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High-precision indoor positioning algorithm based on visible light communication using complementary metal–oxide–semiconductor image sensor

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Abstract. Visible light positioning (VLP) is widely believed to be a cost-effective answer to the growing demand for indoor positioning. There are two critical elements in VLP: positioning accuracy and real-time ability. Nevertheless, because of the nonlinear and highly complicated relationship between three-dimensional world coordinate and two-dimensional image coordinate, developing an effective VLP location algorithm to locate the positioning facility using complementary metal–oxide–semiconductor image sensor is of great need. Additionally, due to the high computational cost of image processing, most existing VLP systems fail to deliver satisfactory performance regarding real-time ability and positioning accuracy, both of which are crucial for the performance of an indoor positioning algorithm. Therefore, we propose a positioning algorithm: the triple-light positioning algorithm based on a situation with three light-emitting diodes (LEDs). The proposed positioning algorithm takes positioning accuracy into consideration. As there are merely binary linear equations to solve, real-time ability is also reflected in the proposed algorithm, which is very worth mentioning because most current positioning algorithms fail to deliver the efficiency. In addition, we treated the LED-ID detection and recognition problem, which is an essential part of the algorithm, as a classification problem in machine learning field and machine learning algorithm into consideration. Experiment results show that the proposed algorithm provides an accuracy of 4.38 cm and the computational time is 65.50 ms, suggesting that the proposed algorithm has a good performance in accuracy as well as real-time ability. [DOI: 10.1117/1.OE.58.2.024101]

Keywords: visible light positioning; real-time ability; positioning accuracy; indoor positioning algorithm; triple-light positioning algorithm; machine learning algorithm; complementary metal–oxide–semiconductor image sensor.

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1 Introduction

Indoor positioning has been a hot topic for the last few years due to the growing demand for accurate location-based services. The high-accuracy indoor positioning is being highly demanded for the fact that large facilities, such as indoor parking lots and commercial malls, are increasing. In addition to positioning accuracy, real-time ability is also needed to put a positioning device into large-scale use. To satisfy the need of indoor positioning, in recent years, the indoor positioning algorithms via the devices, such as Bluetooth, ZigBee, and so on, are put forward. Nevertheless, most of them fail to provide high positioning accuracy, while others fail to meet the demand of large-scale application since they rely on extra expensive facilities. The traditional methods cannot give a satisfying answer for indoor positioning. Compared to traditional positioning methods, visible light positioning (VLP) is highly applicable for indoor positioning owing to high positioning accuracy. In addition, the light-emitting diodes (LEDs) that are used to lighting can be just used for indoor positioning, so it is very cost-saving. VLP is promising in the position field. Generally, VLP indoor positioning has two physical components to choose to achieve the goal: photoelectric detector (PD) or image sensor.[1] Given the research,[2–7] obviously, PD has a big shortcoming in that its accuracy highly depends on the direction of light beam. Given that, PD is not an ideal device to locate the moving terminal. In addition, when PD put into positioning system, the positioning result is very inaccurate because the measured signal strength is changing by the intensities of light, which results in an unaccepted error in most situations. Considering all the drawbacks of PD, taking an image sensor as an indoor positioning terminal receiver is an applicable alternative. In fact, a commercial mobile phone is commonly equipped with the image sensor, so VLP via IS can be used in not only an experimental situation but also without extra cost in practice.

So far, there have been many image sensor-based VLC methods proposed, but few of them are practically available due to the lack of consideration for the actual scene and are not ready yet for high-speed indoor positioning in practice. In Ref. 8, an additional 6-axes sensor is used to determine the receiver's direction along with its position. This scheme uses collinearity condition to relate the three-dimensional (3-D) coordinates of the LEDs to the two-dimensional (2-D) coordinates of the image sensor. Simulation results show that the receiver's position can be estimated with accuracy of within 1.5 m if the pixel size is 36×10^{-6} m. In Ref. 9,

