worst scenario, where the tags are completely in Non-Line Of Site (NLOS) with respect to the anchors. The anchor spacing is maintained to approximately 10 meters. The numbers of the tags are varied from 1 to 4 and they are put in centric area A4 to A7 respectively (Figure 5). This experiment aims at investigating the following effects:

- When the tag is placed closer to the blocks, whether the blockage effect will become more severe.
- When the signal between the tag and a certain anchor is interrupted by the block, whether the errors will increase on account of using only three anchors.
- When the blockage effect exists, whether the signal can penetrate the block and improve the accuracy itself.
- Whether the numbers of the tags will significantly influence the accuracy of the estimate location.

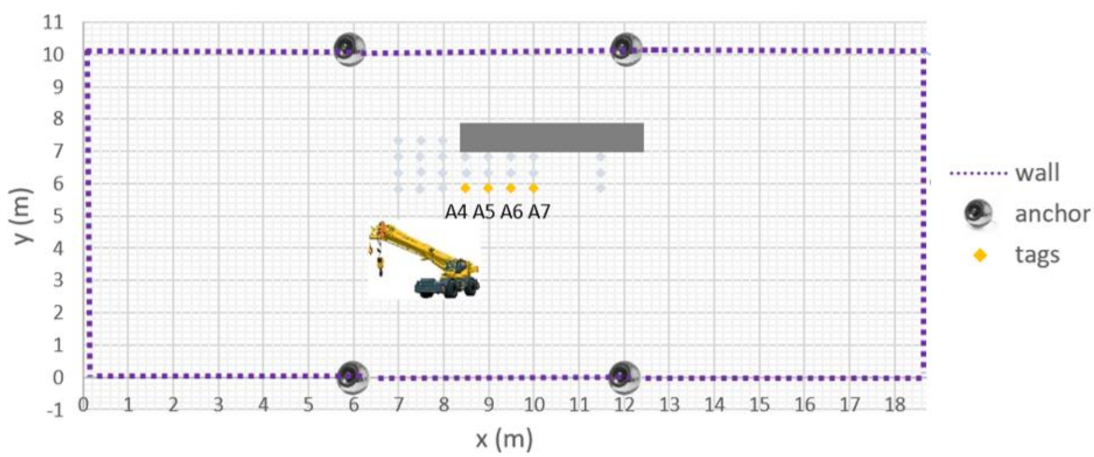

Figure 5: Construction site experiment configuration

4.3 Dynamic Real-time Location Estimation Accuracy Measurement

In construction sites, what we care about most are the moving people and objects which could possibly enter a dangerous zone or collide with each other. A robotic total station (Leica TS30) is used to determine the actual location in real time. It is able to automatically rotate horizontally and vertically to aim at the prism which is simultaneously attached by a tag for location estimation. The data generation frequency of the UWB tool MDEK 1001 is set as 10 Hz, which means ten data points are generated within one second. In order to be closer to the real case, a real person which has uncertainty in moving directions and velocities instead of any regular moving objects in previous studies is designed to take the prism pole and walk around the room in speed of approximately 0.35m/s and 0.8m/s respectively.

5 RESULT AND ANALYSIS:

5.1 Accuracy Analysis of Lab Experiment: DRMS and MRSE Accuracy Distribution

As shown in Figure 6, the investigated area is the region circulated by the red rectangular in Figure 3, and the circles in these plots represent the actual location of the tags. Based on the estimated location of the tags and the actual location surveyed by the total station, the DRMS and MRSE accuracy for every tag location is calculated. The Natural Neighbour Interpolation is utilized to obtain the error distribution of the whole area as shown in Figure 6. The result shows that the tags placed at the center tend to have higher accuracy. This is because when the tags are placed closer to one certain anchor eccentrically, it's further from the others. Therefore, in order to detect the location of the tag, the UWB signal must travel through a larger distance which could definitely lead to more errors. Overall, the majority of the area has a DRMS accuracy better than 10 cm and a MRSE accuracy around 15~20 cm. Hence it could be concluded that the UWB RTLS can achieve a high degree of accuracy in static mode when there is no blockage effect.

