UWB ranging error analysis based on TOA mode

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Abstract. By analysing the UWB algorithm based on TOA mode and using the least square location algorithm, the original TOA ranging value is processed, and then the UWB ranging experiment is carried out in the non-line-of-sight environment. It can be found that the least square positioning algorithm adopted in this paper improves the accuracy of UWB ranging to a certain extent, by analysing the experimental data. At the same time, the influence of human shielding on UWB ranging is analysed through concrete experiments, and suggestions on improving the accuracy of UWB ranging are provided.

1. Introduction
Traditional GPS positioning is mainly used in open areas. When the GPS mobile station encounters occlusion, the positioning accuracy will be greatly reduced, and even the deviation will reach tens of meters. In indoor positioning, the traditional GPS positioning has been unable to meet the engineering needs, therefore, UWB indoor positioning technology is gradually rising and developing rapidly [1]. The advantages of UWB positioning technology mainly lie in its ultra-high bandwidth, high efficiency transmission and low power consumption cost [2]. At present, the more mature UWB location algorithm is mainly TWR location algorithm, TOA location algorithm and TDOA location algorithm. This paper mainly describes the UWB ranging accuracy based on TOA positioning algorithm, using the least square positioning algorithm to modify, reduce the impact of noise, and improve the ranging accuracy.

2. TOA positioning model
The positioning algorithm based on TOA (Time of Arrival) estimates the distance between two points by measuring the transmission Time between signals [3]. As shown in Figure 1, A0, A1 and A2 are three positioning base stations. By recording the one-way time between the label and the three base stations and multiplying by the propagation speed of electromagnetic wave in the air, the distance between the label and the three base stations can be obtained, which is denoted as R0, R1 and R2.

![Figure 1 TOA positioning model](image-url)
If we take A0, A1 and A2 as the centre of the circle, and R0, R1 and R2 as the radii to draw three circles, and then the intersection point of the three circles is the location of our label. We can set the coordinate of the label as (x, y), coordinate of A0 (x0, y0), coordinate of A1 (x1, y1), coordinate of A2 (x2, y2), the following formula can be obtained:

\[
\begin{align*}
(x_0 - x)^2 + (y_0 - y)^2 &= R_0^2 \\
(x_1 - x)^2 + (y_1 - y)^2 &= R_1^2 \\
(x_2 - x)^2 + (y_2 - y)^2 &= R_2^2 
\end{align*}
\]

(1)

3. Least squares positioning algorithm

The least square method is a mathematical optimization technique. It looks for the best functional match of data by minimizing the sum of squares of the error. The least square method can be used to obtain the unknown data easily and minimize the sum of squares of errors between the obtained data and the actual data [4]. Assume that the tag coordinates are (x, y, z), the base station coordinates are set to A1 (x1, y1, z1), A2 (x2, y2, z2), ……, An (xn, yn, zn). The following formula can be obtained:

\[
\begin{align*}
(x_1 - x)^2 + (y_1 - y)^2 + (z_1 - z)^2 &= R_1^2 \\
(x_2 - x)^2 + (y_2 - y)^2 + (z_2 - z)^2 &= R_2^2 \\
& \quad \text{……} \\
(x_n - x)^2 + (y_n - y)^2 + (z_n - z)^2 &= R_n^2 
\end{align*}
\]

(2)

Then, by subtracting the last term of each of the previous formulas, we can get:

\[
\begin{align*}
x_1^2 + y_1^2 + z_1^2 - x_2^2 - y_2^2 - z_2^2 - 2(x_1 - x_2)x - 2(y_1 - y_2)y - 2(z_1 - z_2)z &= R_1^2 - R_2^2 \\
& \quad \text{……} \\
x_n^2 + y_n^2 + z_n^2 - x_1^2 - y_1^2 - z_1^2 - 2(x_n - x_1)x - 2(y_n - y_1)y - 2(z_n - z_1)z &= R_n^2 - R_{(n-1)}^2
\end{align*}
\]

(3)

According to the least square principle, the objective function of the least mean square error can be obtained. We can convert the above formula into matrix form as follows:

\[
J(x, y, z) = (A^TA)^{-1}A^Tb
\]

(3)

among them

\[
A = -2 \begin{bmatrix}
x_1 - x_n & y_1 - y_n & z_1 - z_n \\
x_2 - x_n & y_2 - y_n & z_2 - z_n \\
\vdots & \vdots & \vdots \\
x_{n-1} - x_n & y_{n-1} - y_n & z_{n-1} - z_n
\end{bmatrix}
\]