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at least three LEDs from the LED lighting array transmit the 3-D coordinate information. The 2-D image sensor receives the lights that are separated spatially by a lens and demodulates the 3-D coordinate information of each LED. The position of the receiver is then calculated by solving two sets of quadratic equations which may result in computational error. Analysis of those works reveals that positioning error of the previously proposed schemes may occur from the precise angular measurements and the solution of quadratic equations for position estimation. In Refs. 10 and 11, at least four LEDs from an LED array transmitted their 3-D coordinate information, which was received and demodulated by two image sensors near the unknown position. Then, the unknown position was calculated from the geometric relations of the LED images created on the image sensor plane using a combination of least-square and vector estimation methods with the accuracy of decimeter level. This method does not require angular measurement, whereas it must be assumed that the image center was at the center of the pixel. However, the center of the LED image is not always at the pixel center, therefore, a quantization error occurred. In addition, positioning accuracy is dependent on the separation between the image sensors. Meanwhile, due to two image sensors, the complexity and quantization error from both image sensors are high. Therefore, in Luxapose,[12] an angle of arrival localization algorithm based on three or more LEDs was proposed, where a camera is regarded as an angle-of-arrival sensor. On an unburdened MacBook Pro with a 2.7 GHz Core i7, the median processing time for the full 33 MP images captured by the Lumia is about 9 s (taking picture: 4.46 s, upload: 3.41 s, image processing: 0.3 s, and estimate location: 0.87 s) without any optimizations.[12] Removing any one transmitter (corner or center) has minimal impact on location error, still remaining within 10 cm for ∼90% of locations.[12] In Ref. 12, its algorithm uses image sensors as well, but its positioning time is 0.87 s, almost 100 times of our algorithm and its average error is >10 cm (including corner point), almost three times of our algorithm. Hossen et al.[13] proposed an indoor positioning algorithm using at least three LEDs, which realized an accuracy of 0.001 m in simulation. Last but not the least, all the existing work mentioned did not take the real-time ability into consideration, but only focused on static positioning and the positioning accuracy, while both accuracy and real-time ability are crucial for the performance of indoor positioning system and considered in proposed algorithm.

The contribution of our work can be listed as follows. We propose an algorithm based on a situation with three LEDs in the vision of the image sensor and take the real-time ability into consideration, which greatly improves the practicality of the algorithm. In addition, different from the traditional LED-ID modulation and demodulation methods, we treated the LED-ID detection and recognition problem as a classification problem in machine learning field. Based on three LEDs, we creatively came up with a modified positioning algorithm with an accuracy of 4.38 cm. It is worthwhile mentioning that it simplifies the calculation and is more applicable to practical operation because it only needs to solve the binary linear equations. Therefore, the computational time of the proposed triple-light positioning algorithm is only 65.50 ms, which is very worth mentioning because most of current positioning algorithms fail to deliver the efficiency. The rest of the paper is organized as follows. Section 2 presents system principle and the proposed positioning algorithm. And the experiments and results of our work are shown in Sec. 3. Section 4 provides concluding remarks.

2 System Principle

2.1 *LED-ID Detection and Recognition*

The proposed algorithm has two essential processes: LED-ID recognition and the computation. LED-ID recognition is achieved when the image sensor-based VLP utilizes the rolling shutter mechanism of the complementary metal–oxide–semiconductor (CMOS) image sensor. The exposure and data readout are performed row by row, and the data of one row are read out instantly when the exposure of this row is finished. This is known as the rolling shutter mechanism. By the rolling shutter mechanism of CMOS sensor, turning on and off the LED light during a period of exposure would result in bright and dark stripes on the image captured by the CMOS sensor.[14] Unlike the traditional LED-ID modulation and demodulation methods, we treated the LED-ID detection and recognition problem as a classification problem in machine learning field. We modulate each LED with a variable frequency and duty-ratio pulse-width modulation method to ensure different LED-ID would have three different features: the number of the bright stripes, the area of the LED image, and the ratio of the bright stripe's width to both the bright and dark stripes' width (duty-ratio of the bright stripes). And once the LED image is captured by a CMOS image sensor, an image processing method that extracts the features of LED-ID is used. Aiming to use the extracted features to identify the LED-ID, we take a Fisher classifier and a linear support vector machine into consideration. By off-line training for the classifiers and online recognition of LED-ID, the scheme proposed could accelerate LED-ID identification. The detail process of LED-ID detection and recognition has been deeply discussed in our prior work[15] and it can be seen in Fig. 1. For the readers that have interest in the LED-ID modulation and recognition, it is a great choice to refer to our previous reports.

2.2 *Triple-Light Positioning Algorithm*

On the base of LED-ID image recognition above, in this section, we mainly introduce the algorithm for three LEDs. In some capacious place, such as shopping malls, factories, and underground garage, there are always more than three LEDs in the vision. It is shown as in Fig. 2.

When there are three or more than three LEDs in the vision of image sensor, we propose a relatively simpler algorithm, i.e., the triple-light positioning algorithm. For simplification, we only discuss the case with three LEDs. As shown in Fig. 2, the coordinates of LEDs are (x_1, y_1, z_1), (x_2, y_2, z_2), and (x_3, y_3, z_3). In general, the ceiling height is the same at a place, thus $z_1 = z_2 = z_3$.

The point P is the midpoint of the lens in the image sensor, which is estimated for the 3-D coordinate of the terminal. The distances from P to the LED anchor are d_{kP}, $k = 1, 2$, and 3 for the three LED lamps. Here, d_{kP} is calculated by the geometrical relationship between the focal length of the lens and the position of the LED pixel on the image sensor.

