Indoor Visible Light Positioning Method Based on TDOA and Fingerprint

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ABSTRACT

Aiming at the problem of large amount of work in the matching stage of traditional visible light fingerprint positioning methods, an indoor high-precision visible light positioning method combining TDOA and fingerprints is proposed. This method first builds a visible light fingerprint library in the positioning area, and then uses the TDOA algorithm to determine the application range of fingerprint positioning. Finally, the weighted K-nearest neighbor algorithm is used to determine the position coordinates of the point to be located within the specified range. The simulation results show that the positioning method proposed in this paper greatly reduces the number of matching in the fingerprint matching stage compared with the traditional fingerprint positioning method, and has a higher positioning accuracy.

INTRODUCTION

Currently available wireless communication technologies for indoor positioning include Zigbee, Rfid, Bluetooth, Wifi, and so on. However, the above-mentioned wireless communication technologies generally have shortcomings such as large electromagnetic radiation, high deployment cost, and low positioning accuracy [3]. Compared with traditional radio frequency communication, visible light communication technology (VLC) has the advantages of no electromagnetic radiation, high practicability, low cost, and high positioning accuracy. It makes up for the shortcomings of traditional communication technology and is widely used in the field of indoor positioning [4].

Common indoor visible light positioning methods include received signal strength indicator (RSSI) method [6], time of arrival (TOA) method [7], time difference of arrival (TDOA) method [8] and angle of arrival (AOA) method [9]. However, among these positioning methods, it is difficult for the RSSI positioning method to find a universal signal propagation model, resulting in low positioning accuracy. TOA positioning and TDOA positioning methods have higher requirements for clock synchronization, and a small amount of clock deviation will produce larger ranging errors, thereby affecting positioning accuracy. AOA positioning requires the use of antenna arrays to analyze angle information, which requires high hardware equipment, and high deployment costs are not conducive to large-scale applications.

Fingerprint positioning is to construct a positioning fingerprint library in advance, and then match the fingerprint of the point to be positioned with the fingerprint in the fingerprint library through a matching algorithm, thereby estimating the coordinates of the point to be positioned. Compared with the above-mentioned positioning methods, fingerprint positioning only pays attention to the corresponding relationship between the received signal strength information and the position, does not require distance measurement, has lower hardware requirements, and has higher application value [11]. However, the fingerprint positioning method needs to compare the received signal strength vector received by the target to be located with the received signal strength vector of each fingerprint point in the fingerprint database in the real-time positioning stage, which has the problem of high fingerprint matching complexity. Too many fingerprint matching times will have a greater impact on the real-time performance of the positioning, thereby affecting the positioning performance.

To solve this problem, this paper proposes an indoor visible light positioning method based on TDOA and fingerprints. The method first builds a visible light fingerprint library in the positioning area, and then uses multiple TDOA positioning algorithms to determine the matching range of subsequent fingerprint positioning, and finally within the specified range The weighted K-nearest neighbor algorithm is used to perform fingerprint matching to determine the position coordinates of the points to be located. The simulation results show that the positioning method proposed in this paper greatly improves the efficiency of fingerprint matching compared with the traditional KNN fingerprint positioning method, and has higher practical value.

POSITIONING SYSTEM AND METHOD

I. POSITIONING SYSTEM

A. Positioning Model

The VLC location model is shown in Fig. 1. The positioning area is the space area of length Am, width Bm and height Cm. four LED light sources are evenly distributed on the indoor ceiling, and the coordinates of the nth LED light source can be expressed as:

$$L_n = (x_n, y_n, z_n) \quad 1 \le n \le 4 \tag{1}$$

Set the target T to be located in the $H=0$ plane in the room, and its coordinates can be expressed as $(x, y, 0)$. The communication between the target to be located and the LED light source follows the VLC communication link model.

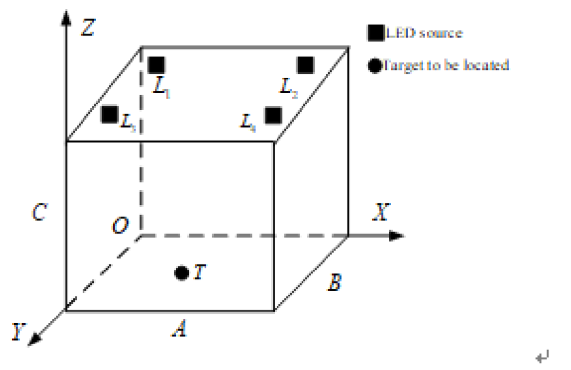

Fig. 1. VLC location model.

