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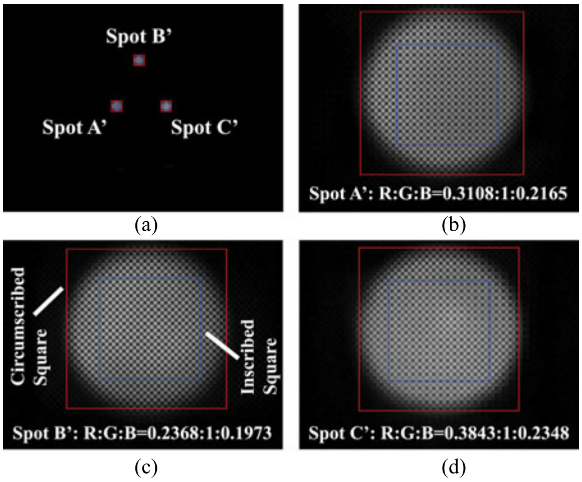

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Indoor Positioning Method Based on Metameric White Light Sources and Subpixels on a Color Image Sensor

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Abstract: An indoor positioning method based on metameric white light sources and subpixels on a color image sensor is proposed in this paper. Metameric white light sources are obtained by merging multiple-color light-emitting diode (LED) chips with different intensity ratios. The output intensity ratios of subpixels on color image sensor at the receiver are employed to identify the respective metameric white light sources. Proof of concept experiments demonstrates that the average error of 2-D indoor positioning is 1.50 cm and 3-D indoor positioning is 3.58 cm. The indoor positioning system with the proposed method is cost effective and convenient because image sensors in nowadays available mobile devices can be utilized.

Index Terms: Light emitting diodes (LEDs), metamerism, visible light positioning.

1. Introduction

With increasing demands for indoor localization and poor indoor positioning performance of global positioning system (GPS), indoor positioning techniques have attracted globally growing interest in recent years [1], [2]. Several indoor positioning methods based on Wireless Local Area Networks (WLANs), Infrared Radiation (IR), Ultra-Wideband (UWB), Bluetooth, ultrasound, inertial navigation, image searching, and coded targets/patterns have been proposed and put into various applications [3], [4]. However, these methods have limitations on accuracy, complexity, additional infrastructure or electromagnetic interference (EMI). With the world-wide utilization of visible light-emitting diode (LED) as green lighting source [5], visible light positioning is considered as a promising candidate for indoor localization owing to the advantages that it is energy saving, radio-frequency (RF) radiation free, and most likely preferred in those areas where the RF signal is restricted, such as a hospital and plane cabin.

For a visible light LED based positioning system, photodiode (PD) or image sensor based receiver can be used to detect light signal [6]–[13]. Since currently available mobile device is equipped with image sensor, it is convenient and cost-effective if an image sensor based receiver in an indoor positioning system is used [9]–[13]. Tanaka has demonstrated a positioning system by utilizing image sensor to identify three different color LEDs, and the positioning error is about 5 cm [9]. However, for an actual imaging positioning system to achieve positioning and illumination simultaneously, the illumination requirement will not be satisfied if the reference light sources are with different colors. Kuo proposed a rolling shutter effect based detect method to improve the frequency sensitivity of an image sensor, and the average positioning error is about 7 cm [10]. However, in order to transport information via rolling shutter effect, multiple images should be taken. Second, the rolling-shutter effect based positioning algorithm needs to convert bright and dark fringes into data sequence, which is limited by the large extinction ratio (ER) variation. Thus, specific thresholding schemes should be used [14]. Moreover, there are gaps between captured frames of an image sensor, and an undesirable effect may happen when taking image from a moving receiver [15]. Specific techniques should be used to deal with these problems. On the other hand, to avoid uncomfortable visual experience, the dimming frequency of light sources should be higher than 200 Hz [16], but typical frame rate of a commercial image sensor is approximately 30 frames per second [17]. Thus, the visible light communication cannot be used directly in a commercial image sensor based positioning system to transport positioning-related information as [13].

