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Analysis of UWB Indoor Positioning Accuracy Based on TW-TOF

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Abstract: UWB has the characteristics of low power consumption, low system complexity, strong anti-interference, high penetration, and high positioning accuracy. In this paper, the principle of ultra-wide-band ranging and positioning is introduced in detail, followed by the TOA positioning method based on two-way time-of-flight ranging, and the positioning results are solved by using the least-squares and Gauss-Newton iterative algorithms, and the experimental positioning The experimental positioning errors were analyzed. The experimental results show that UWB has good indoor ranging and positioning accuracy.

Keywords: UWB, Localization, TW-TOF, TOA.

1. Introduction

In recent years, ultra-wideband (UWB), a new high-precision wireless intersection positioning technology, has emerged as one of the top positioning technologies with its unique advantages. It has developed into a mainstream indoor high-precision ranging and positioning technology, especially in the fields of emergency positioning, intelligent storage, asset monitoring, smart prisons, nursing homes, and seamless navigation, etc. [1-2], because it has unparalleled advantages in positioning accuracy when applied to indoor wireless positioning systems.

In order to study the UWB in indoor high-precision ranging and positioning, this paper adopts the popular UWB devices in the market, conducts ranging and positioning experiments using the TOA positioning method of bidirectional ranging TW-TOF, and solves the positioning coordinates using the least squares algorithm and Gauss-Newton iterative algorithm, and analyzes the accuracy of the positioning results of the simulation experiments to prove the accuracy and reliability of UWB positioning.

2. UWB Distance Measurement Principle

This paper adopts the two-way time-of-flight (TW-TOF) ranging method of UWB system to measure the distance between the tag and the base station, which is a two-way ranging technique. The distance between the base station and the tag can be calculated by calculating the transmission time between the two. This method does not require the time synchronization of the base station, which can effectively improve the ranging accuracy. The two-way ranging process is shown in Figure 1.

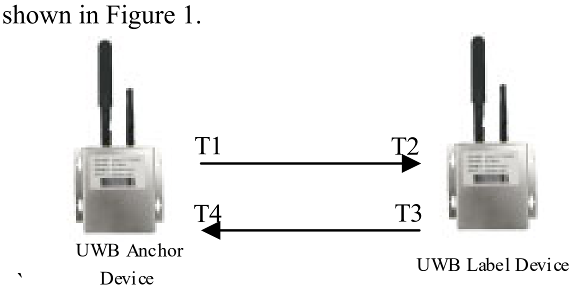

Figure 1. Two-way ranging process

In the ideal case the distance between the UWB base station and the UWB tag can be expressed as in equation (1).

$$d = c \times \left[(\mathrm{T}2 - \mathrm{T}1) + (\mathrm{T}4 - \mathrm{T}3) \right] / 2 \tag{1}$$

Formula: c is the speed of propagation of electromagnetic waves in a vacuum, 3*108m/s; T1 is the anchor transmitting signal time; T4 is the signal reception time of the anchor; T2 is the Label reception time of the signal; T3 is the Label transmitting signal time.

3. TOA Positioning Model

According to the principle of wireless ranging, the high temporal resolution of UWB signals is used to achieve high positioning accuracy and low complexity of the positioning system without the need for base station time synchronization, and the TOA positioning model is selected in this paper. At least three UWB base stations are required in the positioning system, and the distance circle is formed by the radius of each base station and UWB tag, and the three circles intersect at one point to achieve positioning [3-4].

Assuming that the coordinates of the i th UWB base station in the positioning system are (x_i, y_i), $i = 1,2,3$ The distance from each base station to the UWB label is d_i, $i = 1,2,3$, (x,y) is the coordinates of the label to be determined., Then the UWB ranging distance model can be expressed as equation (2):

$$d_i = \sqrt{(x_i - x)^2 + (y_i - y)^2} \tag{2}$$

The three distance values of the three distance circles can form the coordinate solution equation (3):

$$\begin{cases} d_1 = \sqrt{(x_1 - x)^2 + (y_1 - y)^2} \\ d_2 = \sqrt{(x_2 - x)^2 + (y_2 - y)^2} \\ d_3 = \sqrt{(x_3 - x)^2 + (y_3 - y)^2} \end{cases} \tag{3}$$

The three equations solve the two unknowns of the label coordinates (x,y), can complete the positioning.

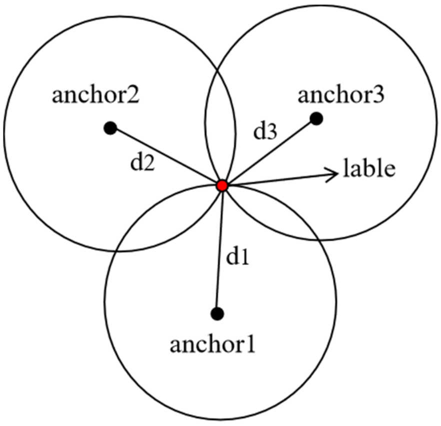

Figure 2. TOA positioning model

In the TOA-based positioning system, the positioning label is continuously ranging with the base station at a known location by transmitting a pulse signal of a certain frequency to obtain the measurements of the label with the base station at a known location. In this paper, we use the time-of-arrival (TOA) localization method to first derive the preliminary localization results of the label by the least squares algorithm [5-6] and solve the three-dimensional coordinates of the label using Gauss-Newton iterative method (x,y,z).

