Development of Low-Cost Indoor Positioning Using Mobile-UWB-Anchor-Configuration Approach

Ang Liu[1], Shiwei Lin[1], Xiaoying Kong[1], Jack Wang[1], Gengfa Fang[1] and Yunlong Han[1]

[1]Faculty of Engineering and Information Technology, University of Technology Sydney, Sydney, Australia

Abstract. In recent years, with the growth of indoor positioning demand, many kinds of indoor positioning technologies have been studied. Compared with other technologies, UWB indoor positioning technology has the advantages of high positioning accuracy and strong anti-interference ability. However, the high cost of UWB hardware limits the application of this technology to practical applications. In particular, the effective communication distance of the UWB is within 10 meters, and if used in a large-area indoor environment, a plurality of anchor points is required to be installed to ensure the positioning accuracy. This leads to a high system hardware cost.

In this paper, we proposed a mobile-UWB-anchor-network approach. We changed the fixed anchors in the UWB system into moving anchors to reduce the number of anchors in the area and reduce the cost of the system. This new approach is verified using experiments.

Keywords: Indoor positioning, UWB moving anchors, low-cost.

1 Introduction

With the development of the internet of things technology, supply chain, and intelligent city, people's activities are more and more concentrated indoors. The traditional positioning technology in the outdoor environment, such as GPS, can no longer meet the positioning requirements in an indoor complex environment. However, the actual requirements of the intelligent warehouse, logistics monitoring, human capital monitoring, and so on, also make the research of indoor positioning technology become a hot spot.

UWB (Ultra-Wideband) has an extremely high bandwidth, operating frequency between 3.1 GHz and 10.6 GHz, does not occupy the existing bandwidth resources and does not interfere with existing bandwidth signals. At the same time, the UWB signal has nanosecond pulse width and good penetration ability. Because of these advantages of UWB, UWB can achieve centimeter-level positioning in an indoor environment, and the positioning accuracy can reach less than 10cm under the condition of no occlusion [1]. On the other hand, the radiation of UWB signal is very low, only 1/1000 of the radiation of mobile phone signal, which is much lower than that of Wi-Fi signal, so it will not interfere with the instrument and equipment, and can meet the indoor positioning needs of some special environments, such as factories and hospitals[2].

At present, there are many research directions and methods of indoor positioning technology, such as Bluetooth positioning technology, Wi-Fi positioning technology, and UWB positioning technology, all of which have their advantages and disadvantages. Kong et al. summarized that a navigation system needs to consider quality attributes which include accuracy, availability, reliability, robustness, safety, security, and response time; On the other hand, also need to consider development constraints which include maintainability, usability, development complexity, cost constraint, time constraint and client and supplier collaboration capacity [3]. One of the difficulties in the development of indoor positioning technology is how to measure the positioning accuracy and system cost.

For some positioning technologies, such as Bluetooth indoor positioning technology, Wi-Fi indoor positioning technology, the deployment cost is low, positioning accuracy is also relatively low. The positioning accuracy can only reach 2 meters. Although the high precision technology such as UWB, can meet the centimeter-level positioning accuracy, the hardware cost is remarkably high, it is difficult to meet the large-scale application.

This paper will pay attention to this research question: how to use a more reasonable hardware configuration to reduce the system cost without affecting the accuracy of UWB indoor positioning. In this paper, we present a new indoor positioning approach to change the fixed-anchor-point in a conventional UWB positioning system into a mobile-anchor-point configuration to reduce the number of anchor points required in a large-area indoor environment, thereby reducing system cost. This approach is verified using the design and experiments at the positioning accuracy level of the mobile anchor point system.

This paper is organized into the following sections. Section II reviews the literature. Section II presents the UWB indoor positioning system hardware and configuration.

2 Literature Review

Indoor positioning has two sides: indoor positioning mechanisms and indoor positioning technologies. Indoor positioning mechanisms are general positioning algorithms that geometrically locate the position of an object. Indoor positioning technologies are using sensors and other hardware related technologies to obtain positioning-related measurements to feed into indoor positioning algorithms. In this section, we will review the current literature on these 2 sides.

2.1 Indoor positioning algorithm

Fingerprint

The fingerprint algorithm first measures the signal strength of each position in the area and builds a database of the measurement results. When locating, it needs to measure the signal intensity of the target point. By comparing the previous fingerprint database which includes RSSI (received signal strength indication) and the corresponding position coordinates, the location of the target point can be determined.

