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UWB Positioning Analysis and Algorithm Research

Yuekui Zhang[a,b], Yunxia Chu[b], Yunfang Fu[a,b], Zhixiang Li[a,b,*], Yufei Song[a,b]

[a]School of Computer Science and Engineering, Shijiazhuang University, Shijiazhuang 050035, China
[b]Hebei Province Internet of Things Intelligent Perception and Application Technology Innovation Center, Shijiazhuang 050035, China

Abstract

In order to improve the accuracy of indoor positioning, this paper studied the three-dimensional positioning method based on TDOA and designed the ranging experiment with or without occlusion. The error data were analyzed by many experiments, and the advantages of strong penetration and good anti-interference ability of UWB signal were verified. At the same time, the UWB positioning direct matrix algorithm is optimized, and the least square matrix method is used to process the positioning data to obtain more accurate position coordinates. The experimental results show that the accuracy of the positioning data can be improved by about 25% by using the least square matrix method.

Keywords: TDOA; Three-dimensional positioning; UWB; Least squares matrix method

1. Introduction

With the development of science and technology, location service is widely concerned, and outdoor positioning technology has been widely used. But indoor positioning technology still cannot be fully promoted [1-2]. Domestic and foreign experts and scholars have done a lot of research on indoor positioning technology, especially ultra-wideband (UWB) positioning technology, which makes indoor positioning technology develop rapidly.

As a positioning technology with high accuracy, low power consumption and strong penetration, UWB can be applied in multiple fields such as robotics, radar aviation, factories, warehousing and logistics, and airport

* Corresponding author. Tel.:+86-153-7390-8389; fax:+86-0311-6661-7198.
E-mail address: leageshine@foxmail.com

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management [3-5]. Zihao Huang et al. studied the sound source location model based on TDOA and AOA algorithm in combination with the three-dimensional sound source location law [6]. Ding Wang et al. studied a new TDOA positioning method under the condition of synchronous clock deviation and sensor position error, which makes the error more robust [7]. Wentao Fu et al. proposed the UWB positioning method based on support vector machine, which is superior to traditional algorithms in accuracy and time [8]. Xiaosi Chen et al. studied the difference UWB system based on TDOA algorithm, which reduced the overall positioning error [9]. Xiaosu Xu et al. proposed an indoor UWB positioning algorithm based on graph optimization to reduce the positioning error [10]. Nan Li et al. analysed the 3D positioning model of UWB, compared several filtering methods and concluded that Kalman filter is more suitable for the requirements of 3D positioning in terms of required time, cost performance and accuracy [11]. The literature [12] proposed an UWB positioning system based on genetic algorithm, which used genetic algorithm to solve the equation and obtain the coordinates of unknown nodes. The literature [13] proposed an ultra-wideband positioning system based on deep learning, which transformed the positioning problem into a regression problem and combined ranging and positioning.

In this paper, the localization method of TDOA is studied, and the three-dimensional coordinate matrix algorithm is compared and analysed. At the same time, an experiment on the influence of occlusion on positioning accuracy was designed to verify the advantages of UWB indoor positioning. The coordinate data calculation method is optimized to improve the accuracy and reduce the calculation error.

2. UWB Positioning Principle

The UWB positioning principle mainly adopts the positioning method based on time difference (TDOA) [8-9]. The hardware of the system includes the base station and the tag, and the precise time synchronization between the base stations is required during the positioning process. Three-dimensional positioning method needs four base stations. After base station time is synchronized, mobile tags (locator card) will broadcast messages. After receiving the message, each base station record timestamp. Then you can get time difference Δt of wireless signal propagation between different base station, and using the distance formula you can get the distance difference $\Delta d = C \times \Delta t$ between the base station, where C is the speed of light.

Due to the principle, R_1 , R_2, R_3 , R_4 respectively represents for the distance from the mobile label $X(x, y, z)$ to four stations A (x_1, y_1, z_1), B (x_2, y_2, z_2), C (x_3, y_3, z_3), D (x_4, y_4, z_4), then we can get :

$$\begin{cases} R_1 = \sqrt{(x_1 - x)^2 + (y_1 - y)^2 + (z_1 - z)^2} \\ R_2 = \sqrt{(x_2 - x)^2 + (y_2 - y)^2 + (z_2 - z)^2} \\ R_3 = \sqrt{(x_3 - x)^2 + (y_3 - y)^2 + (z_3 - z)^2} \\ R_4 = \sqrt{(x_4 - x)^2 + (y_4 - y)^2 + (z_4 - z)^2} \end{cases} \tag{1}$$

Suppose that the distance difference between the mobile label to the Nth base station and to the first base station is $R_{n1} = R_n - R_1 (n = 2,3,4)$. The distance difference is a known condition, and the position coordinates of the four base stations are known, then:

$$\begin{cases} R_{21} = R_2 - R_1 \\ R_{31} = R_3 - R_1 \\ R_{41} = R_4 - R_1 \end{cases} \tag{2}$$

According to formula (1) and (2), the *X* coordinate value of the mobile label can be calculated.