The system of observation equations to solve for the label 3D coordinates (x,y,z) is equation (4):

$$\begin{cases} p_1=\sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} \\ p_2=\sqrt{(x-x_1)^2+(y_2-y)^2+(z-z_2)^2} \\ \vdots \\ p_n=\sqrt{(x-x_n)^2+(y_n-y)^2+(z-z_n)^2} \end{cases} \quad (4)$$

in the formula: $p_1, p_2, \cdots p_n$ denotes the distance between the base station and the label. $(x_1,y_1,z_1),(x_2,y_2,z_2),\cdots(x_n,y_n,z_n)$ indicates the coordinates of the anchor.

After squaring the two sides of each equation in equation (4) and making the difference, and simplifying it to matrix form we get equation (5):

$$AX_0=b \quad (5)$$

$$A=2\begin{bmatrix} x_1-x_2 & y_1-y_2 & z_1-z_2 \\ x_1-x_3 & y_1-y_3 & z_1-z_3 \\ \vdots & \vdots & \vdots \\ x_1-x_2 & y_1-y_n & z_1-z_n \end{bmatrix};$$

$$X_0=(x,y,z);$$

$$b=\begin{bmatrix} p_2^2-p_1^2+x_1^2-x_2^2+y_1^2-y_2^2+z_1^2-z_2^2 \\ p_3^2-p_1^2+x_1^2-x_3^2+y_1^2-y_3^2+z_1^2-z_3^2 \\ \vdots \\ p_n^2-p_1^2+x_1^2-x_n^2+y_1^2-y_n^2+z_1^2-z_n^2 \end{bmatrix}$$

Based on the least squares principle, the coordinates of the initial position of the label are derived as in equation (6):

$$X_0=\left(A^TA\right)^{-1}A^Tb \quad (6)$$

$X_0=(x_0,y_0,z_0), \delta X=(\delta x,\delta y,\delta z)$ are the initial value and correction number of label coordinates, respectively, $p_1, p_2, \cdots p_n$ is the approximate distance between the base station and the label, and the position coordinates of the label are derived according to the Gauss-Newton iterative algorithm as shown in equation (7):

$$X=\left(B^TB\right)^{-1}B^TL+X_0 \quad (7)$$

$$B=\begin{bmatrix} \frac{x_1-x_0}{p_{1,0}} & \frac{y_1-y_0}{p_{1,0}} & \frac{z_1-z_0}{p_{1,0}} \\ \frac{x_2-x_0}{p_{2,0}} & \frac{y_2-y_0}{p_{2,0}} & \frac{z_2-z_0}{p_{2,0}} \\ \vdots & \vdots & \vdots \\ \frac{x_n-x_0}{p_{n,0}} & \frac{y_n-y_0}{p_{n,0}} & \frac{z_n-z_0}{p_{n,0}} \end{bmatrix}, \quad L=\begin{bmatrix} p_{1,0}-p_1 \\ p_{2,0}-p_2 \\ \vdots \\ p_{n,0}-p_n \end{bmatrix}$$

$p_{1,0}, p_{2,0}, \cdots p_{n,0}$ Indicates the distance between the Anchor and the initial position of the label.

4. Experiment and Analysis

The instrumentation used for this experiment includes the software MATLAB2019a, a computer configured with Intel(R) Core(TM) i5 1.70GHz, Windows 7 64-bit operating system with 4GB RAM, and UWB positioning device.The environment of this experiment was selected at the address of Teaching Building F, College Building, Daxing Campus, Beijing University of Architecture. The experimental data collection site is shown in Figure 3.

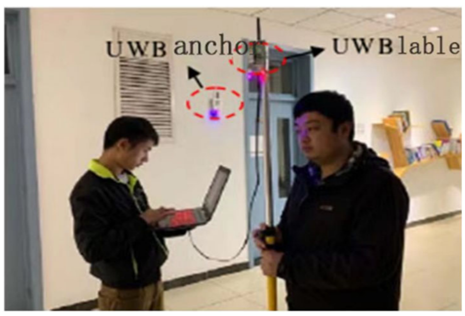

Figure 3. Experimental data acquisition

In order to verify the positioning accuracy and algorithm robustness of TW-TOF UWB positioning model, eight UWB anchors were deployed at the experimental site for testing experiments. The coordinates of UWB anchors are shown in Table 1, and the deployment of UWB anchors is shown in Figure 4:

UWB anchor coordinates Table 1.