The fingerprint algorithm can be divided into two steps. The first step is called the off-line phase. The main purpose of the off-line phase is to build a database. The second part, called the on-line phase, is to get the location information by comparing the database information [4]. Fingerprint algorithm also has some disadvantages, first, it needs to collect a large amount of data when building a database. If it is applied in a large regional environment, it will be a lot of work in building such a database [5]. Secondly, after the establishment of the database in the first step, if the indoor facilities or arrangements change, the signal strength of each point will be affected, which will also lead to the localization error.

TOA (Time of Arrival)

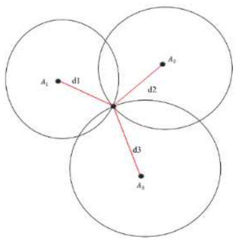

Fig. 1. Time of Arrival

TOA is a method to locate the target by measuring the distance [6]. The principle of this method is to calculate the distance between the target point and the anchor point by measuring the arrival time of the signal and then calculate the Tag coordinates by the distance. The positioning in a 2D plane requires at least 3 anchors. After measuring the distance between the target label and three different anchors, the exact position of the target label can be obtained by a series of geometric algorithms [7]. The working principle of TOA will be explained by the mathematical formula below.

As shown in Figure 1, the coordinates at the target point of the positioning system is $tag\ T = (x, y, z)$, anchors coordinates are $A_i = (x_i, y_i, z_i)$ i=1,2,3...N.

$$d_i = (t_i - t_0)*c \tag{1}$$

where d_i : Distance between anchor i and tag, t_i : Signal arrival time, t_0 : Signal sending time, c: speed of light

$$\begin{aligned} d_1^2 &= (x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 \\ d_2^2 &= (x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 \\ d_3^2 &= (x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 \\ d_4^2 &= (x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2 \end{aligned} \tag{2}$$

From the above mathematical formula, the following results can be obtained

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 2(x_1 - x_2) & 2(y_1 - y_2) & 2(z_1 - z_2) \\ 2(x_1 - x_3) & 2(y_1 - y_3) & 2(z_1 - z_3) \\ 2(x_1 - x_4) & 2(y_1 - y_4) & 2(z_1 - z_4) \end{bmatrix}^{-1} * \begin{bmatrix} d_2^2 - d_1^2 - x_2^2 + x_1^2 - y_2^2 + y_1^2 - z_2^2 + z_1^2 \\ d_3^2 - d_1^2 - x_3^2 + x_1^2 - y_3^2 + y_1^2 - z_3^2 + z_1^2 \\ d_4^2 - d_1^2 - x_4^2 + x_1^2 - y_4^2 + y_1^2 - z_4^2 + z_1^2 \end{bmatrix} \quad (3)$$

TOA algorithm requires extremely high time accuracy and time synchronization between anchor and tag. Even if the time error is small, for example, the time error of 1ns will produce a distance error of 0.3m when multiplied by the speed of light.

Therefore, TDOA (Time Difference of Arrival) which is easier to implement is obtained based on TOA.

TDOA (Time Difference of Arrival)

The basic principle of TDOA is to make use of the characteristics of hyperbolic, that is, the difference between the distance from the point on the hyperbola to the two focal points is a fixed value [8]. Figure 2 shows the schematic diagram of the TDOA.

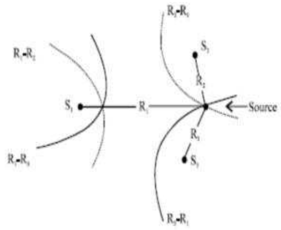

Fig. 2. Time Difference of Arrival

The basic principle of TDOA is to locate the transmission time delay difference between Tag and two anchors. As shown above, S_1 , S_2 , S_3 represent three anchors, R_1 , R_2 , R_3 represent the distance between Tag and the corresponding anchor point, respectively. If the distance difference between Anchor 1 and Anchor 2 is R_{21} , then the tag must be on a hyperbola that takes S_1 and S_2 as the focus. By the same token, Tag will also be on hyperbolic curves with S_1 and S_3 as the focus. The coordinates of the tag are obtained by calculating the intersection of the two hyperbolic curves.

The advantage of TDOA over TOA is that when calculating the distance between anchors, the initial time t_0 is eliminated by subtraction.