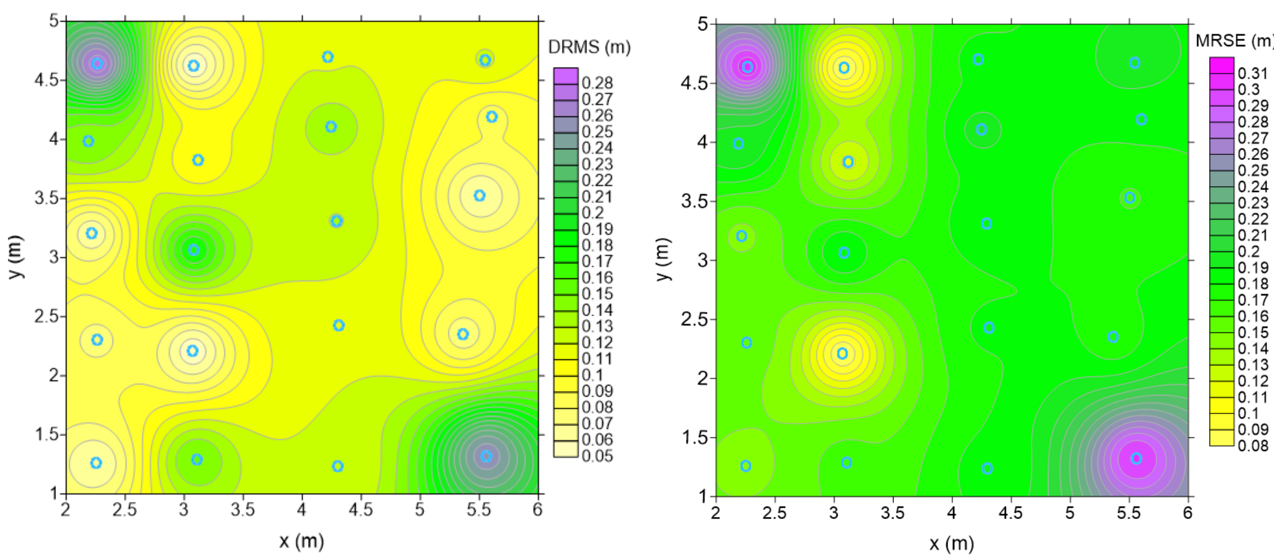

Figure 6: 2D accuracy (DRMS) and 3D accuracy (MRSE)

5.2 Accuracy Analysis of Construction Site Experiment: Non-Line Of Site and Multiple Objects

As shown in Figure 7, the errors always increase abruptly at some certain time and then gradually decrease to a small value. After comparing with the log profile which displayed the UWB signal quality, this is because when the blocks exist, only three anchors are working. Since this RTLS utilizes ranging measurement, at least ranges generated by three anchors are utilized to solve the equation to obtain the values of x, y and z. The fourth anchor which serves as a checker could dramatically decrease the possibility of the huge errors. Without the fourth anchor, the errors will increase significantly as the Figure 7 shows. However, after the sudden increase, the error starts to decline towards back the original small range. This indicates the UWB signal can sometimes penetrate the blocks to convey the data to the blocked anchor and decrease the errors.

In addition to the above analysis, the tag location A4 shows a relatively larger but steady error. This location is almost attached to the metal crane, which means the block would influence the accuracy when it is much too close to the tag. However, when the crane interrupts the signal between the tag placed at A4 and the anchor behind the crane, the errors of y direction did not show the trend of build-up but start to decrease. This is because even if the UWB signal between the tag at A4 and the anchor behind the crane could penetrate the metal crane, the estimated y values are severely influenced by the metal block. Without this wrong correction of the anchor ranging data interfered by the blocks, the accuracy is even better. Thus, it could be concluded that even if the UWB signal could possibly penetrate metal blocks, if the tag is placed much too close to the metal, the accuracy is still influenced. From A5 to A7, the frequency of the errors' abrupt jump is decreasing, which indicates two conclusions: (1) the metal compared with the concretes plays a more important role in blocking the UWB signal; (2) the possibility of interrupting the signal between the tag and the anchor behind the metal frame decreases as the tags are placed further from the metal block. Furthermore, the effect of multiple tags is also investigated to achieve multiple objects tracking. The accuracy of A5 are compared by configuring different numbers of tags from one to four. From Figure 8, it can be concluded that the numbers of the tags is not a significant factor to decrease the accuracy of this UWB RTLS.

