A Visible Light Indoor Location System Based on Lambert Optimization Model RSS Fingerprint Database Algorithm

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Abstract. In order to further improve the positioning accuracy of indoor positioning based on visible light communication, this paper proposes an RSS fingerprint database location algorithm based on Lambert optimization model, which significantly improves the positioning accuracy. The Internet of Things technology is used to realize the connection between devices and mobile phones, and the positioning information is transmitted to mobile phone clients in real time. To test this system, a visible light indoor positioning system based on STM32F407 development platform was built, which verified that the positioning error of the system was basically stable within 30 mm in the area of 800 mm * 800 mm. This system has stable signal transmission, high precision, small time consuming and low cost of power consumption, which has a good development and application value.

Keywords: Visible light communication · Indoor location · Location algorithm · Internet of Things · High precision

1 Introduction

In recent years, visible light communication technology has been increasingly mature, and the scale of investment in the industry has also gradually increased. It has effectively made up for the deficiencies of existing wireless communication technologies, such as low positioning accuracy, high power consumption and slow speed, via its prominent advantages, such as rich spectrum resources, unrestricted use of sensitive areas, high confidentiality and low cost [1]. As a new indoor positioning technology, visible light communication has become a hot research and application field. However, most existing visible indoor positioning systems have low positioning accuracy, long time delay and high-power consumption, which reduce the availability of the system.

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Visible light communication technology is transmitting digital signals in the visible light band to achieve communication between sending and receiving points via using light-emitting diodes. Compared with traditional wireless communication, visible light communication technology has both lighting and communication functions, and has its unique advantages, that is, rich spectrum resources, unlimited use of sensitive areas, green safety, high confidentiality, and low-cost. Therefore it is more suitable for application in the field of communications, with very considerable application prospects.

At present, the commonly used indoor positioning algorithms [2] based on visible light communication mainly include geometric measurement method, fingerprint identification method [3], approximate perception method, image sensor imaging method and so on. Geometric analysis location algorithm mainly includes RSS, TOA, and TDOA algorithms [1]. These location algorithms have their own advantages and disadvantages. Although indoor positioning can be achieved theoretically [4], it is difficult to achieve accurate and efficient positioning when used alone due to the complex actual situation. And it is difficult to obtain accurate parameters of the lighting model in the actual environment [5]. Among them, RSS algorithm, the received light intensity algorithm [5], is the most widely used visible light indoor location algorithm at present. And the key point is to estimate the distance between the measured point and the luminous spot. The accuracy of distance estimation directly determines the positioning accuracy. Generally, the distance can be estimated according to the phase detection method and the intensity estimation method. However, the phase detection method requires high synchronicity and is difficult to realize positioning [6], while the intensity estimation method can estimate the distance of optical transmission by directly detecting the optical power [6], which is usually used in combination with the three-side algorithm. Although this algorithm is easy to implement, it has certain defects [7].

To solve the existing problems, this paper proposes an RSS fingerprint database location algorithm based on Lambert optimization model, and builds a visible light indoor location model device. The spectrum of visible band is used for high-speed data transmission in order to improve the positioning accuracy up to the magnitude of mm, then comprehensively improve the positioning accuracy and speed of the system. Through software coding realize signal filtering, data storage and other functions, and the location information can be transmitted to the client in real time.

2 RSS Fingerprint Database Location Algorithm Based on Lambert Optimization Model

2.1 Lambert Optimization Model

In general, we regard the lighting model of a single LED as the Lambert radiation model [8], that is, the light intensity of the received signal conforms to the law of cosine of light intensity between the light intensity and the light propagation distance. In lambert radiation model, if you want to determine the value of the parameter *m*, you need to convention half the range of power Angle $\theta_{1/2}$ at first, thus lambert parameter *m* also has a scope of constraint.

However, most LED do not contain only one lamp bead, but may contain multiple lamp beads. In this case, the upper half power Angle of the same LED in different radiation directions may be different, and its Lambert parameter may also deviate to some extent, then results a positioning error. Therefore, in practice, lambert parameters need to be optimized to obtain high precision positioning. A new estimation method of Lambert parameters is proposed in literature [9]. Based on this method, a geometric diagram of the lambert radiation parameter optimization model proposed in this design for its existing problems.