3. UWB Algorithm

3.1. Direct Matrix Method

The direct matrix method is the matrix solution of the expression based on formula (1) and formula (2), and calculate unknown coordinates by using a system of linear algebraic operations.

Formula (3) and (4) can be obtained by simplifying Formula (1) and (2):

$$R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} \tag{3}$$

$$R_n^2 = (R_1 + R_{n1})^2 = R_1^2 + 2 * R_1 * R_{n1} + R_{n1}^2 \tag{4}$$

By combining formula (3) and formula (4), it can be obtained:

$$(x_n - x)^2 + (y_n - y)^2 + (z_n - z)^2 = R_1^2 + 2 * R_1 * R_{n1} + R_{n1}^2 \tag{5}$$

Putting $R_1 = \sqrt{(x_1 - x)^2 + (y_1 - y)^2 + (z_1 - z)^2}$ into the formula (5), and ordering $k_i = x_i^2 + y_i^2 + z_i^2$, $x_{ni} = x_n - x_i$, it can be obtained:

$$2 * R_1 * R_{n1} + 2 * x_{n1} * x + 2 * y_{n1} * y + 2 * z_{n1} * z = k_n - k_1 - R_{n1}^2 \tag{6}$$

The system of equations can be obtained by formula (6):

$$\begin{bmatrix} x_{21} & y_{21} & z_{21} \\ x_{31} & y_{31} & z_{31} \\ x_{41} & y_{41} & z_{41} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = - \begin{bmatrix} R_{21} \\ R_{31} \\ R_{41} \end{bmatrix} * R_1 + \frac{1}{2} * \begin{bmatrix} k_2 - k_1 - R_{21}^2 \\ k_3 - k_1 - R_{31}^2 \\ k_4 - k_1 - R_{41}^2 \end{bmatrix} \tag{7}$$

(x, y, z) can be solved by using formula (7), and then substituted into R_1 to obtain the value of R_1. Negative results that do not conform to physical meaning are eliminated, and positive numbers are substituted into formula (7) again to obtain the final moving label coordinates.

By converting the formula (7) to the matrix form $AX = B$, we know that:

$$A = \begin{bmatrix} x_{21} & y_{21} & z_{21} \\ x_{31} & y_{31} & z_{31} \\ x_{41} & y_{41} & z_{41} \end{bmatrix} \tag{8}$$

$$X = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{9}$$

$$B = \begin{bmatrix} - R_{21} * R_1 + \frac{1}{2}(k_2 - k_1 - R_{21}^2) \\ - R_{31} * R_1 + \frac{1}{2}(k_3 - k_1 - R_{31}^2) \\ - R_{41} * R_1 + \frac{1}{2}(k_4 - k_1 - R_{41}^2) \end{bmatrix} \tag{10}$$

You can also solve for $X = A^{-1}B$ with linear algebra, and then you can get the three-dimensional coordinate data, provided that the matrix A is invertible.

3.2. Least Squares Matrix Method

There is some error in the direct matrix method, but the least square matrix method can reduce the error and obtain more accurate coordinate data.

Taking the coordinate X of the moving label as the output value of a group of samples, the process of solving the unknown variable by the least square method is relatively simple, and the optimal solution is obtained by the idea of taking the derivative of the extreme value. Let $f(X) = \|AX - B\|_2^2$, and derive the least squares matrix according to the sum of square variance, 2-norm and matrix calculation， the specific derivation process of the least squares matrix is as follows:

$$\|AX - B\|_2^2 = (AX - B)^T(AX - B) = (X^T A^T - B^T)(AX - B) \tag{11}$$

$$(X^T A^T - B^T)(AX - B) = X^T A^T AX - X^T A^T B - B^T AX + B^T B \tag{12}$$

The X corresponding to the minimum value of $f(X)$ is obtained, namely:

$$\frac{d(X^T A^T AX - X^T A^T B - B^T AX + B^T B)}{d(x)} = 2A^T AX - 2A^T B = 0 \tag{13}$$

The final calculated formula is:

$$X = (A^T A)^{-1} A^T B \tag{14}$$

By solving the system, the three-dimensional coordinate value corresponding to the moving label X can be calculated, but the solution of the system requires the matrix A to be invertible.