In this paper, we propose a reference light source discrimination scheme by employing metameric light sources and demonstrate it in an image sensor based indoor visible light positioning system. In the proposed scheme, metameric light sources with same color coordinate of white light is obtained by combining different color LED chips. A color image sensor which is commonly equipped by available mobile device is used to identifying the different spectral power distributions of different light sources in a white lighting scenario, while such spectral difference is not perceptible for human eyes. We first discuss and analyze the positioning principle with metameric light sources. Then, proof-of-concept experiments are demonstrated, and the positioning accuracy is evaluated. Experimental results show that the positioning accuracy of the proposed scheme is several centimeters.

2. Positioning Principle with Metameric white Light Sources

2.1 Merged Metameric White Lighting Sources with LED Chips of Multiple Colors

An indoor visible light positioning system should first have the illumination function. White light sources are commonly used in illumination scenarios. It is well known that a white lighting can be obtained by merging LED chips of multiple colors. If LED chips of N colors are used to merge a light, the color coordinate $(x_{\mathrm{C}}, y_{\mathrm{C}})$ and the illuminance I_{C} of merged light can be expressed as

$$\begin{cases} x_{\mathrm{C}} = \frac{\sum_{n=1}^{N}\int_{380}^{780} I_{n,\mathrm{T}} S_n(\lambda)\bar{x}(\lambda)d\lambda}{\sum_{n=1}^{N}\int_{380}^{780} I_{n,\mathrm{T}} S_n(\lambda)[\bar{x}(\lambda)+\bar{y}(\lambda)+\bar{z}(\lambda)]d\lambda} \\ y_{\mathrm{C}} = \frac{\sum_{n=1}^{N}\int_{380}^{780} I_{n,\mathrm{T}} S_n(\lambda)\bar{y}(\lambda)d\lambda}{\sum_{n=1}^{N}\int_{380}^{780} I_{n,\mathrm{T}} S_n(\lambda)[\bar{x}(\lambda)+\bar{y}(\lambda)+\bar{z}(\lambda)]d\lambda} \\ I_{\mathrm{C}} = \sum_{n=1}^{N}\int_{380}^{780} I_{n,\mathrm{T}} S_n(\lambda)\,\mathrm{V}(\lambda)\,d\lambda \end{cases} \tag{1}$$

where $S_n(\lambda)$, $n \in [1, N]$ is the spectral power distribution of each color LED chip; $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the tristimulus values defined by the international commission on illumination (CIE); $I_{n,\mathrm{T}}$ is LED chip's intensity of the n-th color; and $\mathrm{V}(\lambda)$ is the luminosity function [18], [19].

According to CIE1931, the color coordinate $(x_{\mathrm{C}}, y_{\mathrm{C}})$ of each merged light source in color space should same and follow the constraint of human eyes' white light perception. Equation (1) are linear equations, thus there are enormous intensity combinations of N-color LED chips to form the metameric merged white light if $N \geq 4$. Light sources who emit such merged light are called metameric light sources, and the spectral power distribution of m-th merged light source is described by

$$S_m(\lambda) = \sum_{n=1}^{N} I_{nm,\mathrm{T}} S_n(\lambda) \tag{2}$$

where $I_{nm,\mathrm{T}}$ is LED chip's intensity of the n-th color in m-th metameric light source.

A commonly available color image sensor is usually integrated with a Bayer optical filter (typically consisting of 1 red, 2 green, and 1 blue filters); thus, one pixel can be divided into four sub-pixels. If $T_R(\lambda)$, $T_G(\lambda)$, and $T_B(\lambda)$ are the transmittance of R-G-B optical filters, respectively, the output intensity of sub-pixels can be expressed as

$$\begin{cases} I_{\mathrm{R}} = t_e H\,(0) \int_{380}^{780} S_m\,(\lambda)\, T_{\mathrm{R}}\,(\lambda)\, \eta_{\mathrm{R}}\,(\lambda)\, d\lambda \\ I_{\mathrm{G}} = t_e H\,(0) \int_{380}^{780} S_m\,(\lambda)\, T_{\mathrm{G}}\,(\lambda)\, \eta_{\mathrm{G}}\,(\lambda)\, d\lambda \\ I_{\mathrm{B}} = t_e H\,(0) \int_{380}^{780} S_m\,(\lambda)\, T_{\mathrm{B}}\,(\lambda)\, \eta_{\mathrm{B}}\,(\lambda)\, d\lambda \end{cases} \tag{3}$$