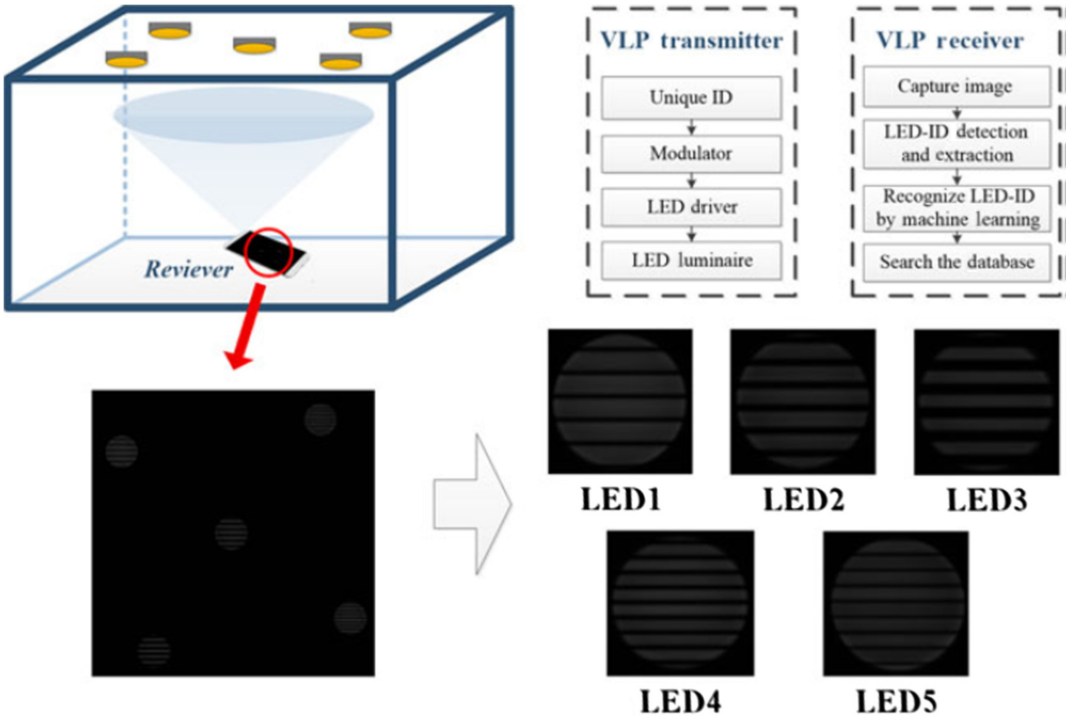

Fig. 1 The process of the LED-ID detection and recognition base on machine learning.