Therefore, TDOA does not need time synchronization between tag and anchor, but only needs to synchronize between base stations, which greatly reduces the technical difficulty

2.2 Indoor Positioning technology

Wi-Fi

Due to the development and popularization of the Internet, the Wi-Fi network has been well constructed. At the same time, the Wi-Fi network construction has the advantages of low cost, easy deployment, and the Wi-Fi network has been widely used to cover the indoor environment as a way for people to visit the Internet in a daily way [8]. As an indoor positioning technology, Wi-Fi mainly uses the fingerprint location method based on RSSI. This method completes the location through off-line sampling and online positioning. It also has some shortcomings of fingerprint location, such as the offline phase is very time-consuming [9]. If the indoor parameters change, the fingerprint database needs to be re-established [10].

The advantages of this method are the hardware cost is low, the transmission rate is high, but the transmission distance is short, and the power consumption is high. It can achieve meter level positioning

Bluetooth

Bluetooth is a low-power wireless transmission technology. By installing Bluetooth access points indoors, multiple users can connect at the same time and determine the location of access devices [11]. Bluetooth positioning technology is generally suitable for small indoor positioning, such as a single room warehouse. The biggest advantage of Bluetooth technology is that the device size is small, the power consumption is low, and it is easy to be integrated into mobile terminals such as mobile phones. However, Bluetooth technology also has some shortcomings, such as poor stability in a complex indoor environment, easy to be interfered with, and expensive equipment [12].

When Bluetooth technology is used for indoor positioning, the commonly used method is also fingerprint location algorithm based on RSSI, and the accuracy can reach about two meters under ideal conditions. Through some auxiliary methods, such as integration of the weighted average algorithm, inertial navigation algorithm, Kalman filter algorithm, and so on, the positioning accuracy can be further improved to decimeter level [12].

UWB (Ultra-wideband)

The UWB (Ultra-wideband) has an exceedingly high bandwidth, the operating frequency band is 3.1-10.6GHz, and the duration is noticeably short. Therefore, the theoretical positioning accuracy can reach centimeter-level [13]. The transmission distance of UWB is generally in the range of 10 meters, and a large amount of data can be transmitted in a short period. Because the UWB uses truly short pulses and the transmission power is exceedingly small, it is very suitable for real-time indoor positioning [14]. The system communicates with unknown nodes entering the communication range by pre-arranged fixed-position anchor nodes and then determines the position information by triangulation or fingerprint algorithm.

UWB has many advantages, such as low power consumption, strong anti-jamming ability, strong penetration, can be used in non-line-of-sight, will not interfere with other equipment, it is also safe for people [15].

Our research will focus on UWB technologies. UWB system can be divided into three layers, management layer, service layer, and site layer. The focus of our approach is the site layer, the site layer is mainly composed of anchor points and positioning tags. The tag is associated with the target and broadcasts its location to the anchor. The anchor receives the location information of the tag and then passes the information to the position calculation engine. After receiving the information uploaded by the anchor points, the calculation engine calculates the exact position of the target tag by the corresponding algorithm.

3 Mobile-UWB-Anchor-network configuration approach

In the conventional UWB positioning approach, a large amount of fixed position anchors is deployed. Figure 3 illustrates this positioning approach.

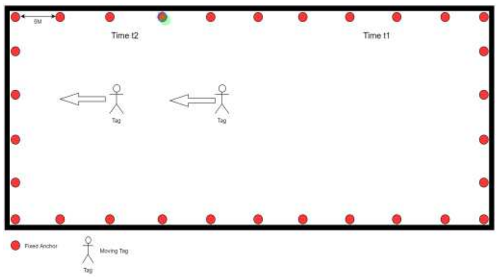

Fig. 3. Conventional UWB anchor network using fixed anchors

If tags are moving from Time t1 to Time t2 and leave the space where these tags were in time t1 without tags, the anchors in the time t1 area are not used for positioning.

We propose a new approach to reduce the deployment of such a large number of fixed anchors.

