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A Precise 3D Positioning Approach Based on UWB with Reduced Base Stations

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***Abstract*—Ultra wide band (UWB) technology is widely used in indoor three-dimensional positioning system because of its wide bandwidth advantage and outstanding anti-narrow band interference ability. However, the high cost of base stations limit widespread use of UWB technology. At present, mainstream UWB positioning algorithms need to use four base stations, and the calculation process is complex. This paper proposes a three-base-station UWB location algorithm based on TOF (time of flight). The proposed algorithm also simplify the calculation procedure of 3D positioning, using three base stations, which effectviely reduces the cost of adoption for UWB 3D positioning system.**

Keywords—indoor positioning; three dimensional positioning; ultra wide band; algorithm optimization

I. Introduction

Positioning technology is used to locate people, equipments and other objects. According to the environment, positioning can be divided into two categories: outdoor positioning and indoor positioning. Indoor positioning has sufficient applications in many specific conditions, which can determine the three-dimensional position of objects in a narrow area such as the interior of buildings continuously and accurately. At present, the mainstream technologies of indoor positioning mainly include radio frequency identification (RFID), ultra wideband (UWB), infrared, ultrasonic, ZigBee, Bluetooth and WLAN [1][2][3]. Among them, UWB technology uses a very narrow pulse to transmit data, which is different from the traditional sinusoidal carrier, which empowers UWB positioning technology to achieve high positioning precision, high penetration ability, low power consumption, strong anti-interference ability [4].

The highest data transmission rate of UWB technology can reach 100 megabits per second (Mbps), which has great advantages in near-field data transmission [5]. In the 1960s, the U.S. military first began to carry out research on UWB technology, and then developed it rapidly [6]. Domestic research on UWB technology in China began in 1999[7]. In 2003, the national "863" plan took UWB technology as a key research project. Since then, the National Natural Science Foundation of China set up a special fund to study UWB related technologies [8].

When UWB technology is applied to indoor 3D positioning, the expensive cost of location base station is an important factor to restrict the widespread adoption of this technology. One direct approach of reducing the cost of UWB technical is to reduce the number of base stations used, without he positioning accuracy of the system cannot be too sacrificing and at the same time, t. At present, at least four positioning base stations are needed in the mainstream UWB indoor 3D positioning system[9][10]. Three of them are in the same plane, while the other is not in the plane. The fourth base station is mainly used to calculate the height information of mobile tags.

In this paper, we propose a three base station UWB location algorithm based on TOF. The algorithm only needs to use three base stations to achieve three-dimensional positioning, and the base station layout does not need to strictly meet the isosceles triangle, just need any three base stations in the same plane and not in the same line. Its main principle is to use the height information of the tag itself to participate in the calculation of three-dimensional coordinates. Even if the tag can move anywhere in the three-dimensional space as a virtual base station, it can achieve the positioning effect similar to the positioning system composed of four base stations.

The remainder of this paper is organized as follows. Section II gives the design details of three base station UWB positioning algorithm based on TOF. The experimental and simulation results are shown in Section III. Finally, this paper is concluded in Section IV.

II. Three Base Station UWB Location Algorithm Based on TOF

TOF algorithm is used to calculate the three-dimensional coordinates of tags by solving the circular equation, which requires four base stations not in the same plane. After the distance between different base stations and tags is obtained by TOF algorithm, the coordinates of tags are obtained by solving circle equations.

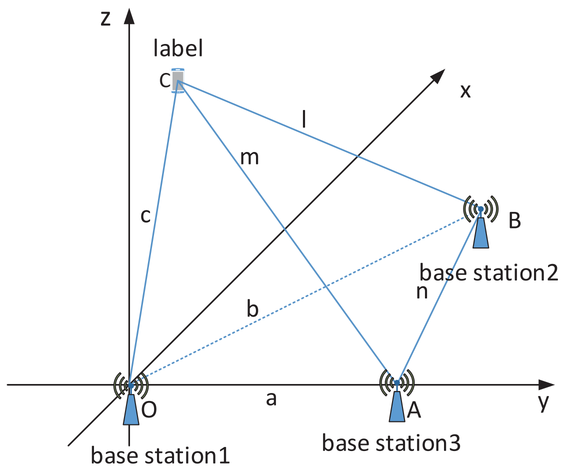

Figure 1. Schematic diagram of label and base station placement

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When the number of base stations is reduced from four to three, the corresponding coordinate calculation method should also be changed. The specific calculation method of tag coordinates in TOF based three base station UWB positioning algorithm is given below.