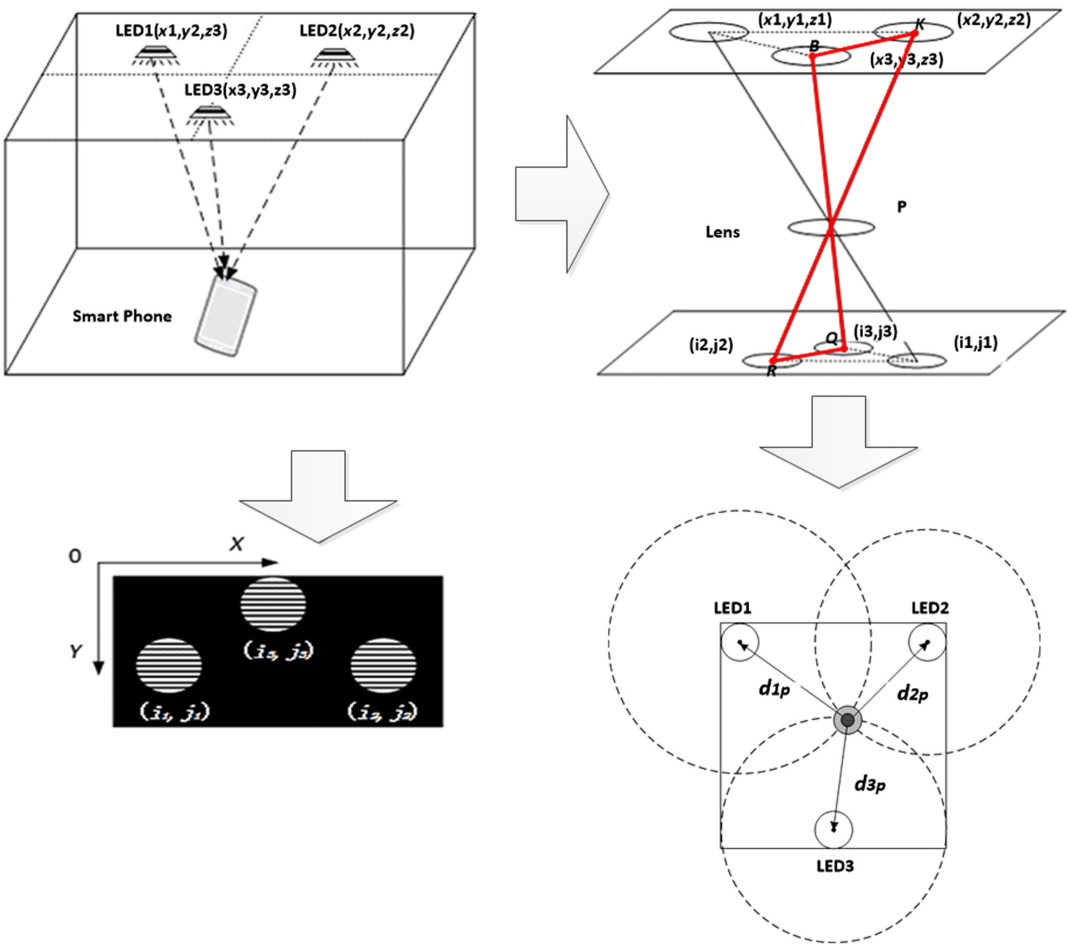

Fig. 2 The propose triple-light positioning system model.

Geometric relationship of the proposed triple-light positioning scheme is detailed in Fig. 2. The focal length of the lens f is the intrinsic parameter of the camera. And the distance between the center of the LED pixel and the center of the image sensors is p_k, $k = 1, 2$, and 3 for the three LED lamps. The pixel coordinate system and image coordinate system are both located on the imaging plane of image sensor, but they have different origin and different units of measurement. And the relationship between the pixel coordinate system and image coordinate system is presented in Fig. 3.

The origin of image coordinate system is the point of intersection of camera's optical axis and the image sensor imaging plane, i.e., the center of midpoint of the image sensor imaging plane. The unit of the mentioned image coordinate system is mm, which belongs to the physical unit. The unit of the pixel coordinate is pixel, which is described by its row and line. Therefore, their relationship is shown as follows: di and dj represent the unit conversion of two coordinate systems, i.e., 1 pixel = dj mm. The conversion is shown below:

$$u = \frac{i}{di} + u_0, \tag{1}$$

$$v = \frac{j}{dj} + v_0. \tag{2}$$

The above equations can be rewritten in the matrix form as

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{1}{di} & 0 & u_0 \\ 0 & \frac{1}{dj} & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i \\ j \\ 1 \end{bmatrix}, \tag{3}$$

where i,j is the coordinate in the image coordinate system, u, v is the coordinate in the pixel coordinate system, and (u_0, v_0) is the midpoint of image sensor's imaging plane in pixel coordinate system. Therefore, we can obtain the conversion of the image coordinate system and the pixel coordinate system. Furthermore, we can get the distance between the center of image sensor and the image of LED on the sensor p_k:

$$p_k = \sqrt{i_k^2 + j_k^2}. \tag{4}$$

And the distance between the LED pixels is

$$\begin{cases} p_{12} = \sqrt{(i_1 - i_2)^2 + (j_1 - j_2)^2} \\ p_{13} = \sqrt{(i_1 - i_3)^2 + (j_1 - j_3)^2} \\ p_{23} = \sqrt{(i_3 - i_2)^2 + (j_3 - j_2)^2} \end{cases}. \tag{5}$$

Then the hypotenuse i_k, $k = 1, 2$, and 3 for the three LED anchors, of the triangle PQR can be expressed as

$$d'_{kP} = \sqrt{f^2 + p_k^2}, \tag{6}$$

and the triangle PQR is similar to triangle (KBP), so

$$d_{kP} = \frac{H \times d'_{kP}}{f}, \tag{7}$$

where H is the vertical distance between the LED and the lens plane

$$H = f\frac{d_{12}}{p_{12}} = f\frac{d_{13}}{p_{13}} = f\frac{d_{23}}{p_{23}}, \tag{8}$$

where d_{12}, d_{13}, and d_{23} are the distance between LED A, B, and C, which can be calculated by the 3-D coordinate of the LED anchor

$$\begin{cases} d_{12} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \\ d_{13} = \sqrt{(x_1 - x_3)^2 + (y_1 - y_3)^2} \\ d_{23} = \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2} \end{cases}. \tag{9}$$