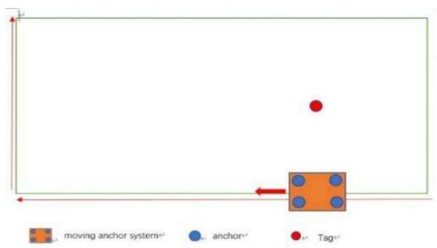

Fig. 4. New Mobile-Anchor-Network approach

We adopted a new way of thinking about the system of placing the originally fixed anchor on a mobile platform to form a mobile anchor point system. This mobile anchor system moves at a constant speed along a fixed track within a certain area. When tags need to be positioned appear in the region, the mobile platform first determines its position based on displacement time, velocity, direction. If there are at least three anchor points to communicate with Tag, the position of the Tag can be calculated by the TOA method, thus achieving the positioning of the mobile anchor system. Here is the experimental flowchart:

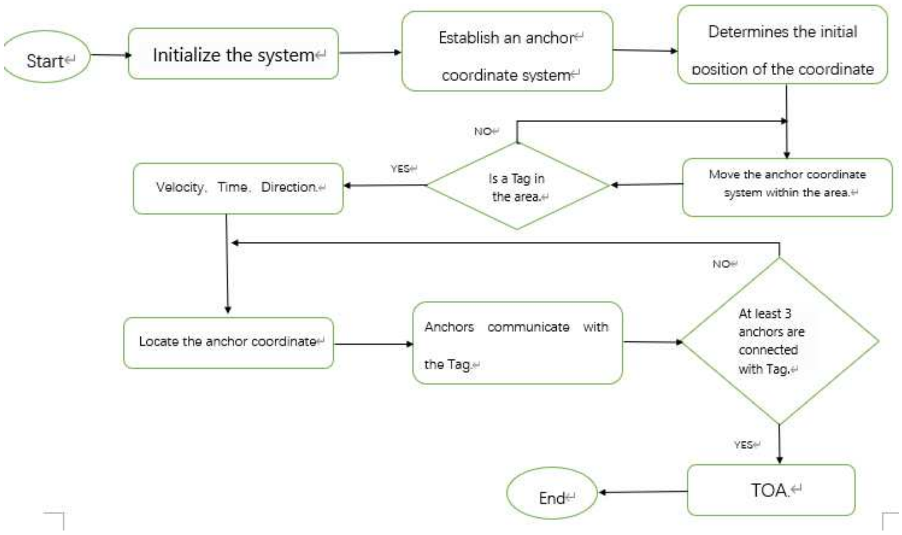

Fig. 5. Mobile anchor system experimental flowchart.

For the positioning algorithm TOA, because the actual experimental state signal will be interfered with by noise and cause the measurement distance error, so the ranging error ε_i is added to the experimental simulation. the actual range should be：

$$d_i = r_i - \varepsilon_i \tag{4}$$

Where i is the number of anchors (i = 1， 2， 3， 4) ; d_i is an actual range between anchor i and Tag; r_i is measuring range between anchor i and Tag; ε_i is ranging error

Assuming：

$$K_i = x_i^2 + y_i^2 + z_i^2 \tag{5}$$

Where (x_i y_i z_i) is coordinate of anchor i (i = 1, 2, 3, 4).

From equations (3), (4), and (5), the following equation can be obtained:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 2(x_1 - x_2) & 2(y_1 - y_2) & 2(z_1 - z_2) \\ 2(x_1 - x_3) & 2(y_1 - y_3) & 2(z_1 - z_3) \\ 2(x_1 - x_4) & 2(y_1 - y_4) & 2(z_1 - z_4) \end{bmatrix}^{-1} * \begin{bmatrix} r_2^2 - r_1^2 + K_1 - K_2 + \varepsilon_2^2 + 2r_1\varepsilon_1 - 2r_2\varepsilon_2 - \varepsilon_1^2 \\ r_3^2 - r_1^2 + K_1 - K_3 + \varepsilon_3^2 + 2r_1\varepsilon_1 - 2r_3\varepsilon_3 - \varepsilon_1^2 \\ r_4^2 - r_1^2 + K_1 - K_4 + \varepsilon_4^2 + 2r_1\varepsilon_1 - 2r_4\varepsilon_4 - \varepsilon_1^2 \end{bmatrix} \tag{6}$$