A. Label Coordinate Calculation

The layout of the base station and the label is shown in Fig. 1. The positions of the three base stations are fixed and in the same plane to form a triangle of arbitrary shape. The approximate calculation process of the label coordinates is as follows:

1) TOF ranging algorithm is used to calculate the distance between base stations and between base stations and labels[11];

2) According to the distance between the base stations, the coordinate system is established and the coordinates of the three base stations are output;

3) The volume of tetrahedron composed of label and base station is calculated by Euler formula;

4) The triangle area of the bottom base station is calculated by Helen formula, and then the coordinate of the label is obtained by using the tetrahedral volume;

5) The X-axis and Y-axis coordinates of the label are calculated by the triangle area conversion formula;

6) Through the cosine theorem to determine the angle size, so as to determine the label X axis and Y axis coordinates positive and negative [12] [13].

B. Establishment Process of Coordinate System

After the base station establishes the connection, the distance between the base stations can be obtained. A, B and C are the locations of the three base stations. After the system is connected, the length of each side of the triangle formed by the base station can be obtained, that is, AB, AC and BC are known, but their specific coordinates are unknown. If the area of triangle ABC is $S_{\triangle ABC}$, according to Helen's formula:

$$S_{\triangle ABC} = \sqrt{(p-AB)\cdot(p-AC)\cdot(p-BC)\cdot p} \tag{1}$$

$$P = \frac{AB+AC+BC}{2} \tag{2}$$

$$S_{\triangle ABC} = OA \cdot BC \cdot \frac{1}{2} \tag{3}$$

Combining Eq. (1) and Eq. (3), OA can be calculated, that is

$$OA = \frac{2 \cdot S_{\triangle ABC}}{BC} \tag{4}$$

From Pythagorean theorem, we can calculate OB and OC, which have the same relationship

$$OB = \sqrt{AB^2 - OA^2} \tag{5}$$

$$OC = \sqrt{AC^2 - OA^2} \tag{6}$$

The system establishes the coordinate system and outputs the coordinates of each base station, namely $A\,(0, OA, 0)$, $B\,(-OB, 0, 0)$, $C\,(OC, 0, 0)$. The 3D coordinate calculation of subsequent tags is based on this coordinate system.

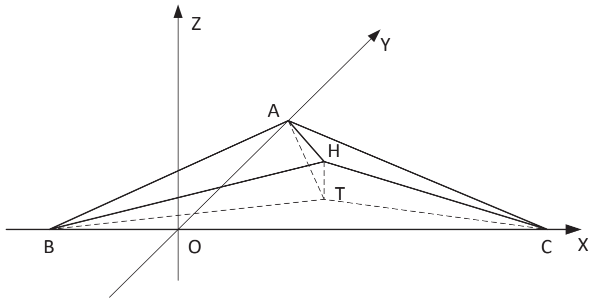

Figure 2. The base station and the tag form a tetrahedron

C. Label Z-axis Coordinate Calculation

H is the actual position of the label in the three-dimensional space, T is the projection of the label on the xoy plane, H coordinates are set as $H\,(x0, y0, z0)$, T coordinates are set as $T(x0, y0, 0)$. HA, HB, HC are the distance from the label to each base station, then the known information after the system is connected is AB, AC, BC, HA, HB, HC.