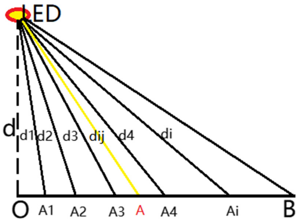

Fig. 1. Lambert optimization model diagram

As shown in Fig. 1, if the matched object point is at A position between the reference point O and B, then A[i] of several known coordinate positions is selected from the direction O to B, and the measurement value of the direct vision distance between the reference point i and the light source is assumed to be d_i. At present, the discrete sequence m[] about Lambert parameters can be obtained with a certain step distance, and each element m[j] in the sequence can be used as the Lambert radiation coefficient to conduct ranging for the reference point Ai with a known distance of d_i, and the measured value can be obtained as *dij*.

The m value is solved as follows: suppose the receiving optical power at O is P_o, and the receiving optical power at reference point A_i is P_i, then:

$$m = \log_{d_i/d} {}^{P_o}/_{P_i} - 3 \quad (1)$$

Where d_i is the direct distance from the reference point i to the light source, and its value can be directly retrieved from the fingerprint database. Then, a sequence m[] about m should be obtained. And named the maximum value of this sequence as m_{max}, the minimum value as m_{min}.

$$m_j = m_{\min} + \frac{m_{\max} - m_{\min}}{n} \times j; j = 0, 1, 2, \cdots n \quad (2)$$

As shown in Eq. (2), n is the number of steps, and the greater the value, the more accurate estimation of m_j. When m_j is taken as Lambert coefficient, we can obtain the theoretical distance *dij* between the reference point Ai and the LED source, via substituting each m_j in Eq. (2) back into Eq. (1).

Then extend the above theory to N reference points, and use variance as error measurement standard. When the minimum value of formula (3) is reached, that is, the error of d_i and *dij* is the minimum, and the corresponding *m*[*j*] is the reliable estimate value of Lambert parameter in this direction.

$$e^j = \sum_i^n \sqrt{(d_i - d_{ij})^2} \tag{3}$$

Then substitute this reliable estimate value into the classic single-lamp Lambert model, the received light intensity at the reference point A*i*, as shown in Eq. (4).

$$P_A = \frac{(m+1)A}{2\pi(d^2 + r^2)} \cos^{m+1}(\theta) T_s(\theta) g(\theta) \times P_t \tag{4}$$

Where, A is the sensor's receiving area, $T_s()$ is the filter gain, g() is the light accumulation gain, and P_t is the LED luminescence power [8]. In general, when the system is stable, these parameters are fixed, while Lambert parameter *m* represents the directivity of luminescence, and its value is related to the half power Angle. According to the geometric relationship, it can be seen that:

$$\cos(\theta) = \frac{d}{\sqrt{d^2 + r^2}} \tag{5}$$

In combination Eq. (4) and (5), the linear distance between point A*i* and point O in the projection plane can be obtained, as shown in Eq. (6).

$$r = d\left(\sqrt[m+3]{\frac{P_o^2}{P_A^2}} - 1\right)^{\frac{1}{2}} \tag{6}$$

2.2 RSS Fingerprint Database Location Algorithm

The RSS fingerprint database location algorithm based on The Lambert optimization model is adopted. Firstly, collecting the light intensity information of reference points then establishing a database. Then introducing an optimization algorithm of the Lambert model in the real-time location stage. Afterwards, the precise estimation value of the obtained Lambert parameter was used for RSS measurement, and the coordinate position of the point to be measured was calculated by the three-side algorithm and sent to the computer and LCD display.

This optimization hybrid algorithm makes up for the disadvantages and limitations of the low accuracy of RSS algorithm and the huge database of fingerprint algorithm. It can not only ensure the accuracy of positioning, but also not introduce a large amount of work. When the positioning points is reference points or within a very small range of their vicinity, it can achieve minimal or even zero errors. Algorithm model is shown in Fig. 2.