where t_e is the exposure time; $H(0)$ is the channel direct current (DC) gain; and $\eta_{\mathrm{R}}(\lambda)$, $\eta_G(\lambda)$, and $\eta_{\mathrm{B}}(\lambda)$ are quantum efficiency of R-G-B sub-pixels. To consider the DC gain of indoor visible light atmosphere channel is nearly spectral independent, and nearly the same for sub-pixels in a pixel. Thus, the output intensity ratio of sub-pixels can be expressed as

$$\begin{aligned} I_{\mathrm{R,R}} : I_{\mathrm{G,R}} : I_{\mathrm{B,R}} = \int_{380}^{780} S_m\,(\lambda)\, T_{\mathrm{R}}\,(\lambda)\, \eta_{\mathrm{R}}\,(\lambda)\, d\lambda : \\ \int_{380}^{780} S_m\,(\lambda)\, T_{\mathrm{G}}\,(\lambda)\, \eta_{\mathrm{G}}\,(\lambda)\, d\lambda : \int_{380}^{780} S_m\,(\lambda)\, T_{\mathrm{B}}\,(\lambda)\, \eta_{\mathrm{B}}\,(\lambda)\, d\lambda\,. \end{aligned} \tag{4}$$

Thus, the respective metameric light sources' projective light spots can be differentiated by output intensity ratio of sub-pixels ($I_{\mathrm{R,R}} : I_{\mathrm{G,R}} : I_{\mathrm{B,R}}$) in it on a color image sensor if each light source is merged by using a unique intensity combination ($I_{1,\mathrm{T}}, I_{2,\mathrm{T}}, \cdots I_{N,\mathrm{T}}$) of multiple-color LED chips, while these metameric light sources cannot be distinguished by human eyes. The output intensity level of the sub-pixel in a typical commercial image sensor is 0 to 255, and therefore, there are theoretically 65536 combinations to achieve a distinguishable metameric white light source by just varying the ratio of ($I_{\mathrm{R,R}} : I_{\mathrm{G,R}}$) if the spectral power distributions of LED chips are not limited. Moreover, for a typical positioning cell, there are three reference light sources in it. Therefore, there are theoretically C_{65536}^{3} combinations of reference light sources for a specific positioning cell, and it is enough for an actual indoor positioning application in which the metameric light sources are identified by output intensity ratios of sub-pixels in projective spots on a color image sensor.

2.2 Positioning Algorithm with the Metameric White Light Sources

Equation (4) indicates that the output intensity ratio of sub-pixels in a specific projective light spot on color image sensor is constant regardless of the position of receiver. The principle of height estimation and imaging positioning is shown as Fig. 1, and for simplicity, the regular triangle distribution of metameric white light sources in an indoor positioning system is considered. In a positioning cell, three reference white light sources are mounted on the ceiling of a room, and their centroid coordinates are described as A($x_1, y_1, 0$), B($x_2, y_2, 0$), and C($x_3, y_3, 0$), if a 3-D Cartesian coordinate system is built in the room. For simplicity, we assume an image sensor is upward vertically as [11], [12], and three reference white light sources have respective projective light spots on the image sensor. A 2-dimensional (2D) Cartesian coordinate system (x', y') is built on the image sensor, with the origin point at the center of image sensor, x' and y' axes are parallel to the row and column of image sensor respectively. The 3-D coordinate of the imaging lens centroid and its focal length is described by (x, y, h) and f respectively. The centroid coordinates of three projective light spots on the image sensor plane are A$'(x + x_1', y + y_1', f + h)$, B$'(x + x_2', y + y_2', f + h)$, and C$'(x + x_3', y + y_3', f + h)$.