Where (x, y, z) is the coordinate point of Tag

Assuming：

$$D = \begin{bmatrix} (x_1 - x_2) & (y_1 - y_2) & (z_1 - z_2) \\ (x_1 - x_3) & (y_1 - y_3) & (z_1 - z_3) \\ (x_1 - x_4) & (y_1 - y_4) & (z_1 - z_4) \end{bmatrix} \tag{7}$$

$$X = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{8}$$

$$c = \begin{bmatrix} r_2^2 - r_1^2 + K_1 - K_2 \\ r_3^2 - r_1^2 + K_1 - K_3 \\ r_4^2 - r_1^2 + K_1 - K_4 \end{bmatrix} \tag{9}$$

$$\Delta = \begin{bmatrix} \varepsilon_2^2 + 2r_1\varepsilon_1 - 2r_2\varepsilon_2 - \varepsilon_1^2 \\ \varepsilon_3^2 + 2r_1\varepsilon_1 - 2r_3\varepsilon_3 - \varepsilon_1^2 \\ \varepsilon_4^2 + 2r_1\varepsilon_1 - 2r_4\varepsilon_4 - \varepsilon_1^2 \end{bmatrix} \tag{10}$$

Substituting equation (7) (8) (9) (10) into equation (6), we can get:

$$2DX = c + \Delta \tag{11}$$

From the least square method, the Tag coordinate can be obtained as：

$$X = \frac{1}{2}(D^T D)^{-1} D^T (c + \Delta) \tag{12}$$

The main purpose of this experiment is to verify whether the moving anchor points can accurately locate Tag after the fixed anchor points are turned into mobile anchor points. The cost of the UWB anchors is high. Using this approach, we reduce the cost of UWB hardware. Our approach can be verified using experiments. The next section will discuss the verification results.

4 Experiment

4.1 Experiment hardware

This section will introduce the verification results. We use experiments and simulation to analyze this approach.

Experiments are set up using DWM1001 UWB equipment. See Figure 6.

Fig. 6. DWM1001-DEV Development Boards

For an indoor positioning system, positioning accuracy and system cost are two especially important factors. We have carried out some tests on the DWM1001 board, and installed four fixed anchors and a moving tag, to compare the data collected by the tag with the real position. It can be determined that the positioning accuracy of the UWB system can reach centimeter-level within the effective communication distance. The biggest problem with using UWB to build an indoor positioning system is the high cost. Because the effective communication range of UWB is generally less than 10m, if UWB indoor positioning is used in a large indoor environment such as an airport or warehouse in the future, hundreds or even thousands of fixed anchors will need to be installed, which will lead to too high the cost of the system. Therefore, in our experiments, we focus on how to reduce the cost of the UWB indoor positioning system and achieve high precision positioning at the same time.

4.2 Experimental results

The overall idea of this experiment is to reduce the number of anchors by changing the fixed anchor into a moving anchor to reduce the cost of the system.

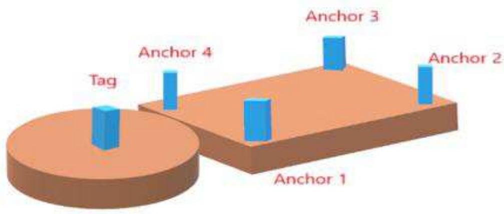

Fig. 7. Mobile-Anchor UWB system

As shown in Figure 7, four UWB anchors are fixed to the four corners of one box, a tag is fixed on a robot and the computer is connected to the tag to read data, then the box and robot are connected, thus building a mobile UWB positioning system.

The coordinate information of the anchor is shown in the following figure 8:

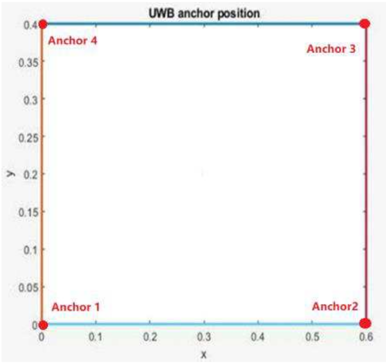

Fig. 8. coordinate of anchor **Fig. 9**. System movement route

Figure 9 shows the experimental site and the moving trail of the UWB system. The experimental site is in the common area of UTS building11 level 12, and the moving trail of the whole system is shown in the figure, from point A to point B then to point C, where the trajectory AB is X-axis and BC is Y-axis. Some of the data is shown in the following table.

Table 1. Experiment 1 data

Time(s)	0	0.06	0.16	0.28	0.66	0.96	1.06	1.26	1.36
x	0.023	0.005	0.016	0.005	0.021	0.02	0.035	0.034	0.039
y	0.034	0.015	0.031	0.041	0.048	0.04	0.058	0.055	0.061
z	0.043	0.044	0.055	0.054	0.065	0.055	0.075	0.059	0.068

From data that was read out from the tag, we can get the information of four anchors, including the anchor ID, coordinate position of anchors, and the distance between the anchor point and Tag. Combining these data, we can analyze the measurement data as shown in figure 10. The following trajectory diagram can be obtained utilizing the data analysis of MATLAB.