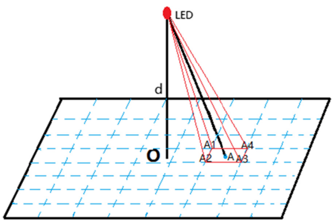

Fig. 2. Model diagram of hybrid positioning algorithm

Where A is the point to be measured and its coordinate position A(X, Y) is unknown; *d* is the vertical distance between point O and the light source. Assuming that the nearest probable point for point A to be detected by fingerprint database matching is A1(X_1, Y_1), then if the system continues to match, the nearest neighbor points to be found as A2(X_2, Y_2), A3(X_3, Y_3), A4(X_4, Y_4). The four reference points will mark out a small illumination region, and there must be an optimal Lambert radiation coefficient *m* in this illumination region, so that the positioning error of all reference points in this illumination region can be minimized when calculating by formula (4).

Then using the Lambert optimization model to calculate the distance between the object point and the three sources, as R1, R2 and R3. Finally, using the Three-side measurement algorithm RSS to figure out the coordinate of the object point.

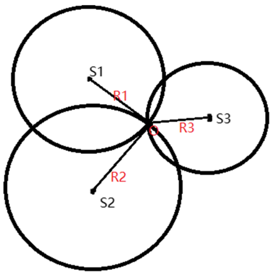

Fig. 3. Three-sided measurement

As shown in Fig. 3. Where, S1, S2, S3 respectively represent the three LEDs' vertical projection on the lighting underside, then set their coordinates as (X_1, Y_1), (X_2, Y_2), (X_3, Y_3), set the coordinates for point O as (X, Y). And the distance of the point of S1, S2, S3 respectively are R1, R2, R3, then using simultaneous system of equations by geometric relations. As shown in formula (7).

$$\begin{cases} (X - X_1)^2 + (Y - Y_1)^2 = R_1^2 \\ (X - X_2)^2 + (Y - Y_2)^2 = R_2^2 \\ (X - X_3)^2 + (Y - Y_3)^2 = R_3^2 \end{cases} \tag{7}$$

Subtracting the system of equations and finishing with each other, then we can obtain Eq. (8).

$$\begin{cases} 2X(X_2 - X_1) + 2Y(Y_2 - Y_1) = R_1^2 - R_2^2 - (X_1^2 + Y_1^2 - X_2^2 - Y_2^2) \\ 2X(X_3 - X_2) + 2Y(Y_3 - Y_2) = R_2^2 - R_3^2 - (X_2^2 + Y_2^2 - X_3^2 - Y_3^2) \\ 2X(X_1 - X_3) + 2Y(Y_1 - Y_3) = R_3^2 - R_1^2 - (X_3^2 + Y_3^2 - X_1^2 - Y_1^2) \end{cases} \tag{8}$$

Making that, $A_i = \begin{cases} A_1 = X_2 - X_1 \\ A_2 = X_3 - X_2 \\ A_3 = X_1 - X_3 \end{cases}$, $B_i = \begin{cases} B_1 = Y_2 - Y_1 \\ B_2 = Y_3 - Y_2 \\ B_3 = Y_1 - Y_3 \end{cases}$,

And $C_i = \begin{cases} C_1 = R_1^2 - R_2^2 - \left(X_1^2 + Y_1^2 - X_2^2 - Y_2^2\right) \\ C_2 = R_2^2 - R_3^2 - \left(X_2^2 + Y_2^2 - X_3^2 - Y_3^2\right) \\ C_3 = R_3^2 - R_1^2 - \left(X_3^2 + Y_3^2 - X_1^2 - Y_1^2\right) \end{cases}$

Finally, we can obtain formula (9), and we can obtain coordinates location (X, Y) of object point.

$$A_iX + B_iY = C_i,\ i = 1, 2, 3 \tag{9}$$

3 The Realization of the System Software

As shown in Fig. 4, the system consists of photoelectric detector receives the signal sent to the microprocessor after preliminary filter amplifier treatment STM32 algorithm processing. The system mainly includes digital filter, RSS fingerprint database established, optimization location algorithm, upload information to cloud server. Then user can enable the system's function of indoor positioning, and access to the location of the detector, just by mobile APP terminal.

