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An Indoor Positioning Scheme for Visible Light Using Fingerprint Database with Multi-Parameters

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Abstract

This paper proposes a novel indoor positioning scheme based on visible light communication (VLC). A new indoor VLC positioning scheme using fingerprint database with multi-parameters have been raised. We conduct simulation and experimental research on the illumination intensity distribution of several direction parameters. In the experiment, four LED matrixes are identified by LED-ID with room dimensions of 3.75×4.00×2.7 m^3. The results show that the mean of the location error is 0.22 m in the receiving plane, verifying the correctness and feasibility of the positioning scheme.

Keywords

visible light communication; direction parameter; fingerprint database with multi-parameters; indoor positioning

1 Introduction

With the popularity of smartphones and the increase of mobile data service, there is a growing demand for positioning and navigation, especially in complex indoor environments, such as airports, exhibition halls, supermarkets, and underground parking lots, where it is often necessary to ascertain the position information of facilities. The recent outdoor positioning is not suitable for indoor application of high precision positioning, due to the multipath fading and interference generated from other wireless devices in complex indoor environments. Therefore, seeking a kind of universal, low power, high precision indoor positioning technology is an imperative. As the supplement of indoor wireless location technology, visible light communication (VLC) has attracted widespread attention in recent years for indoor positioning service because of its features of unlicensed spectrum, immunity to electromagnetic interference, and free use in radio frequency restricted areas [1], [2]. The research of VLC provides a good basic support for the development of indoor positioning technology [3]–[5].

At present, the main algorithms adopted in indoor positioning system based on VLC are triangulation and scene analysis. Triangulation is a technique that uses the geometric properties of triangles to estimate the target localization [6], [7]. It has two branches: lateration and angulation. Lateration technique estimates the location of a target point according to its distances from multiple reference points. The distance is mainly derived by measuring time of arrival (TOA), time difference of arrival (TDOA) and received signal strength (RSS). Angulation measures angles relative to several reference points, namely angle of arrival (AOA) [8]. The system based on TOA [9], [10] is inconvenient in application because it requires strict clock synchronization between the reference points and the target point. Unlike TOA, TDOA-based systems measure the time difference of arrival. In [10], the difference in phase among three different frequency signals is used to calculate the value of TDOA and evaluate the performance of the system by the simulation. A RSS-based method measures the received signal strength and calculates the propagation loss that the mitted signal has experienced. An AOA-based method derives the angles of arrival relative to the reference points through the imaging receiver. This method does not need synchronizing, but the positioning accuracy will decrease sharply when the target point is away from the reference points because of the limitation of imaging resolution of the receiver.

In addition, scene analysis technique is performed in two phases: offline and online. During the offline, collection of the location information of sample points is called fingerprints, and a fingerprint database would be established. Then, the target's location will be found by matching real-time measurements to these fingerprints in the online phase. The method can combat the multipath effects in complex environments without parameters of estimated distance in an improved precision [11]. In view of the traditional fingerprint of visible light RSS, this paper puts forward a novel fingerprint (θ, RSS) by introducing the direction of the mobile terminal parameter θ combined with the traditional RSS. The approach is called the indoor positioning method for visible light using fingerprint database with multi-parameters.