Anchor ID	Anchor coordinates(m)
34484127	(7.535, 0.698, 1.057)
34484126	(7.561, 2.440, 2.440)
3448411C	(25.908, 0.037, 3.430)
34484133	(26.005, 2.586, 1.594)
34484A3D	(43.573, 2.122, 1.656)
3448412E	(43.567, 3.351, 1.977)
3448411E	(60.062, 2.005, 1.447)
34484129	(59.539, 3.535, 0.965)

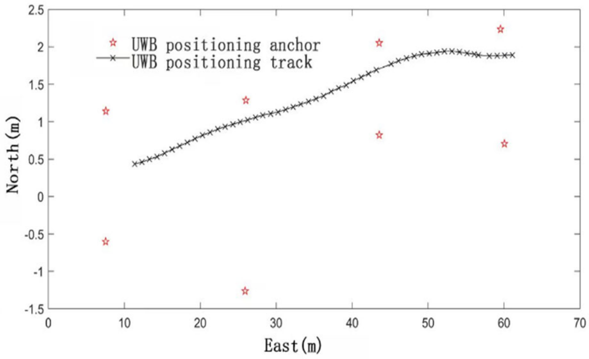

Figure 4. UWB anchor deployment location

Firstly, the UWB anchor deployment sites are reasonably selected and UWB anchor deployment is carried out in the experimental field. Then plan the pedestrian movement trajectory and use a high precision total station to measure a large number of localizations on the movement trajectory and compose a digital trajectory for later experimental accuracy analysis.

Secondly, the experimenter carries the UWB label in the test field according to the pre-planned motion trajectory, and the UWB label and its surrounding UWB anchor measure each other's distance and transmit the data to the laptop record in real time through the serial port.

Finally, the designed UWB positioning model is used to solve the real-time point position of the motion trajectory and make accuracy analysis. the motion trajectory generated by UWB positioning is shown in Figure 5, and the UWB positioning error is shown in Figure 6.

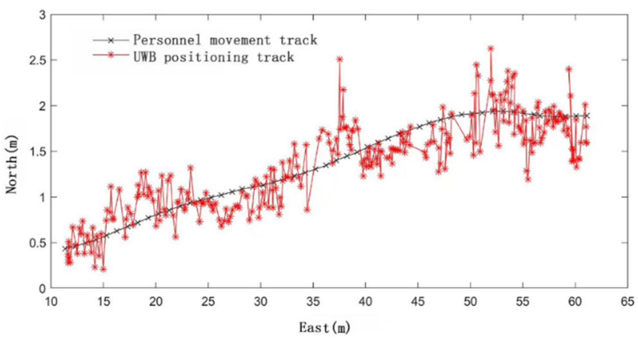

Figure 5. UWB positioning trajectory

The experimenter's motion trajectory solved by the TW-TOF-based UWB localization model proposed in this paper is the red curve in Figure 5, and it is obvious that the UWB localization coordinate trajectory fluctuates up and down slightly around the real planning trajectory curve. In the process of UWB positioning, there are inevitably large errors in the measured values due to the influence of many different factors, which leads to large deviations in the positioning results. On the one hand, the errors of UWB positioning coordinates solved by the positioning model are random, and some points have large errors, which may be caused by the flow of other people in the UWB test site or the experimenters themselves blocking the straight-line transmission of signals between the UWB anchor and the label during the experimental data collection. On the other hand, the trajectory floating indicates the existence of errors in UWB positioning, which is caused by the existence of UWB ranging errors and UWB positioning model perturbation.

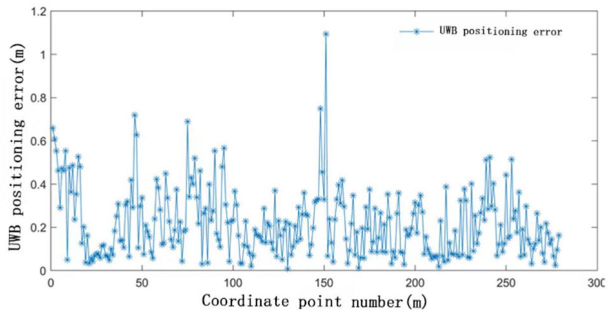

Figure 6. UWB positioning error

As can be seen from the figure, the UWB positioning error is small and mainly concentrated between 0 and 0.4 m. Therefore, the positioning model can achieve UWB sub-meter positioning accuracy, which is the best among many indoor positioning technologies at present, fully verifying the high accuracy and effectiveness of UWB positioning technology and the UWB positioning model proposed in this paper. The specific values of UWB positioning accuracy were obtained: the maximum UWB positioning error was 1.09 m, the average positioning error was 0.21 m, the standard deviation of positioning error was 0.15 m, and the variance of ranging error was 0.02 m. The accuracy reliability of UWB positioning error less than 0.2 m was 54.12%, and the accuracy reliability of UWB positioning error less than 0.4 m was 87.81%.

5. Conclusion

In this paper, through simulated positioning experiments and real UWB dynamic positioning experiments, the TOA positioning method based on bi-directional ranging TW-TOF is used for ranging and positioning experiments, and the least squares algorithm and Gauss-Newton iterative algorithm are used to solve the positioning coordinates. The accuracy and reliability of UWB positioning are proved by the accuracy analysis of the experimental positioning results.

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