4. Positioning Experiment and Analysis

The UWB positioning experiment site is selected in the experimental area on the third floor of Shangxue Building, Shijiazhuang University. In order to eliminate controllable errors and improve positioning accuracy, the test data collected several times were preprocessed, and the error or outlier values were removed by statistical analysis method for data cleaning, and then the average value was calculated as the measured results.

4.1. Positioning Analysis with or without Occlusion

The positioning analysis experimental area of UWB with or without occludes included people walking around, desks and chairs debris and other occludes. After the experimental scene is set up, ten standard distance test points are selected and numbered as A1, A2, ... A10, and the distance between two adjacent test points is one meter, and then the difference between the standard distance and the measured distance is counted to obtain data analysis.

4.1.1. Positioning Experiment without Occlusion

According to the above experimental scenario without occlusion, the comparison line chart between the standard distance and the measured distance of the 10 test points in Fig. 1 on the left under the condition of no occlusion can be obtained through testing. The measured distance data is the average of multiple measurement results. Fig. 1 on the right shows the bar chart of the corresponding ranging error.

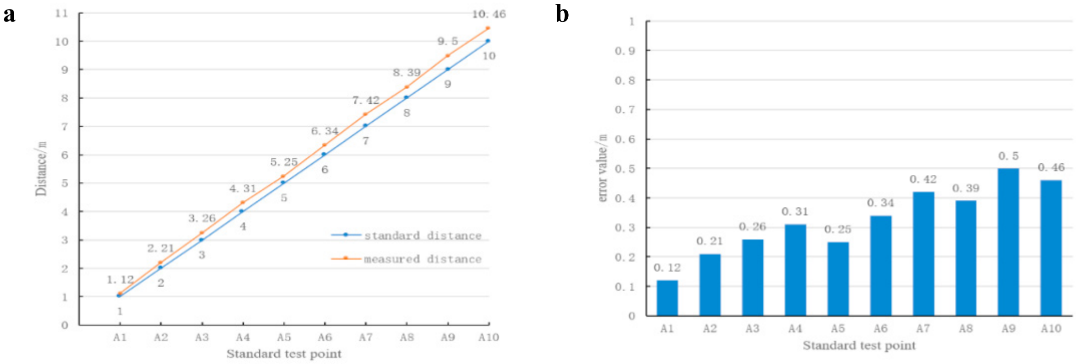

Fig.1. (a) Line chart of ranging data without occlusion; (b) Histogram of ranging error without occlusion.

According to the analysis of Figure 1, in the case of no occlusion, the measured distance is larger than the standard distance, with the maximum error of 50 cm, the minimum error of 12 cm, and the average error of 32.6 cm. As the distance increases from the close to the distant, the distance error increases from small to large, and the cumulative error increases, and the distance and error show a positive correlation. On the whole, the positioning error of UWB without occlusion is small and stable, and the positioning accuracy is higher.

4.1.2. Positioning Experiment with Occlusion

According to the above experimental scene, the shielding objects are sundries such as desks, chairs, books and so on. After testing, the line chart of the comparison between the standard distance and the measured distance as shown in Figure 2 on the left can be obtained, and the measured distance data is the average of multiple measurement results. Figure 2 on the right shows the bar chart of the corresponding ranging error.

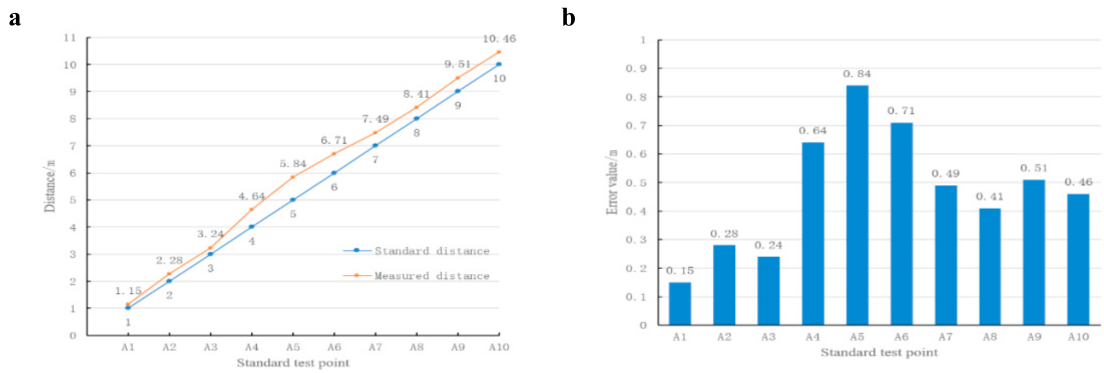

Fig.2. (a) Line chart of ranging data with occlusion; (b) Histogram of ranging error with occlusion.