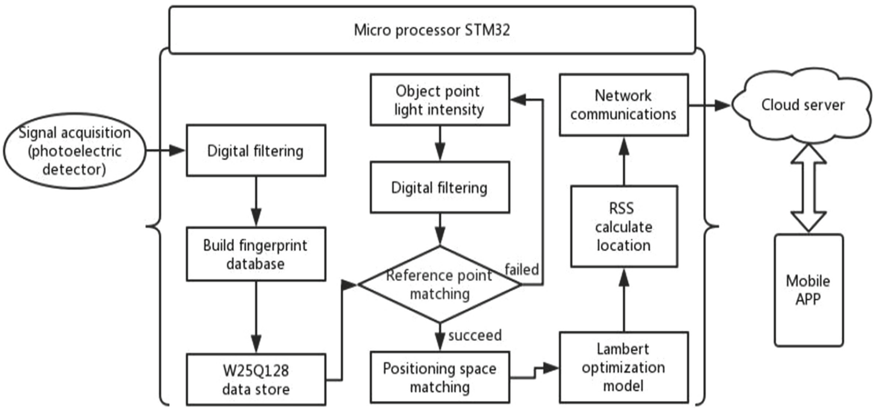

Fig. 4. The software design block diagram

3.1 Optimization Localization Algorithm Module

The receiver control processor STM32F407 communicate with external memory W25Q128 using SPI. When system running localization algorithm, it will match reference point data from memory firstly. Take the variance between object point's signal strength and fingerprint data as the matching error measure, and minimum variance of the corresponding fingerprint information is the closest reference point data information.

As shown in Fig. 2, assuming that the matched results of closest reference point from the fingerprint database is A1(X1, Y1), then system will continue to find the nearest neighbor points respectively, as A2(X_2, Y_2), A3(X_3, Y_3), A4(X_4, Y_4). Finally, four reference points can box out a small piece of illumination area.

Since then, the system will calculate corresponding lambert parameters of four reference points respectively, and deposit them into the array *m*[] following the growing up order. Then get the corresponding lambert parameters in the direction of extreme value by doing 400 times step by step, coexist in the array *m*[]. Then calculate the light power of this point using each element of array *m*[] via plugging in formula (4), and match with object point information once again to find the best Lambert radiation parameter *m*. And then calculate the distance between the object point and three sources respectively, as R1, R2 and R3, via plugging in formula (6). Finally, using RSS to figure out the coordinate of the object point.

3.2 Remote Control and Information Interaction Module

This system use ATK-ESP8266 module (WIFI devices) with STM32F407 controller to develop Gizwits Agent, it realized system device terminal docking with the cloud server and mobile phone user interaction.

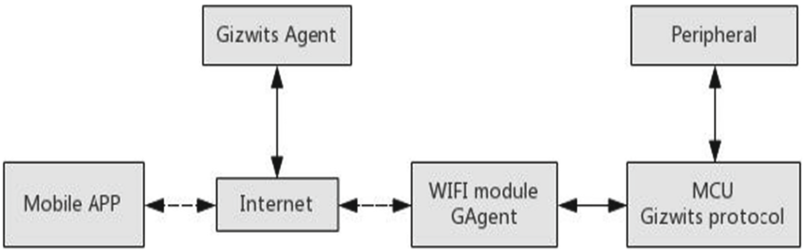

Fig. 5. Gizwits-Agent product control process

The working process of device terminal and client information interaction is shown in Fig. 5, after WIFI equipment receiving instructions sent by users, those instruction will send to MCU through the protocol frame format, and processor STM32F407will send receiving data into buffer. Then processor will catch bag from buffer at set intervals, and begin depth analysis if it was right, then push those data into event processing (the action execution), and MCU will implement its own logic according to the data point corresponding events.