B. VLC Link Model

At present, Lambert radiation model is widely used in visible light direct link model [12]. The relationship between transmitting and receiving power is as follows:

$$P_r = P_t \cdot H(0) + N(t) \tag{2}$$

P_t is the transmitting power of any LED light source, P_r is the receiving power of the light source received by the receiving device, $N(t)$ is the noise superimposed by the signal in the transmission process, $H(0)$ is the DC gain of the channel, which can be expressed as:

$$H(0) = \frac{A(\alpha+1)}{2\pi r^2} \cos^{\alpha} \varphi T_s(\theta) g(\theta) \cos\theta \tag{3}$$

Where $0 \le \theta \le \theta_{FOV}$, A is the effective area of the receiving section of T. φ and θ are the radiation angle of the transmitting end and the incident angle of the receiving end, $T_s(\theta)$ is the gain of the optical filter, and $g(\theta)$ is the gain of the light perspective mirror. θ_{FOV} is the width of the field of view, r is the distance between the transmitting end and the receiving end, and α is the number of radiation lobe patterns.

II. POSITIONING METHOD

A. Building Fingerprint Database

The location area $H=0$ plane is evenly divided into M square areas, and each square side length is set as d. a random point in each square is taken as the reference fingerprint point. In the fingerprint database construction stage, the RSSI of different LED light sources received at each reference fingerprint point is measured and recorded in the database. The fingerprint information corresponding to the m-th reference fingerprint point can be expressed as:

$$F_m = (m, x_m, y_m, P_{m1}, P_{m2}, P_{m3}, P_{m4}) \tag{4}$$

Where x_m and y_m are the real coordinates of the m-th fingerprint point, and P_{mn} is the RSSI of the n-th LED light source received by the m-th fingerprint point. Then the constructed visible light fingerprint database FB can be expressed in the following form:

$$FB = (F_1, F_2, \cdots F_N)^T \tag{5}$$

B. TDOA Determines the Matching Range

In this paper, we use the TDOA algorithm to determine the area of fingerprint matching. The TDOA algorithm first measures the time difference of the unknown node receiving signals from several known stages, then multiplies the time difference by the speed of light to obtain the distance difference. The joint equations are used to solve the unknown coordinates of the target to be located.

Three groups of TDOA positioning are carried out for the node to be located, and three different combinations of LED light sources are selected from $L_1 \sim L_4$ for each group of positioning. In a group of TDOA positioning, the selected LED light source is $L_1 \sim L_3$, t_0 is the light source signal transmission time, and $t_1 \sim t_3$ is the receiving time of $L_1 \sim L_3$ signal received by the target T to be located. Let the signal propagation time difference between L_1 and L_2 to t be $\Delta t_{1,2}$, and the signal propagation time difference between L_1 and L_3 to t be $\Delta t_{1,3}$, then $\Delta t_{1,2}$ and $\Delta t_{1,3}$ can be expressed as:

$$\begin{aligned}\Delta t_{1,2} &= (t_1 - t_0) - (t_2 - t_0) = t_1 - t_2 \\ \Delta t_{1,3} &= (t_1 - t_0) - (t_3 - t_0) = t_1 - t_3\end{aligned} \tag{6}$$

Then the distance difference Δd_{12} from L_1, L_2 to T, and the distance difference Δd_{13} from L_1, L_3 to T can be expressed as follows:

$$\begin{aligned}\Delta d_{1,2} &= c \cdot \Delta t_{1,2} \\ \Delta d_{1,3} &= c \cdot \Delta t_{1,3}\end{aligned} \tag{7}$$

Where c is the speed of light, and the simultaneous TDOA equation is as follows:

$$\begin{aligned}\sqrt{(x-x_1)^2+(y-y_1)^2+z_1^2} - \sqrt{(x-x_2)^2+(y-y_2)^2+z_2^2} &= \pm\Delta d_{1,2} \\ \sqrt{(x-x_1)^2+(y-y_1)^2+z_1^2} - \sqrt{(x-x_3)^2+(y-y_3)^2+z_3^2} &= \pm\Delta d_{1,3}\end{aligned} \tag{8}$$

Using Chan algorithm to solve the problem, the first group of TDOA coordinates estimation points $P_1(x, y)$ of the target to be located can be obtained.