2 Positioning Scheme

2.1 Principle and Establishment of the Fingerprint Database

Fig. 1 shows the proposed scheme that has offline and on-

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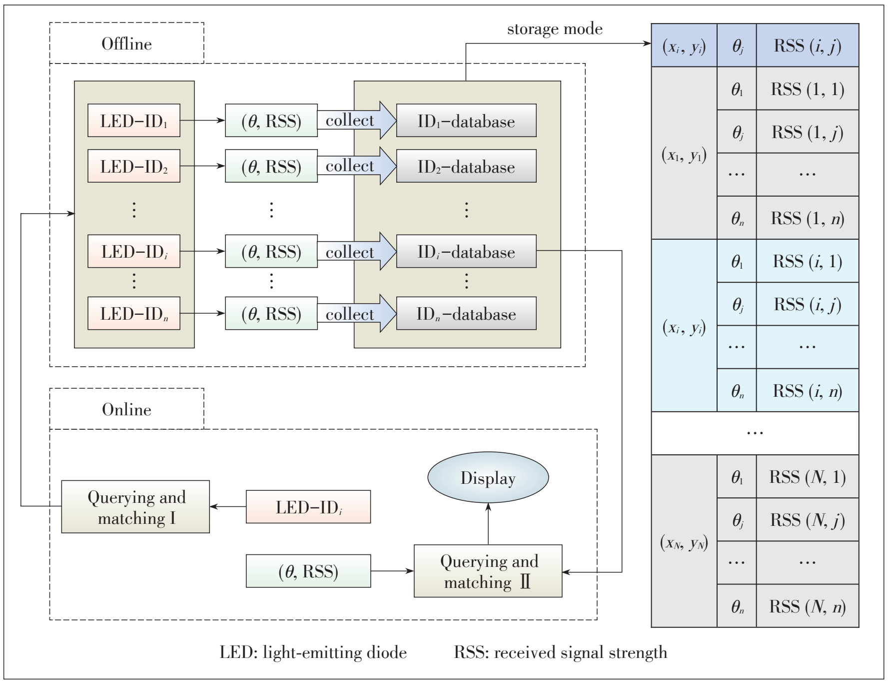


▲**Figure 1. The principles of the proposed positioning scheme.**

line phases. We collect the direction parameter θ of the mobile terminal and the RSS value of each sample point under the coverage of each light-emitting diode (LED) light source, which generates a series of corresponding ID_i-databases in the offline phase. As shown in Fig 1, the LED-ID_i is the location information of the ith LED light source. Data in the fingerprint databases is stored in the form of (θ, RSS) and (x_i, y_i) are the coordinates of the sample points. If the direction parameter of each sample point is expressed as θ_j, then the received light intensity can be represented as RSS (i, j), and N and n are the number of sample points and the direction parameters, respectively. In the online positioning stage, the mobile terminal executes the operation of querying and matching according to the current LED-ID_i. After the ith database is downloaded to the mobile terminal, the location of the mobile terminal will be estimated by matching the received (θ, RSS) to these fingerprints.

2.2 Modeling

Compared to the ideal indoor illumination model, this paper provides a practical model for a small office building as shown in **Fig. 2**. The illumination lights are installed in a non-symmetrical layout. The detector is located in the plane with the level of 0.8 m and α is its elevation. A (3.06, 2.66, 2.7), B (3.07, 1.44, 2.7), C (0.68, 1.44, 2.7) and D (0.67, 2.66, 2.7) are the middle coordinates of each LED.

According to the proposed positioning scheme, we need to pre-store the illumination intensity under the direction θ of the sample point in the offline stage. It just needs to consider the I to IV quadrants on account of the upward receiving plane generally in 3D. We define the direction parameter as (α , β), where α and β denote elevation and azimuth.

The white LED is an incoherent source, thus the total illumination received from all the light sources is the sum of contribution from every LED, which can be expressed as:

$$E=\sum_{i=1}^{N}E_i\ , \tag{1}$$

where E_i is the illumination of the ith LED and N is the amount of LEDs.