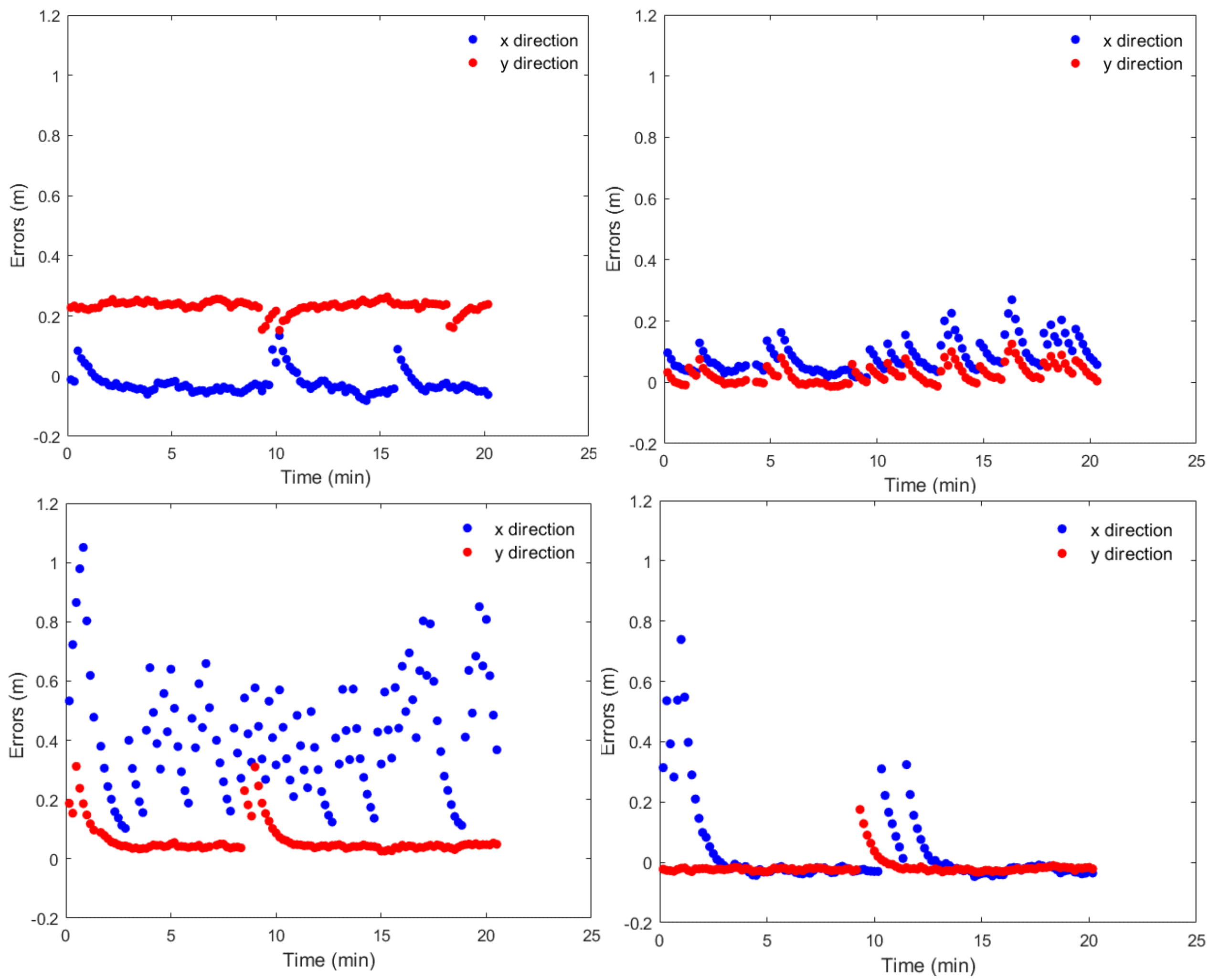

Figure 7: Errors in x and y directions for tag locations A4, A5, A6, A7

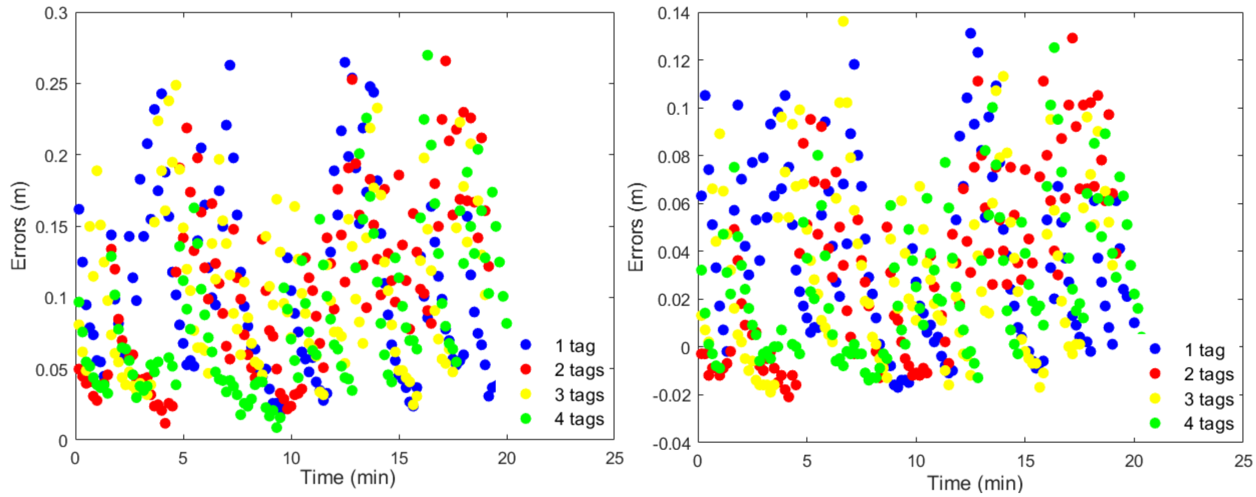

Figure 8: Errors in x and y directions for A5 with different number of tags

5.3 Dynamic Accuracy Analysis: Low and High Speed

As shown in the Figure 9, for both the low speed and high-speed cases, the accuracy drops almost at the same location where x is less than 13 m and the tag is at the corner of the room. This is because when the tag is at the corner, it is further from the other three anchors. Because of the tilt angle of the prism, it can also block the signal between the tags and the anchor behind the prism pole. In addition, the accuracy drops more obviously for the high-speed scenario, which is in accordance with the common sense that the higher the velocity, the larger the errors. Overall, the dynamic scenario shows reasonable accuracy with a range of 15~25 cm, which is suitable and applicable for construction sites.

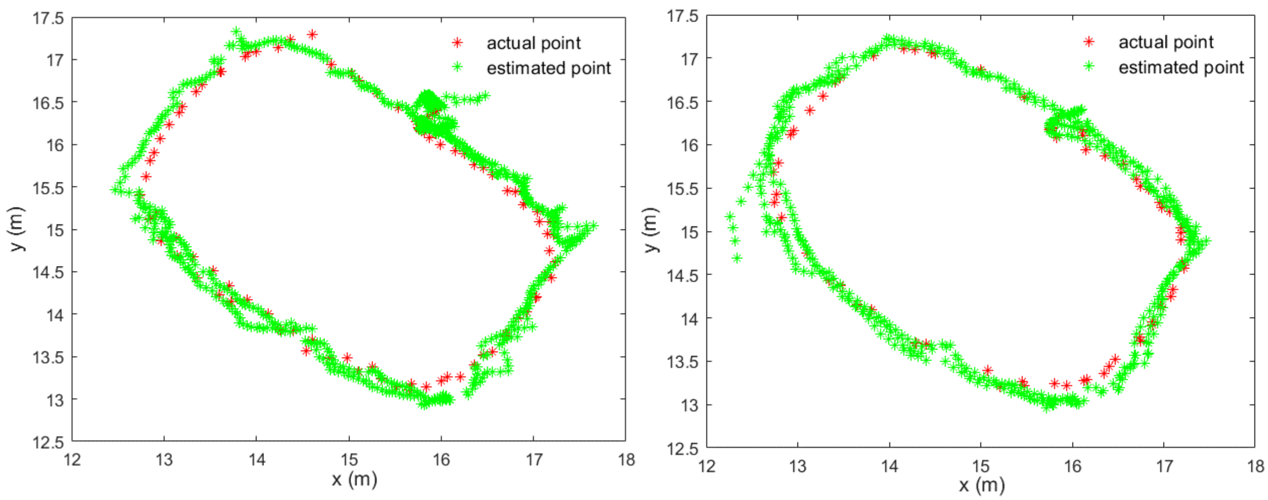

Figure 9: Dynamic errors for lower and higher speeds

6 CONCLUSION:

In this paper, a new generation of UWB RTLS is evaluated for industry application. This new system overcame the traditional difficulties concerning the time cables between different anchors, reference tags, noise filtering approaches requirements, clock drift issues and also high expenses as well. The three experiments in this research revealed the high static (0.0753 m (2D), 0.2 m (3D)) and dynamic accuracy (0.15~0.25 m) of this system in both Line-Of-Sight and Non-Line Of Site, which provides solid references for congested construction environments application. The error fluctuation process in the second experiment was detailly analyzed. Even with the worst scenario when we put the tags directly on the ground to create totally Non-Line Of Site, the majority of signals still could penetrate the barriers and achieve two-way ranging. After a very short time of signal interruption where the errors abruptly increase, the signal communication recovers quickly and the errors gradually go back within 10cm, which means the UWB RTLS has great advantages for application in congested construction sites. This research also concluded high accuracy of simultaneous multi-object tracking, which is also one of the industrialized requirements for construction applications. The absolutely wireless configuration of anchors and tags provide solid foundations for anchor configuration optimization in construction sites.

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