According to the analysis of Figure 2, in the case of occlusion, the measured distance is larger than the standard distance, and the error fluctuates greatly, with the maximum error being 84 cm, the minimum error being 15 cm, and the average error being 47.3 cm. Moreover, as can be seen from the line chart, the error of A1-A3 test points has little difference from the error without occlusion. The two broken lines after A7 are almost parallel, and the error value is basically stable. On the whole, UWB signal has strong penetrating power and good anti-jamming effect.

4.2. Analysis of Positioning Algorithm

In UWB positioning experiment scene, a three-dimensional environment with a space size of 2.5m*2.5m*2.5m is built. The setup scene hardware consists of 4 base stations and 10 tags. When the base station is laid, it is necessary that the 10 mobile tags are within the effective range of the signal coverage of the 4 base stations. Otherwise, the signal of the base station cannot be received. At the same time, in order to avoid all base stations in the same height plane, there must be a certain height difference, which directly affects the accuracy of tag positioning [14]. Therefore, in order to ensure the label coordinates to obtain more accurate, this experiment sets the four base station coordinates to A (0,0,2.5), B (2.5, 2.5, 2.5), C (,2.5 0, 0), D (2.5, 0, 0), that will be in meters, and every three base stations' location presents an equilateral triangle when putting the attachment, namely putting the base station on the four corners of a cube, and the target label can move freely in cube three-dimensional space. Then, the 10 tags were placed in different positions in three-dimensional space, and the coordinate data of the same tag was measured for 20 times. The average value of the coordinates of each tag was calculated, and then the standard deviation of the measured coordinates of each tag was calculated. Using the direct matrix algorithm(DMA) and the least square matrix algorithm(LSMA) to calculate the coordinate data of each label, the following data table can be obtained:

Table 1. Algorithm comparison data table.

tag	Real coordinates	Mean standard deviation of measured coordinates		average error	
		DMA	LSMA	DMA	LSMA
1	(0.50, 0.50, 0.60)	(0.07, 0.17, 0.39)	(0.08, 0.18, 0.34)	0.41	0.36
2	(0.75, 0.20, 0.40)	(0.08, 0.16, 0.42)	(0.09, 0.17, 0.36)	0.45	0.38
3	(0.80, 0.50, 0.50)	(0.06, 0.18, 0.48)	(0.07, 0.17, 0.34)	0.51	0.38
4	(1.10, 2.00, 0.80)	(0.07, 0.19, 0.46)	(0.07, 0.18, 0.30)	0.47	0.33
5	(1.25, 1.00, 1.00)	(0.08, 0.17, 0.43)	(0.08, 0.18, 0.28)	0.45	0.30
6	(1.40, 0.80, 1.20)	(0.06, 0.18, 0.48)	(0.08, 0.19, 0.29)	0.49	0.32

7	(1.60, 1.00, 0.50)	(0.08, 0.17, 0.51)	(0.09, 0.18, 0.38)	0.52	0.40
8	(1.80, 1.50, 1.00)	(0.08, 0.16, 0.48)	(0.09, 0.17, 0.33)	0.50	0.36
9	(2.00, 1.80, 0.80)	(0.07, 0.19, 0.37)	(0.08, 0.19, 0.31)	0.39	0.32
10	(2.20, 2.00, 1.50)	(0.06, 0.18, 0.46)	(0.07, 0.18, 0.32)	0.48	0.35

According to the experimental results, the average error value of the labels obtained by the direct matrix algorithm is 0.467m, and the average error value of the labels obtained by the least square matrix algorithm is 0.350m, which reduces the average error by 0.117m and improves the accuracy by about 25%. Experiments show that the least square matrix method can obtain more accurate coordinate data and improve the precision of 3d positioning.

5. Conclusion

UWB technology is an indoor positioning technology based on location service, which has a broad market prospect. Based on the TDOA 3D positioning method, this paper designs the ranging experiment with or without occlusion, analyzes and compares the ranging errors, and verifies the advantages of strong penetration and good anti-interference effect of UWB. At the same time, the coordinate data calculation methods of UWB are compared and analyzed. The data show that the least square matrix algorithm can reduce the calculation error, improve the accuracy of positioning coordinates by 25%, and make the position information more accurate.

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