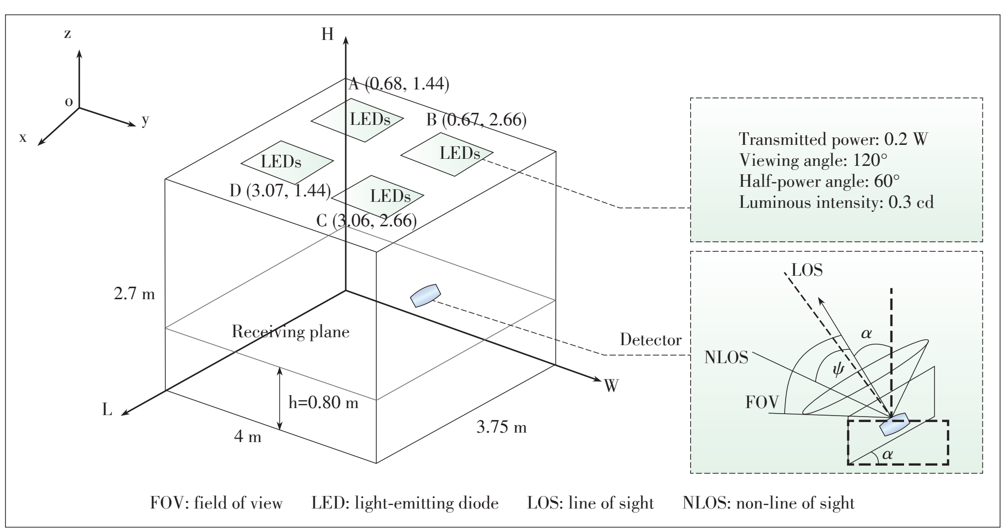
The radiation of a LED chip follows the Lambertian Radiation Pattern [12]. The luminous intensity formula is given by

$$I(\theta)=I(0)\cos^m(\theta)\ , \tag{2}$$

where $I(0)$ is the center luminous intensity of the LED, and the order m is given by $m=-\ln 2/\ln\cos(\theta_{1/2})$ in which $\theta_{1/2}$ denotes the LED view angle at half power. Thus, the illumination intensity on the receiving plane with the distance D to light source can be expressed as:

$$E_{hor}=I(0)\cos^m(\theta)/D^2\cdot\cos(\varphi)\ . \tag{3}$$

Every LED array is composed of 12×8 LED chips. The pa-



▲**Figure 2. The proposed indoor positioning model of visible light.**

rameters of each LED chip adopted in the simulation and experiment in this paper are shown in Fig. 2.

3 Simulation Analysis

In the proposed VLC positioning system where the downlink is considered only, the signal propagation path includes the line of sight (LOS) and non-line of sight (NLOS). As the direct visible light power to the detector accounts for 95% [13], only the LOS link was considered in the simulation. According to the above model, the paper studies the indoor illumination distribution with and without the direction by simulation.

3.1 Illumination Distribution

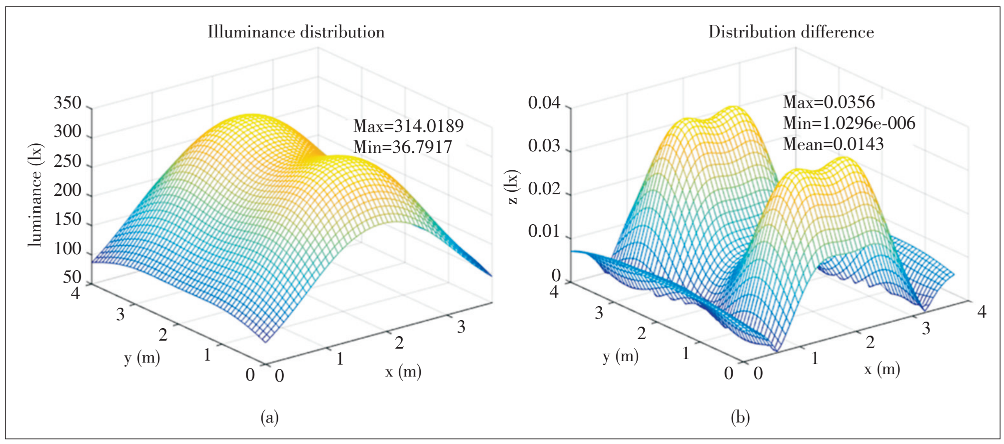
To explore the influence of the point light source and array source for this positioning method, the simulation for studying illumination distribution without direction parameters was carried out (**Fig. 3**).