Assuming $a = HA$, $b = HB$, $c = HC$, $l = BC$, $m = AC$, $n = AB$, the tetrahedral volume formula is obtained according to Euler formula, and the tetrahedral $HABC$ volume is set as V_{HABC}, there is

$$V_{HABC}^2 = \frac{1}{36}\begin{vmatrix} a^2 & \frac{a^2+b^2-n^2}{2} & \frac{a^2+c^2-m^2}{2} \\ \frac{a^2+b^2-n^2}{2} & b^2 & \frac{b^2+c^2-l^2}{2} \\ \frac{a^2+c^2-m^2}{2} & \frac{b^2+c^2-l^2}{2} & c^2 \end{vmatrix} \tag{7}$$

According to Fig. 2, the volume of tetrahedral $HABC$ can be expressed as

$$V_{HABC} = \frac{1}{3} S_{\triangle ABC} \cdot HT \tag{8}$$

The simultaneous Eq. (7) and Eq. (8) can be obtained

$$HT = 3 \cdot \frac{V_{HABC}}{S_{\triangle ABC}} \tag{9}$$

The z-axis coordinate of label is calculated, $z0 = HT$.

D. Y-axis Coordinate Calculation of Label

The x-axis and y-axis coordinates of the label are calculated and regressed to the two-dimensional plane. First, the determination of the y-axis coordinates of the label is discussed, as shown in Fig. 3.

T is the projection of label H on the xoy plane, and the three-dimensional coordinates are $(x0, y0, 0)$. Tx is the projection point of T on the X-axis and Ty is the projection.

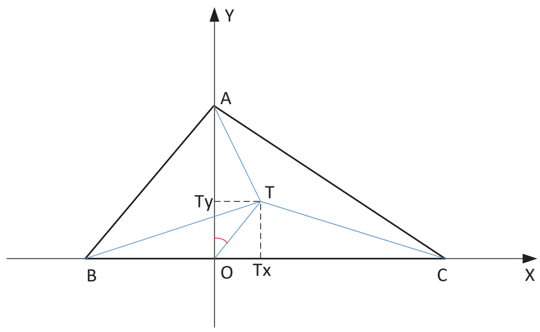

Figure 3. Y-axis coordinate calculation

of T on the y-axis. $y0$ can be obtained from the area conversion of S_TBC.When the volume of tetrahedral $HABC$ is not zero, TA, TB and TC can be calculated by HA, HB and HC. The specific method is as follows:

$$TA = \sqrt{HA^2 - HT^2} = \sqrt{HA^2 - z0^2} \tag{10}$$

$$TB = \sqrt{HB^2 - HT^2} = \sqrt{HB^2 - z0^2} \tag{11}$$

$$TC = \sqrt{HC^2 - HT^2} = \sqrt{HC^2 - z0^2} \tag{12}$$

$p0$ is set as the half circumference of $\triangle TBC$, that is

$$p0 = \frac{TB+TC+BC}{2} \tag{13}$$

According to Helen's formula, there is

$$S_{\triangle TBC} = \sqrt{p0(p0-TB)(p0-TC)(p0-BC)}$$
$$= \frac{1}{2}BC \cdot TT_x = \frac{1}{2}BC \cdot OT_y \tag{14}$$

$$|y0| = \frac{2S_{\triangle TBC}}{BC} \tag{15}$$

After that, we need to determine the positive and negative value of $y0$, and we need to determine whether T is located in the upper half axis or the lower half axis of Y axis according to $\angle AOT$. Because we need to get the size of $x0$, the positive and negative judgment of $y0$ will be carried out later.