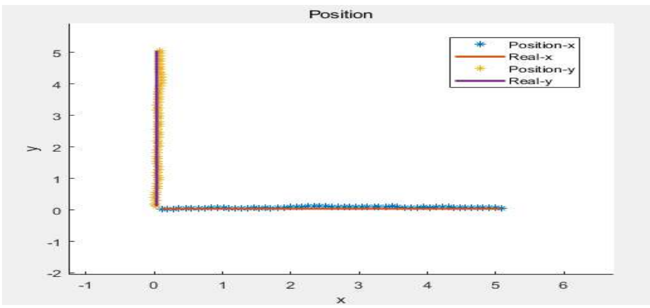

Fig. 10. Experiment trajectory diagram

The red line in figure 10 represents the trajectory of the anchor and the real trajectory of the whole system; the blue and yellow points represent the trajectory of the Tag located through the anchor. The mobile UWB anchor positioning system moves 5 meters along the X-axis and the Y-axis. From the above figure, it can be found that the system can accurately locate the tag position during the movement. The specific positioning error is represented by the following two figures:

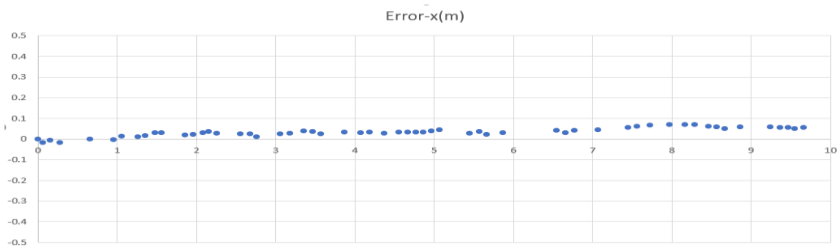

Fig. 11. Tag position during the system moves along the X-axis

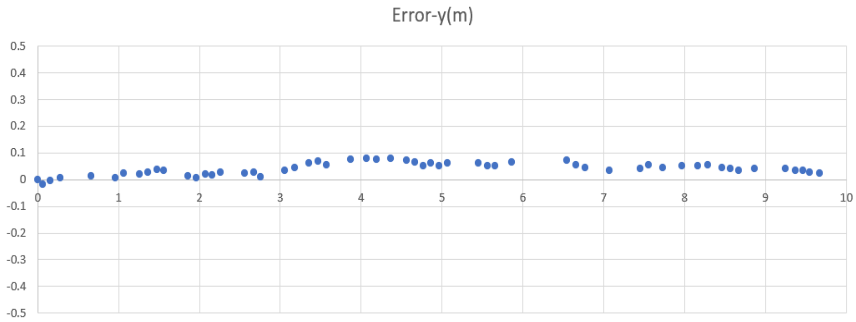

Fig. 12. Tag position during the system moves along the Y-axis

Table 2. Data analysis

	AVG	MAX	RMS
X-Error	0.033193	0.07	0.039183
Y-Error	0.039596	0.08	0.045534

Figure 11 and Figure 12 respectively show the result of tag positioning during the period when the mobile UWB anchor positioning system moves along the X-axis and the Y-axis. From the above two figures and table, it can be found that when the system moves along the X-axis, the tag's positioning error is 7cm, the average error is 3.32cm, and when the system moves along the Y-axis, the tag's positioning error is 8cm, the average error is 4cm. Therefore, the above results can show that the mobile UWB anchor positioning system can accurately locate the tag when the system moving on a fixed track, and it also verifies the feasibility of the method of reducing the cost by turning the fixed anchor point of the UWB into a mobile anchor point.

5 Conclusion and Future work

This article introduces several mainstream indoor positioning methods and algorithms in detail and proposes a new mobile anchor UWB positioning method for the high hardware cost of the UWB positioning system which can reduce the usage of anchor points in the same area. Through experiments, the positioning error of the mobile anchor UWB point positioning system moving along a fixed track is about 10cm, which verifies that this method is feasible. In future work, we will coordinate different positioning methods, such as inertial navigation, lidar, or visual SLAM, with the UWB mobile anchor positioning system, so that the mobile positioning system can no longer move along a fixed track, also it can move to the area that needs positioning more flexibly.

6 References

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