Fig. 3a shows the illumination distribution of the point light source and the hump shape is due to the short interval of LEDs in the x axis direction. The maximum luminance is 314.0189 lx on the hump top derived from the superposition of light sources, while the minimum is appeared in the four corners. The illumination distribution decreases with the increasing distance to the center of LEDs. Under the same conditions, the source was regarded as one point and one array source respectively in the calculation process, and their difference distribution is shown in Fig. 3b. The figure shows that the maximum difference is only 0.0356 lx, while the mean is 0.0143 lx. The sensitivity of illuminometer adopted in the paper is 0.1 lx, therefore, the impact of the array source on the positioning results can be ignored.

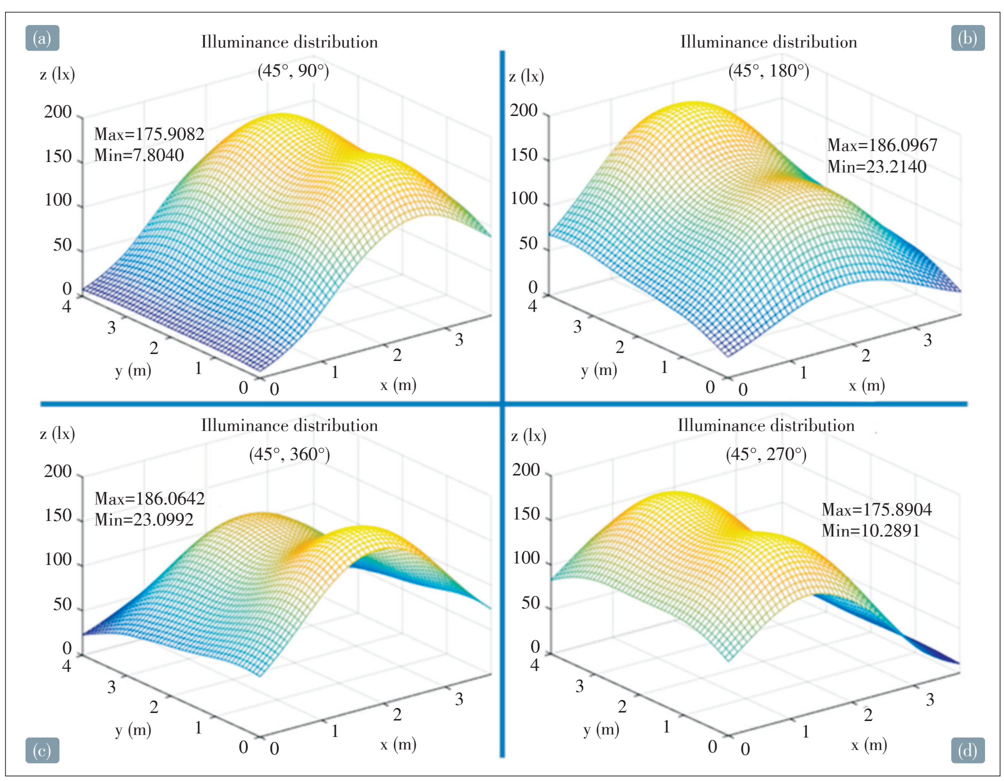
Fig. 4 shows the illumination distribution of several direction parameters of (45°, 90°), (45°, 180°), (45°, 270°) and (45°, 360°). It changes along with the different direction parameters at the same location in the room. Additionally, it reaches the maximum when facing the receiving surface of a mobile terminal, and reduces behind of the surface. Therefore, the proposed positioning fingerprint (θ, RSS) is significant.