The location distance formula of LED and receiving terminal is as follows:

$$(x - x_k)^2 + (y - y_k)^2 + (z - z_k)^2 = d_{kP}^2, \tag{10}$$

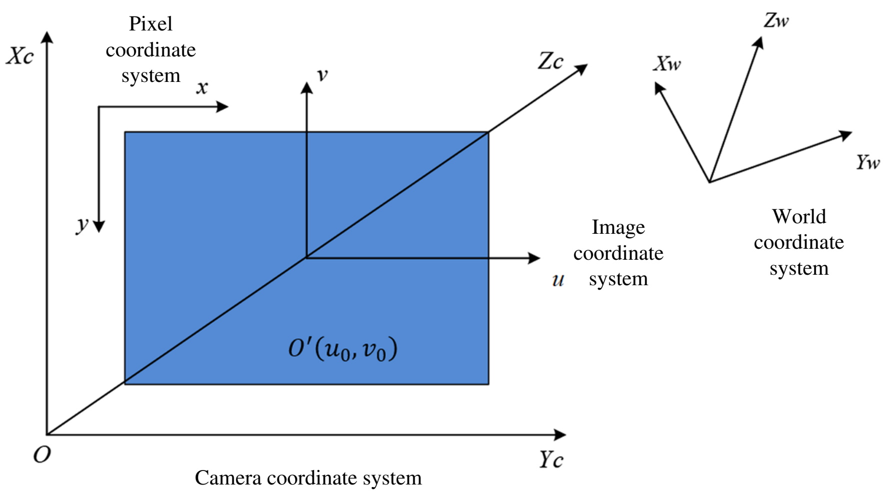

Fig. 3 The *xy* is the pixel coordinate system, *vu* is the image coordinate system, *XcYc* is the camera coordinate system, and *XwYwZw* is the world coordinate system.

$$(x - x_k)^2 + (y - y_k)^2 + (H)^2 = \left(\frac{H \times d'_{kP}}{f}\right)^2. \tag{11}$$

Assuming that $a_k = \left(\frac{H \times d'_{kP}}{f}\right)^2$, which can be obtained by Eq. (8). So, a_k, $k = 1, 2$, and 3 are constant. Therefore,

$$(x - x_k)^2 + (y - y_k)^2 + (H)^2 = a_k \Rightarrow \begin{cases} (x - x_1)^2 + (y - y_1)^2 + (H)^2 = a_1 \\ (x - x_2)^2 + (y - y_2)^2 + (H)^2 = a_2 \\ (x - x_3)^2 + (y - y_3)^2 + (H)^2 = a_3 \end{cases}. \tag{12}$$

Then we can get the following equations according to the above mathematical expression:

$$2(x_2 - x_1)x + 2(y_2 - y_1)y + (x_1^2 + y_1^2 - x_2^2 - y_2^2) = a_1 - a_2, \tag{13}$$

$$2(x_3 - x_1)x + 2(y_3 - y_1)y + (x_1^2 + y_1^2 - x_3^2 - y_3^2) = a_1 - a_3, \tag{14}$$

The formula above can derive the horizon coordinate x, y of the unknown node:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \frac{1}{2}\begin{bmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \end{bmatrix}^{-1} \begin{bmatrix} a_1 - a_2 - (x_1^2 + y_1^2 - x_2^2 - y_2^2) \\ a_1 - a_3 - (x_1^2 + y_1^2 - x_3^2 - y_3^2) \end{bmatrix}. \tag{15}$$

And the z coordinate is

$$z = z_1 - H = z_2 - H = z_3 - H. \tag{16}$$

Though Wuan et al.[7] had proposed a positioning algorithm based on three LEDs, it is relatively complex and needs to solve three quadratic equations. And it also has some limitations as what have been mentioned in Sec. 2. Compared with the algorithm based on three LEDs in Ref. 7, the proposed triple-light positioning algorithm (only binary linear equations are solved) significantly enhances the speed of the computation, which not only simplify the calculation but also is more applicable to actual operation.

Fig. 4 The circuit board of transmitting terminal.

Table 1 Parameters in this paper.

Parameter	Value
Indoor space unit size ($L \times W \times H$) (m^3)	$0.8 \times 0.8 \times 2$
The focal length (mm)	3
Height of the camera (m)	0 to 0.3 (resolution: 0.1)
Plan range of the camera (m)	0.1 to 0.7 (resolution: 0.2)
Voltage of each LED (V)	28.43
Current of each LED (A)	0.1
The resolution of the camera	2048×1536
The exposure time of the camera (ms)	0.05
The power of LED (W)	9
The diameter of the LED luminescence part (mm)	130
The voltage of LED (V)	DC 26
Computer parameter	Acer Aspire VN7-593G, Intel (R) Core (TM) i7-7700HQ CPU@ 2.8GHz, Ubuntu 16.04 LTS