E. X-axis Coordinate Calculation

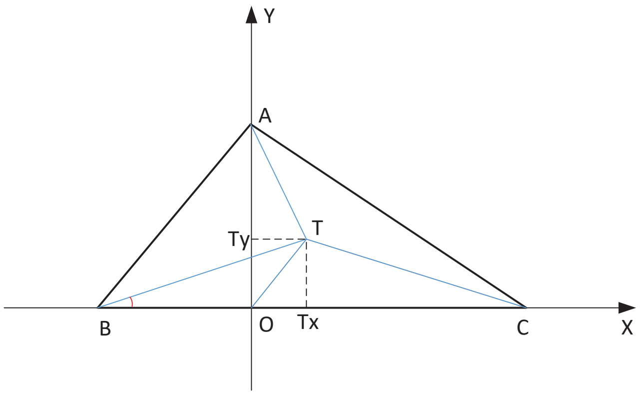

Figure 4. Calculation of X positive half axis coordinate

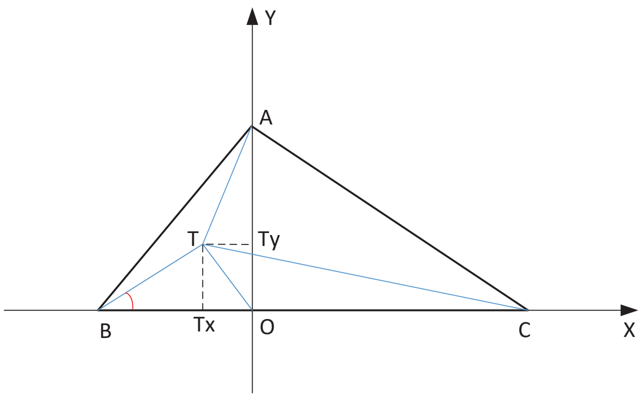

Figure 5. Calculation of X negative half axis coordinate

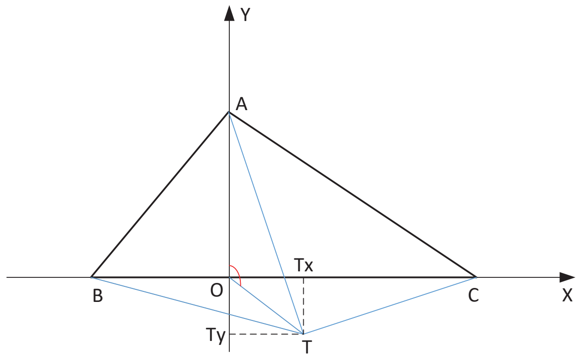

Figure 6. Y-axis coordinate calculation

As shown in Fig. 4, when T_x is in the positive half of the X axis, the length of OT_x is the abscissa $x0$ at this time. Since the positive and negative values of $y0$ have not been determined, you can directly use $y0^2$ to participate in the calculation and cross the positive and negative determination process of $y0$, there is

$$BT_x = \sqrt{TB^2 - y0^2} \tag{16}$$

$$x0 = BT_x - OB \tag{17}$$

When T_x is in the negative half of the X-axis, as shown in Fig. 5,

$$BT_x - OB = -T_xO = x0 \tag{18}$$

When $T_xO < OB$, it is not necessary to judge the positive and negative of $x0$ independently, and Eq. (17) can be used to solve $x0$ uniformly.

When$T_xO > OB$, there is

$$x0 = -T_xO = -(BT_x + OB) \tag{19}$$

F. Positive and Negative Determination of Y-Axis Coordinate of Label

TO, TA and OA are known, $TO^2 = x0^2 + y0^2$,

1) When$TO^2 + OA^2 - TA^2 > 0$, $\angle AOT$ is the acute angle, as shown in Fig. 3. At this time, the result calculated according to Eq. (15) is the Y-axis coordinate $y0$ of the label, that is

$$y0 = \frac{2S_{\triangle TBC}}{BC} \tag{20}$$

2) When $TO^2 + OA^2 - TA^2 < 0$, $\angle AOT$ is an obtuse angle, as shown in Fig. 6

$$y0 = -\frac{2S_{\triangle TBC}}{BC} \tag{21}$$

3) When $TO^2 + OA^2 - TA^2 = 0$, $\angle AOT$ is a right angle, that is, the Tx and T points in Fig. 6 coincide. At this time, Eq. (20) and Eq. (21) calculate the same result, that is, $y0 = 0$. Therefore, this step can be incorporated into the second step.

III. Experiment And Simulation

For the specific positioning effect and related performance of the designed algorithm, MATLAB software is needed for simulation. In this section, the obtained simulation data are