3.2 Analysis of Positioning Results

To obtain the superior performance of the proposed positioning scheme visually, the isophotes are utilized to analyze the positioning results in the paper. First of all, the above simula-



▲Figure 3. Simulation results: (a) the illumination distribution of the point light source and (b) the distribution difference of the point and array light sources.



▲Figure 4. The illumination distribution with four direction parameters: (a) (45°, 90°), (b) (45°, 180°), (c) (45°, 360°), and (d) (45°, 270°).

tion results are indicated with isophotes, making the isophotes of different direction parameters intersect. Then, instead of the query matching process, the intersection is taken as an estimated position of the mobile terminal to verify the correctness and feasibility of the system.

Moreover, the normalization method is used to solve the issues of inconsistent range of illumination in this paper. The normalization is expressed as:

$$E_i^* = \frac{E_i - E_{\min}}{E_{\max} - E_{\min}} \, , \tag{4}$$

where E_i and E_i^* denote the illumination values before and after the normalization with the normalized range [0, 1]. E_{max} is the maximum and E_{min} is the minimum of the sample data. Furthermore, by using the illumination received with different direction parameters as sample data, we obtain E_{max} is 314.0189 lx and E_{min} is 7.8040 lx.

For example, when the real position was (2.85, 3.84), the location of the mobile terminal could be estimated by the illumination values of the direction parameters it received. The intersection point of the isophotes is the estimated position (**Fig. 5**). The first element of θ_i in Fig. 5 is the original illumination value, and the second is the normalized data. As it can be seen, the isophotes eventually intersect at the point of (2.85, 3.84), which verifies the feasibility and correctness of the proposed positioning method.

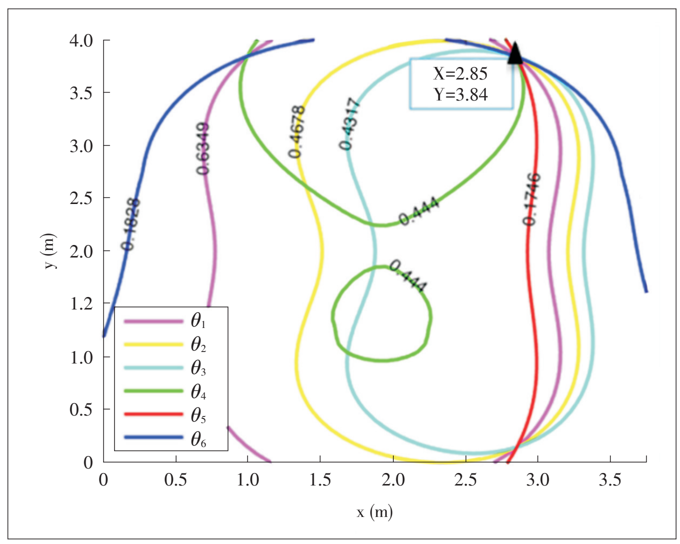
4 Experiment and Results

The verification test of the proposed model was carried out in the environment of a darkroom. The LED light sources were arrays that consists of 12×8 ZT5050WOS3 lamp beads. We used a CEM DT-1309 illuminometer with the sensitivity of 0.1 lx. The experimental model and the parameters of the light source were in accordance with the proposed model in Fig. 2. In the experiment of illumination distribution, 154 sample points were selected to be measured.