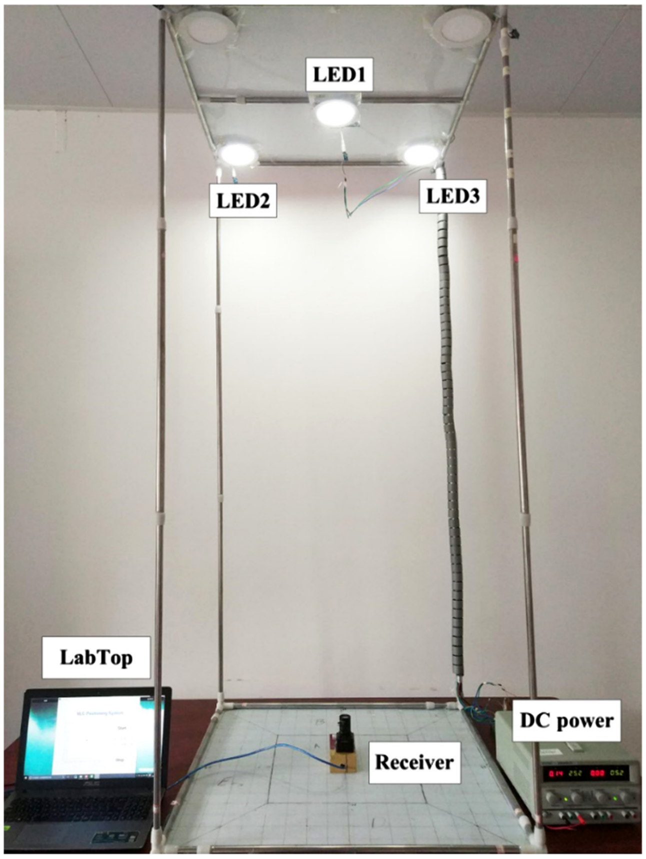

Fig. 5 The experimental platform of VLP system based on triple-light positioning algorithm.