(4)

\[
b = \begin{bmatrix}
R_0^2 - R_1^2 + x_0^2 + y_0^2 - x_0^2 - y_0^2 \\
R_1^2 - R_2^2 + x_1^2 + y_1^2 - x_1^2 - y_1^2 \\
& \quad \text{……} \\
R_{(n-1)}^2 - R_n^2 + x_{(n-1)}^2 + y_{(n-1)}^2 - x_{(n-1)}^2 - y_{(n-1)}^2
\end{bmatrix}
\]

(5)

In accordance with the above algorithm we can undertake four base station simulation test in laboratory, the origin of the coordinate axes placed A0 is given priority to base station, the base station respectively along the x axis direction is ten metres of A1, the base station along the y direction is ten meters place base station A2, A3 placed along the z axis is the direction of ten meters base station, tag activity in the coordinate values are in a non-blocking, non-interference environment with a range of positive number.

By actual measurement, we can calculate our matrices A and B and calculate the root mean square error. The actual test results are shown in Figure 2.
As can be seen from the figure above, in an ideal environment, the distance mean square error is about 22cm without using the least square positioning algorithm. In indoor environment, the error is still relatively large. After using the least square positioning algorithm, the mean square error (MSE) is greatly reduced, which is about 16cm. In addition, when we actually use, there will be some other interference, which will affect our ranging, such as the deployment of base station, clock synchronization, multipath effect and multiple access interference will have an impact on our ranging accuracy. Therefore, we need other measures to further improve our ranging accuracy.

4. NLOS actual test error test and cause analysis

In this experiment, the model used in the previous simulation test is used, and the ranging frequency is 1Hz. Firstly, a half-hour unobclusion visual test is conducted between the label and the main base station A0, base station A1, A2 and A3, and data is recorded at the same time. Then arrange the station between the tag and the base station with the interval of 0.1m. The interval of each test is increased by 0.1m for shielding, simulating the non-line-of-sight environment for 15 minutes each time and recording data at the same time. The experiment ended when the distance between the person and the label is 1.5m. Then we collect and analyse the data, calculate the mean square error, and draw the chart below.

| Distance between the person and the tag (m) | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 |
|------------------------------------------|-----|-----|-----|-----|-----|-----|-----|
| Root-mean-square error (m)              | 0.504 | 0.408 | 0.342 | 0.286 | 0.232 | 0.209 | 0.233 |
Distance between the person and the tag (m) | 0.8  | 0.9  | 1.0  | 1.1  | 1.2  | 1.3  | 1.4  \\
---|---|---|---|---|---|---|---
Root-mean-square error (m) | 0.189 | 0.180 | 0.213 | 0.178 | 0.193 | 0.188 | 0.169

It can be found from the above figure that the ranging accuracy in the non-line-of-sight environment is much lower than that in the visual environment. When the shielding of human body exceeds 0.6m, the change trend of root mean square error is flat, which can be identified as the influence of UWB signal propagation in the air. The influence of human occlusion is mainly reflected in the range of 0-0.6m, and the root mean square error decreases with the increase of the distance between the person and the label, and the fluctuation range decreases. When the distance exceeds 0.6m, the shielding of human body has a certain influence on UWB ranging, but it is not the most important factor affecting the accuracy of UWB ranging.

The reasons for the error are as follows: the multipath effect in non-line-of-sight environment is more serious. When the UWB signal propagates around the human body, the direct UWB signal cannot be measured due to the shielding of the human body. The signal propagates in the surrounding space, and the inconsistent arrival time leads to a large error. In the actual use process, a base station does not correspond to a label, and multiple tags, multiple tags sent by the signal will also exist interference, resulting in a certain error. Not only that, devices are not wired, requiring their clocks to be fully synchronized is nearly impossible, and devices with out-of-sync clocks can cause some error.

So the base station should be set up reasonably. When erecting base stations, all base stations should not be placed on the same plane, but one or more stations should be placed at different heights. The base station should be set up in relatively empty places as far as possible to reduce the error caused by non-line-of-sight occlusion. A number of base stations are set up in the space, and the distance measured by the best base stations is selected through data fusion to calculate the location coordinates. Base stations are better connected by wire to ensure the synchronization of the clock. In the case of wireless communication only, the clock can be adjusted in a wired way first [5].
5. Conclusion
This paper mainly verifies that the least square positioning algorithm can improve the accuracy of UWB ranging in TOA mode. In the non-line-of-sight environment with human occlusion, the range of 0.6m from the label will produce a large error of UWB ranging with human occlusion, and the error will decrease with the increase of distance. Beyond 0.6m, the shielding of human body is not the most important factor for the error of UWB ranging. The reasonable installation of base station can improve the accuracy of UWB ranging and make the location more accurate in practical engineering.

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