The MCU will send data sampled by sensor to WIFI devices according to the protocol stack frame format packaging, and WIFI devices is responsible for sending those data to cloud server. Finally, the mobile client can receive object-point's location information after sending control command in APP interface.

4 Testing Results and Analysis

In order to test the stability of this system and avoid the accident of test results, we tested this system many times and recorded 192 effective data points. Use the positioning error as precision standard, and analyze its positioning accuracy. Where, the positioning error is defined as the absolute gap between the actual location of the object point (x0, y0) and the detected location by this system (x, y), and it also use the standard gap sigma σ and the average error μ, as shown in Eq. (10) and Eq. (11).

$$\delta = \sqrt{\delta_x^2 + \delta_y^2} = \sqrt{(x - x_0)^2 + (y - y_0)^2} \tag{10}$$

$$\sigma = \sqrt{\frac{1}{N}\sum\nolimits_{i=1}^{N} (\sigma_i - \mu)^2}, \mu = \frac{1}{N}\sum\nolimits_{i=1}^{N} \delta_i \tag{11}$$

The positioning error statistical analysis diagram is shown in Fig. 6. Take these positioning error of test data for statistical analysis, we find that the maximum position error is less than 50 mm, the average error is 25.92 mm, and the standard error is 10.195 mm.

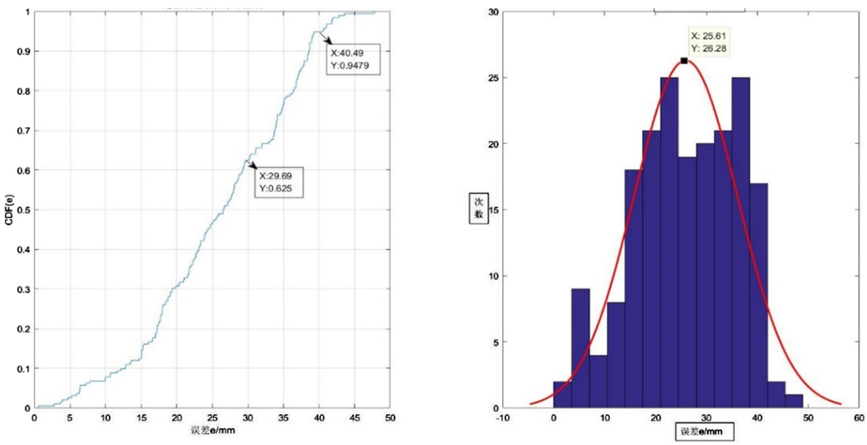

Fig. 6. (a) Positioning error of the cumulative distribution, (b) Gauss curve fitting

Here, the positioning error cumulative distribution function is mainly used for observation the current error value percentage of all error, and Gauss curve is mainly used for observation the statistical distribution of all error values. As shown in Fig. 6 (a), the test point which positioning error are under 30 mm occupy 62.5%, and the test point which positioning error are under 40 mm occupy 94.8%. And as shown in Fig. 6 (b), we find that the positioning error distribution between 20 mm to 40 mm basically, the center value of Gaussian fitting curve is 25.61 mm.

5 Conclusion

The system can only obtain basic error in 70.7 mm through using traditional fingerprint algorithm, which take the nearest fingerprint data as the object points coordinate, while this system can realize the average positioning error less than 30 mm through using RSS fingerprint database location algorithm based on Lambert optimization model proposed by this paper.

Compared with the traditional visible light indoor positioning system, this system has its advantages, such as ideal speed, high positioning accuracy, low latency, low consumption, and without any complicated sensors and other synchronization devices. Combining the device terminal with mobile phone via Internet of things technology, it achieves the user's information interaction with the cloud server. Within the scope of network coverage, users only need to send control commands in the APP, then he can get the location of the object in real time. To summary, this visible light indoor positioning has high feasibility, high positioning accuracy and strong practicability.

In future, we can achieve free or portable positioning via improving the hardware design of the receiving end and adopting a mobile power supply, so that it can be miniaturized for easy wearing. For the last mile of navigation, we can consider using visible light indoor positioning technology to achieve seamless connection between indoor and outdoor positioning.

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