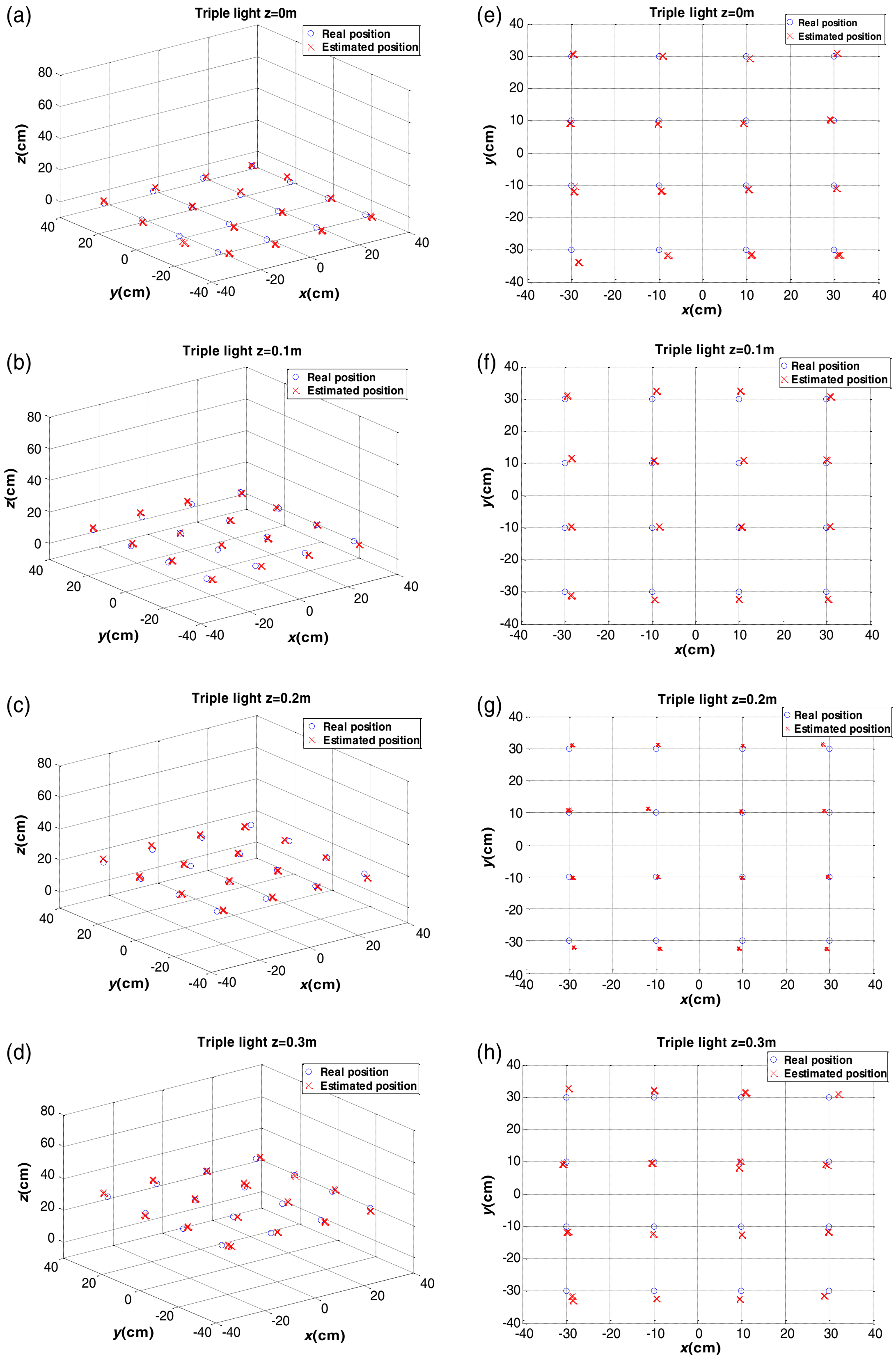

Fig. 6 The positioning results of triple-light positioning system. (a)–(d) The 3-D positioning results at the height of 0, 0.1, 0.2, and 0.3 m, respectively; (e)–(h) the horizontal view of the 3-D positioning results at the height of 0, 0.1, 0.2, and 0.3 m, respectively.

3 Experiment and Analysis

We carry out experiments to demonstrate the performance of the proposed positioning algorithm as shown in Fig. 5, in which there are five LEDs mounted on the top of the frame. Only three LEDs are used for the proposed algorithm. Each LED luminaire is embedded with an 8-bit microcontroller unit, which encodes the unique identifiers to a codeword appropriate for not only for optical transmission but also for flicker mitigation and dimming support. Using on–off keying intensity modulation, the LED driver is capable to convert the codeword into modulated digital signals and driving the LED luminaire to transmit the optical signals. And the drive circuit board is shown in Fig. 4. Furthermore, we measure the time efficiency of our algorithm with the CMOS industrial camera (as the positioning facility) and the computer Acer Aspire VN7-593G, Intel (R) Core (TM) i7-7700HQ CPU@ 2.8GHz, Ubuntu 16.04 LTS (as the software platform). All the key system parameters are provided in Table 1.

3.1 *Triple-Light Positioning Experiment and Analysis*

As shown in Fig. 5, the performance of triple-light algorithm is tested by the experiment, in which the coordinate (in cm) of the LEDs are (−33, 33, 200), (33, 33, 200), and (0, 0, 200). There are 16 evenly distributed test points at the height of 0, 0.1, 0.2, and 0.3 m, respectively. Each position is tested for 6 times, and there are 384 positions tested in the experiment totally. The positioning results are shown in Figs. 6(a)–6(d). And Figs. 6(e)–6(h) show the horizontal view of them.

As shown in Fig. 6, the estimated positions match well with the real positions, which ascertain that the proposed triple-light positioning algorithm can achieve high positioning accuracy. The spots in Fig. 7 prove that with different height of the camera, the positioning mean error is barely changed. To better analyze the performance, Fig. 8 gives the cumulative distribution function (CDF) of positioning error. CDF is defined as the probability that random positioning error takes on a value less than or equal to the positioning accuracy. As can be seen from the CDF curve that over 90% of the errors are within 3.23 cm, the histograms of the 3-D

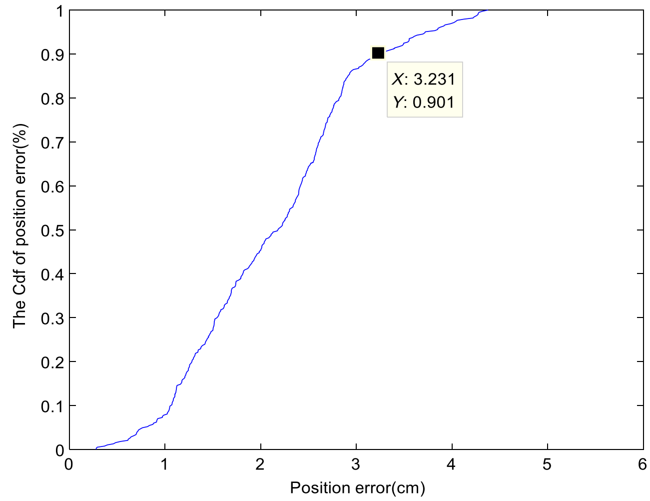

Fig. 8 The CDF curves of positioning error in triple-light positioning system.

positioning error are shown in Fig. 9, which shows the average error of the proposed triple-light positioning algorithm is 2.14 cm and all of the positioning errors are within 4.38 cm. Furthermore, the time efficiency of the proposed triple-light positioning algorithm is also measured; the computational time is reduced to 65.50 ms on average.