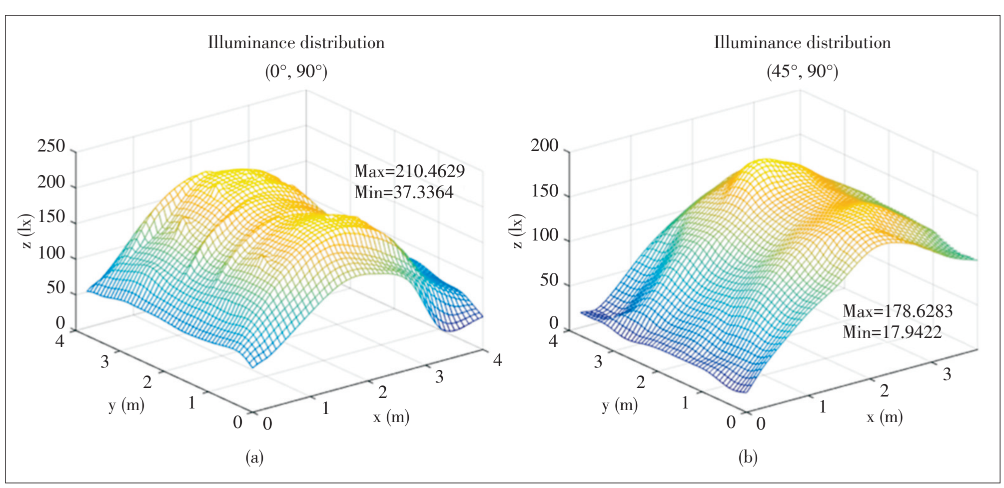
4.1 Analysis of Results

This paper investigates the spatial light intensity of five direction parameters of (0°, 90°), (45°, 90°), (45°, 180°), (45°, 270°) and (45°, 360°) with field measurements, and the obtained maximum and minimum are 210.4629 lx and 17.9422 lx, respectively. The measured results of (0°, 90°) and (45°, 90°) are shown in **Fig. 6** after interpolation processing. It can be seen that the variation trends are consistent with those in Fig. 4, but the overall illumination values are slightly lower than the simulation values. Taking the point of (2.85, 3.84) selected in the simulation as example, the received light intensity is normalized and then the results of positioning is analyzed.

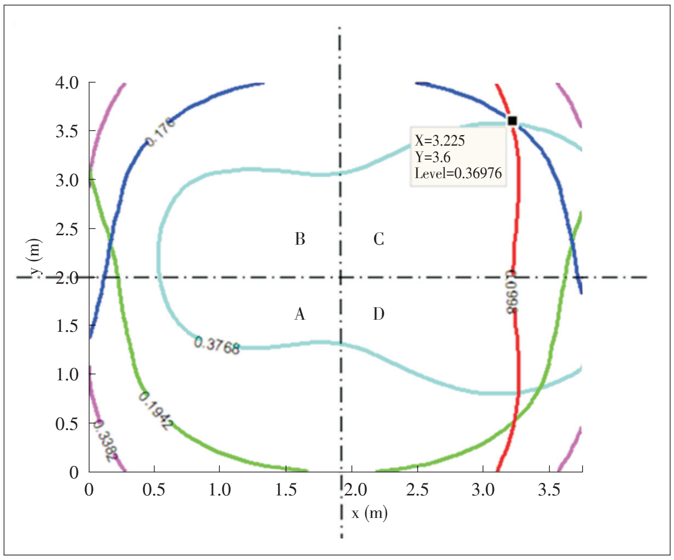
Fig. 7 shows the isophotes graph at the point of (2.85, 3.84), where there are several intersection points. The proposed positioning method based on multi-parameters fingerprint databases is a higher-precision positioning process based on the information of LED-ID. Consequently, the results in Fig. 7 are obtained on the premise of the received information of LED-ID for C#. Therefore, there is only one node for (3.225, 3.6) as the estimate point in the case. If there are multiple intersection points under the C# LED, we took the center location of the overlapping area as the target point, which should be set in advance in the principle. The positioning error of the target point is 0.45 m according to the Euclidean distance between the real and estimated positions of the mobile terminal.