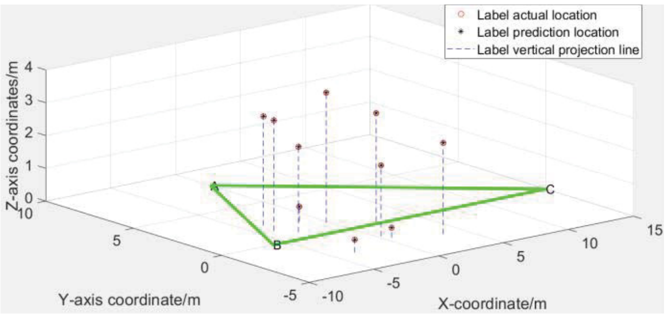

Figure 7. Location of ten points inside and outside the base station triangle

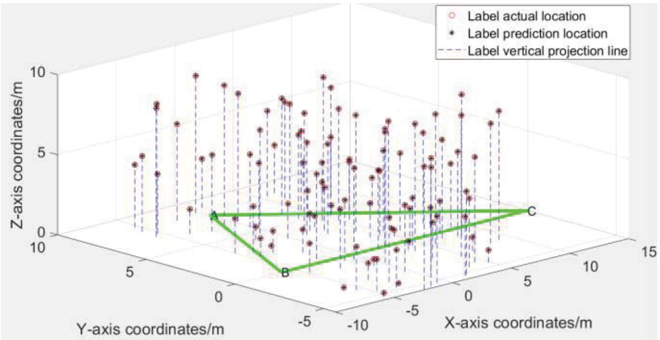

Figure 8. Positioning of 100 points inside and outside the base station triangle

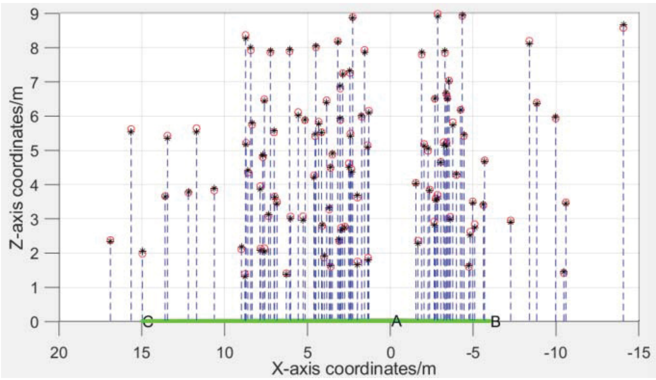

Figure 9. Simulation results of positioning error in X-axis direction

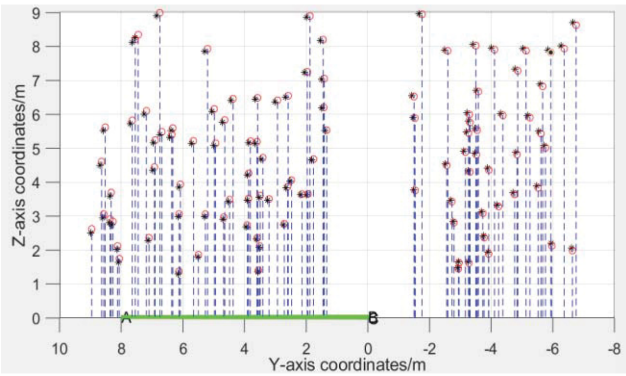

Figure 10. Simulation results of positioning error in Y-axis direction

analyzed, and the results are displayed graphically. Finally, the positioning error of the algorithm in the case of non ideal base station placement is explored.

A. Simulation Results of Location Algorithm

Firstly, ten points are randomly generated inside and outside the triangle formed by the base station. The improved algorithm is used for positioning calculation, and the results are displayed in three-dimensional graphics. As shown in Fig. 7,

In the Fig. 7, the green triangle is the triangle composed of base station A, B and C. The red circle is the preset three-dimensional position of the label, and the black star is the calculated label position of the system. From Fig., we can see that the two completely coincide, and the positioning result of the system is accurate.

100 points are randomly set inside and outside the base station triangle to simulate the situation of multi-target continuous positioning. The positioning results are shown in Fig. 8. The three-dimensional diagram shows that the new algorithm can correctly handle the calculation of multi label continuous positioning.

B. Research on Positioning Speed of Algorithm

In the simulation, the running time of the algorithm is extracted. The specific process is that each time the system locates 100 groups of tags randomly generated, a total of 10 times, and the total time is extracted. Because the new algorithm can deal with the special situation that the base station is placed in an irregular triangle, there is an additional time to establish the coordinate system and output the location of three base stations. After adding this part of time, the simulation is also carried out. The final results are shown in Table 1. The establishment and output of coordinate system have limited influence on the overall positioning speed, which makes the algorithm designed in this paper get rid of the strict placement limit of three base stations without excessive sacrifice of positioning speed.