According to the above steps, three TDOA positioning is performed on the target to be positioned, and three sets of coordinate estimation points of the target to be positioned are obtained, namely $P_1 \sim P_3$, as shown in Fig. 2:

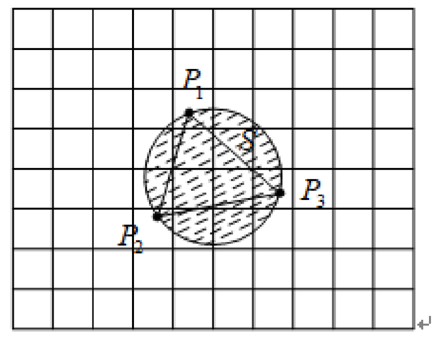

Fig. 2. Schematic diagram of fingerprint matching range.

Connect P_1, P_2, P_3, construct a triangle with P_1, P_2, P_3 as vertices, construct a circumscribed circle of the triangle, and define the area S covered by the circumscribed circle as the matching range of subsequent fingerprint positioning.

C. WKNN Fingerprint Matching

In the positioning stage, suppose the RSSI vector composed of 4 LED light sources received by the target to be positioned is, which can be expressed as follows:

$$X_r = (p_{r1}, p_{r2}, p_{r3}, p_{r4}) \tag{9}$$

It is assumed that there are a total of H reference fingerprint points in the target area S, and R_h is the RSSI vector of each LED light source received by the h-th $h(h \le H)$ reference fingerprint point. In the fingerprint matching stage, the matching degree of the R_h and X_r of the H reference fingerprint points is calculated, and the criterion of the matching degree is the Euclidean distance between the two. The smaller the Euclidean distance, the higher the similarity between the two vectors. The Euclidean distance $L_2(X_r, R_h)$ between X_r and fingerprint database R_h can be expressed as:

$$L_2(X_r, R_h) = \|X_r - R_h\|_2 \tag{10}$$

Where: $\| \ \|_2$ represents a two-norm operator. The H reference fingerprint points in S are fingerprint matched with X_r respectively, and the H fingerprint points are sorted from high to low according to the similarity with X_r. The $K(K \le H)$ reference fingerprint points with the highest similarity are screened, and the real coordinates corresponding to the K reference fingerprint points are:

$$T_i = (x_i, y_i), (i = 1, 2, \cdots, K) \tag{11}$$

The weighted K-nearest neighbor (WKNN) algorithm is used to estimate the final positioning coordinates (x, y), and the final positioning coordinates of the target to be measured are obtained as:

$$(x, y) = \sum_{i=1}^{K} W_i T_i \tag{12}$$

The weight W_i of the i-th fingerprint point can be expressed as:

$$W_i = \frac{\dfrac{1}{L_2(R_i, X_r)}}{\dfrac{1}{\sum_{i=i}^{K} L_2(R_i, X_r)}} \tag{13}$$

SIMULATION RESULT AND ANALYSIS

III. SIMULATION RESULTS AND ANALYSIS

In order to verify the feasibility of the positioning method, the proposed positioning method is simulated and analyzed. Take the parameters $A = B = 4\text{m}$, $C = 3\text{m}$, $d = 0.1\text{m}$, that is, perform numerical simulation in a space of $4\text{m} \times 4\text{m} \times 3\text{m}$, and the total number of fingerprint points is 1600. Assuming that the coordinates of the four LED light sources are respectively $l_1(1,1,4)$, $l_2(1,3,4)$, $l_3(3,1,4)$, and $l_4(3,3,4)$, the inherent clock error between the light sources is $\Delta t = 1ns$. Model the coordinates of each reference fingerprint point and the received signal strength to construct a visible light fingerprint library. First, analyze the positioning error of the TDOA positioning method. The number of Monte Carlo is 300, as shown in Fig. 3:

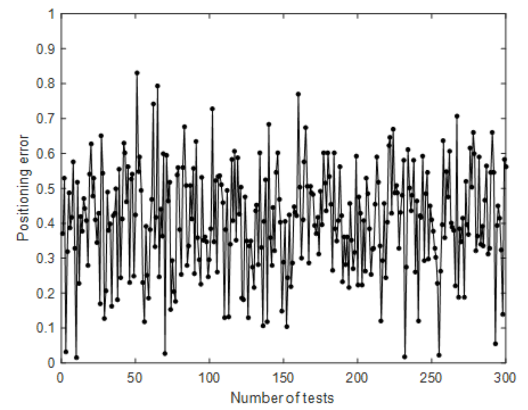

Fig. 3. TDOA positioning error

According to the calculation in Fig. 3, the average positioning error of TDOA positioning method is 0.4028m. Different LED light sources are selected to locate the target for three times, and the fingerprint matching range of subsequent fingerprint matching algorithm is determined. WKNN fingerprint matching algorithm is used in the fingerprint matching stage of the proposed positioning method. The value of K in WKNN algorithm has a great impact on the positioning accuracy. The positioning error of the proposed positioning method under different K values is compared, as shown in Fig. 4:

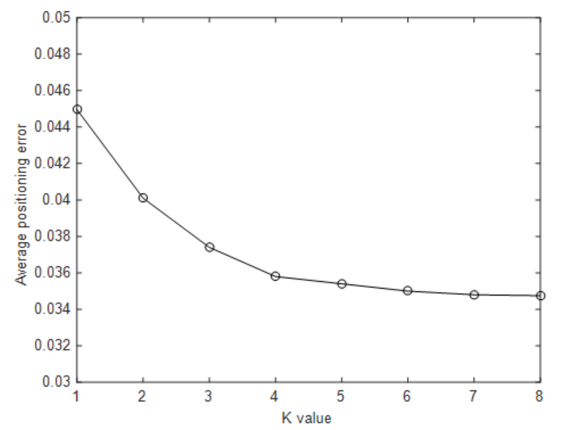

Fig. 4. positioning error of different K values

In Fig. 4, the abscissa is the value of K, and the ordinate is the average positioning error. It can be seen from Fig. 4 that as the value of K increases, the average positioning error decreases. When K is set to 4, the average positioning error is 0.0358m, and the average positioning error tends to be stable as the value of K increases. Considering the positioning accuracy and positioning cost, K=4 is selected as the default K value of the WKNN algorithm in the simulation scenario of this article.

The positioning method proposed in this paper reduces the number of fingerprint matching by narrowing the fingerprint matching range. Assuming that the distance between adjacent fingerprint points is constant, the area of the positioning plane is changed by changing the value of the positioning model length A, so as to compare the fingerprint matching times of the positioning method proposed in this paper and the traditional KNN fingerprint positioning method in the fingerprint matching stage. For example, as shown in Fig. 5:

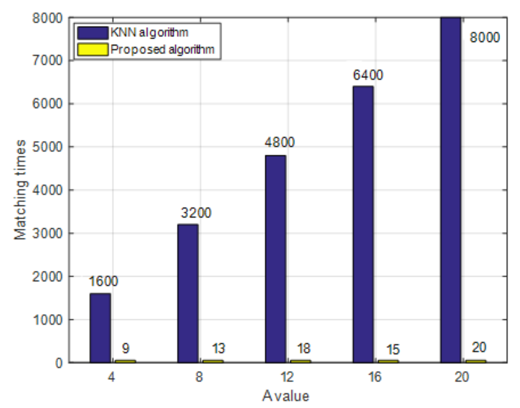

Fig. 5. Comparison of fingerprint matching times

In Fig. 5, the abscissa represents the length A of the positioning model, and the ordinate represents the number of fingerprint matching. It can be seen from Fig. 5 that the fingerprint matching times of traditional fingerprint location methods are higher, and increase significantly with the increase of location plane area. In the fingerprint matching stage, the proposed method only needs about 15 fingerprint matching on average to complete the positioning. The reason is that the proposed method greatly reduces the scope of fingerprint matching by using TDOA algorithm, avoids redundant fingerprint matching process, and increases the efficiency of fingerprint matching.

SUMMARY

In this paper, an indoor visible light location method based on TDOA and fingerprint is proposed. Firstly, the visible light fingerprint database is constructed in the location area, and then the matching range of subsequent fingerprint location is determined by using multiple TDOA location algorithm. Finally, the weighted k-nearest neighbor algorithm is used for fingerprint matching within the specified range to determine the location coordinates of the points to be located, The simulation results show that the proposed method has higher positioning accuracy, greatly improves the fingerprint matching efficiency compared with the traditional KNN fingerprint positioning method, and has higher practical value.

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