▲**Figure 5. The isophotes graph at the point of (2.85, 3.84) based on the simulation.**

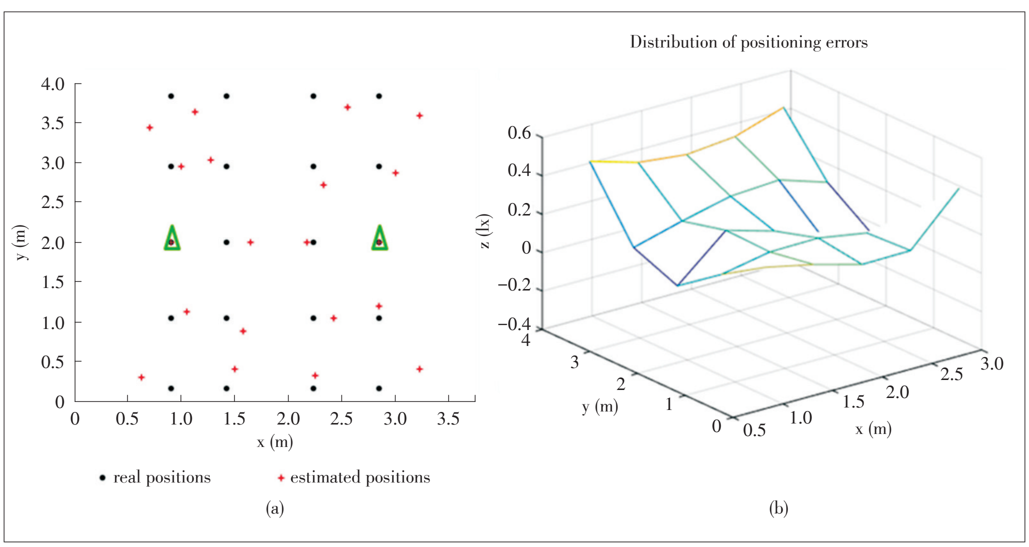


▲**Figure 6. The illumination distribution with direction parameters (a) (0°, 90°) and (b) (45°, 90°)**



▲**Figure 7. The isophotes graph at the point of (2.85, 3.84) based on the experiment.**

The accuracy is usually defined as the mean value of positioning errors. The positioning accuracy in our experiment is based on twenty points. **Figs. 8a** and **8b** show the real and estimated positions and their distribution of positioning errors, respectively. The positions of the two green triangles are the complicated superpositions of light sources, where the illumination intensity reaches the maximum, resulting in the poor positioning errors. Therefore, they are abandoned in order not to affect the overall positioning accuracy. In this way, when faced with complicated situations, the handling method must be defined in advance in the scheme to reduce the positioning error. As shown in Fig. 8b, in the edges and corners of the receiving plane, positioning errors also increase due to the decrease of the received light intensity. The maximum error is 0.4452 m and the average one is 0.2237 m.



▲**Figure 8. The (a) real and (b) estimated positions of the mobile terminal at twenty points.**

4.2 Analysis of Error

Factors affecting the location accuracy can be summarized into two main aspects. One is the sensitivity of detector and LED spacing. The illuminometer sensitivity adopted in this article is 0.1 lx. The mean deviation of illumination distribution between the point and array source is 0.01431 lx (Fig. 3b), an order of magnitude smaller than the sensitivity. Therefore, the difference was ignored in this paper under the experimental condition. The other influencing factor is the stability of light sources. The brightness of the LED is often instable with the change of supply voltage. On the other hand, the stability of LED light sources for the work played a vital role in the precision of the proposed positioning scheme. Although we tried to maintain the brightness stability by using constant current drive in the experiments, it still affected affect the positioning accuracy of the system, especially in the case of long working hours.

5 Conclusions

Compared to traditional indoor wireless location technology, the visible light positioning technology has the prominent features of ubiquitous coverage, energy saving, simple layout, low cost, etc. [14]. Therefore, it is expected to become one of the main means for indoor location. This paper presents an indoor positioning system model based on fingerprint databases. The simulation and experimental verification were conducted. The positioning errors of twenty points in the receiving plane with the accuracy of 0.22 m were also calculated, which visually verifies the correctness and feasibility of the proposed positioning scheme. Our work lays a theoretical and experimental basis for future research work.

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