C. Research on Positioning Error of Algorithm

The above positioning results are only limited to the ideal situation that base stations A, B and C are placed strictly in the same horizontal plane. Because the automatic establishment of the coordinate system is considered in the design of the algorithm, the improved algorithm is not sensitive to the horizontal placement position of the base station, and can allow the base station to be placed into a triangle of arbitrary shape. In practical application, the main error factor is the deviation of the vertical position of the base station.

Based on the above factors, the positioning results when the placement position of the base station is offset by 0.01m are also simulated. Fig. 9, Fig. 10 and Fig. 11 are the simulation results observed from different directions when the placement position of the base station is offset. The simulation results show that there is a certain deviation between the predicted position of the label and the actual position of the label in the X-axis, Y-axis and Z-axis directions.

TABLE I. ALGORITHM SIMULATION TIME

	No coordinate system attached	**Additional coordinate system**
Simulation time (s)	0.01642	0.017125

TABLE II. POSITIONING ERROR RANGE STATISTICS

Error range	<0.3%	0.4%~0.6%
Number of tags	59	36
Error range	0.6%~0.8%	>0.8 %
Number of tags	5	0

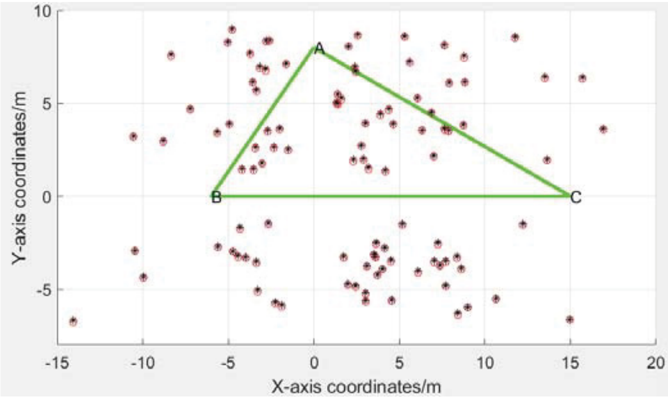

Figure 11. Simulation results of positioning error in z-axis direction

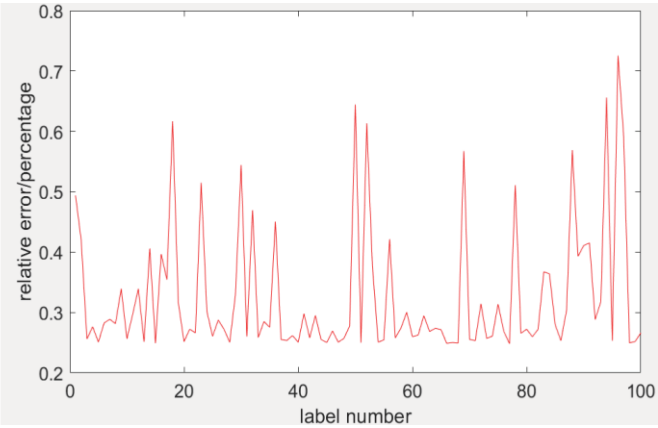

Figure 12. Positioning relative error

In addition, the relative error of continuous positioning of 100 labels is extracted, as shown in Fig. 12. The maximum relative positioning error is less than 0.8% when the base station vertical position offset is 0.01m.

From table 2, it can be seen that the relative error of 95 labels is less than 0.6% of 100 labels. The above results show that the algorithm can ensure high positioning accuracy when there is deviation in vertical position of base station.

IV. SUMMARY

This paper focuses on UWB indoor three-dimensional positioning technology, aiming at the existing UWB three-dimensional positioning algorithm needs at least four base stations, proposes a new three base station UWB positioning algorithm based on TOF. The new algorithm can satisfy that three base stations are placed at any position of different lines on the same plane. The algorithm is verified in MATLAB. The results show that the three base station UWB positioning algorithm based on TOF can get rid of the strict placement restrictions of the three base stations without sacrificing the positioning speed excessively, and can ensure high positioning accuracy when the vertical position of the base station is deviated.

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