Through the experiment, it can be clearly seen that, the proposed positioning algorithm can achieve a high positioning accuracy and take the real-time ability into account. The proposed triple-light positioning algorithm provides an average positioning accuracy of 2.14 cm and an average computational time of 65.50 ms. In comparison with Ref. 7, as representative for the existing research on three LEDs in the VLP, which realize positioning by solving three quadratic equations in the simulation, the proposed positioning algorithm only require solving binary linear equations. So, the proposed positioning algorithm has a good real-time ability. As for the positioning accuracy, the errors of the experiment are caused by the following reasons. First, some errors are caused by the measurement in image processing. Second, the installation of LEDs and the placement of the camera can also cause some errors, i.e., there are some coordinate

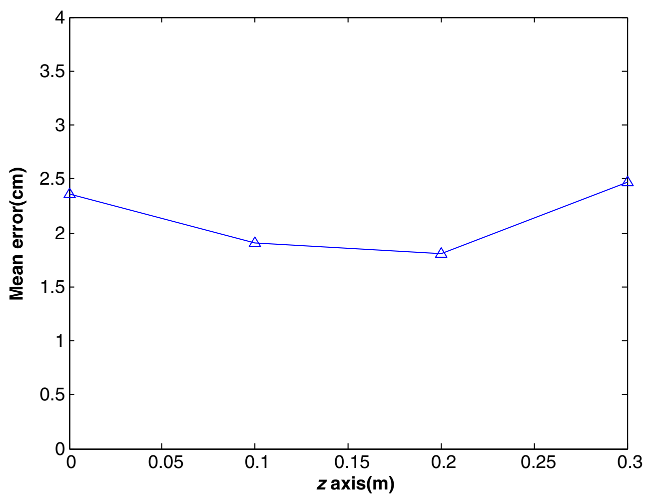

Fig. 7 The positioning mean error varies with height.

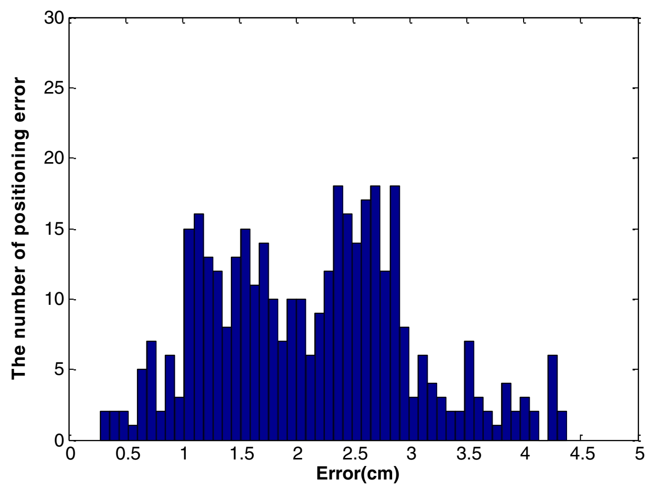

Fig. 9 Histogram of the triple-light positioning error in triple-light positioning system.

deviations of the receiver between the reality and the measured value. Finally, additional errors occurred by calculation and equipment. As for the real-time ability, the proposed positioning algorithm can realize positioning for 15 times in 1 s. The proposed algorithm promises high accuracy as well as high speed.

Based on the discussion above, when there are more than three LEDs in the view, the distances between LEDs and the camera are relatively long, which will cause a larger error when the diameter of the LED is measured. Thus, the proposed triple-light positioning algorithm should be adopted to cope with the problem. Therefore, it can be concluded that an enhanced VLP algorithm which promises real-time ability and positioning accuracy for three LEDs' situation should be adopted for the tasks that require both efficiency and accuracy.

4 Conclusion

We propose an algorithm based on a situation with three LEDs in the vision of the image sensor and take the real-time ability into consideration, which greatly improves the practicality of the algorithm. More vitally, the real-time ability of our algorithm gives a satisfactory answer to the relevant industry fields that have high command of efficiency and real-time need. In addition, different from the traditional LED-ID modulation and demodulation methods, we treated the LED-ID detection and recognition problem as a classification problem in machine learning field.

A series of experiments are conducted based on the proposed algorithm to demonstrate the positioning performance. Experimental results show that over 90% of the errors are within 3.23 cm, and the average error of the proposed triple-light positioning algorithm is 2.14 cm and all the positioning errors are within 4.38 cm. So, the proposed positioning algorithm can provide an accuracy of 4.38 cm. Meanwhile, in regard to the real-time ability, the computational time of the proposed algorithm is reduced to 65.50 ms, and the proposed positioning algorithm can realize positioning for 15 times in 1 s. The proposed algorithm promises high accuracy as well as high speed, which is very worth mentioning because most of current positioning algorithms fail to deliver the efficiency. So, it can be concluded that the proposed algorithm delivers satisfactory performance in terms of real-time ability and positioning accuracy.

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