Assuming the diameters of light sources are D and the average diameter of their projective light spots is $\bar{d}$, the height of the imaging lens can be estimated roughly by geometrical optics as

$$h' = \frac{f \times D}{\bar{d}} \tag{5}$$

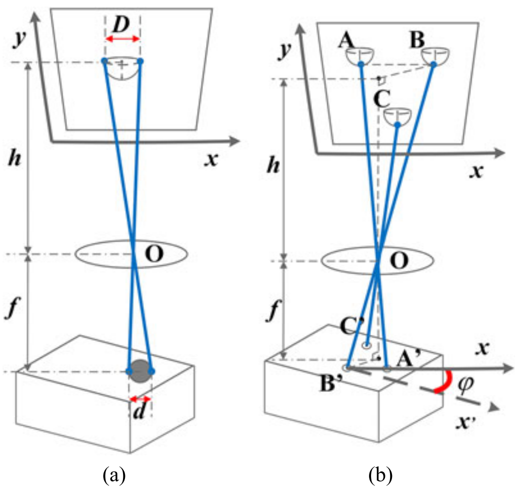

Fig. 1. Principle of (a) height estimation (b) image positioning and orientation measurement.

To the positioning algorithm, if light source A is considered, according to geometrical optics, we get

$$\frac{h^2}{f^2} = \frac{(x - x_1)^2 + (y - y_1)^2}{x_1'^2 + y_1'^2}. \tag{6}$$

Since the focal length f of lens is constant and the relative coordinates of light spot's centroid on the image sensor plane (x_1', y_1') can be directly measured, we define a constant

$$C_1 = \frac{f^2}{x_1'^2 + y_1'^2} \tag{7}$$

and then, (6) is simplified as

$$C_1(x - x_1)^2 + C_1(y - y_1)^2 - h^2 = 0. \tag{8}$$

For light source B and C, we can get similar equations. In all, we get

$$\begin{cases} C_1(x - x_1)^2 + C_1(y - y_1)^2 - h^2 = 0 \\ C_2(x - x_2)^2 + C_2(y - y_2)^2 - h^2 = 0 \\ C_3(x - x_3)^2 + C_3(y - y_3)^2 - h^2 = 0 \end{cases} \tag{9}$$

with

$$C_2 = \frac{f^2}{x_2'^2 + y_2'^2}, \quad C_3 = \frac{f^2}{x_3'^2 + y_3'^2}. \tag{10}$$

With metameric white light sources in an indoor positioning system, flow chart of the positioning algorithm is described in Fig. 2. When a color image sensor captures the projective light spots of three reference white light sources, the average diameter of these spots is calculated, and the height of the imaging lens is roughly estimated by (5). The average output intensity ratio of sub-pixels $(I_{R,R} : I_{G,R} : I_{B,R})$ inside a spot is calculated, and then the corresponding reference light source with the centroid coordinate of $(x_i, y_i, 0)$, $i \in [1, 2, 3]$ is identified by the ratio. The 2-D-coordinate of the light spots' centroid on the image plane can also be obtained as (x_i', y_i'), $i \in [1, 2, 3]$. Finally, with the obtained values of $(x_i, y_i, 0)$ and (x_i', y_i'), $i \in [1, 2, 3]$, 3-D coordinate of the centroid of imaging lens (x, y, h) is calculated by solving (9), i.e. the position of the receiver is localized. It is worth

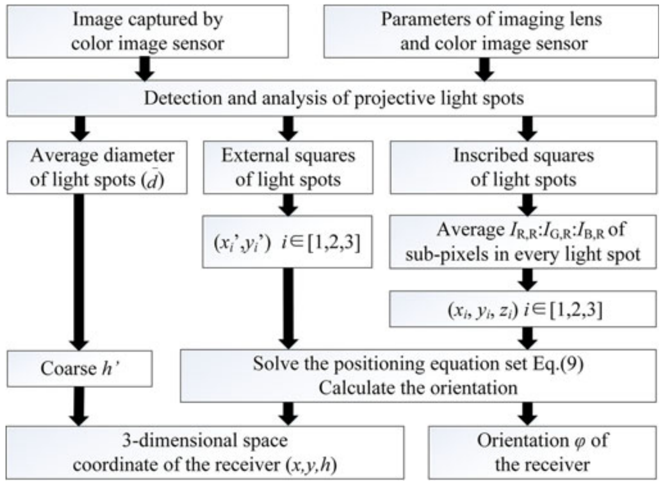

Fig. 2. Flow chart of the positioning algorithm.

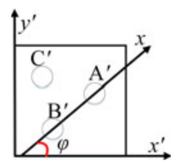

Fig. 3. Orientation measurement of the image sensor.

noticing that there are multiple sets of solutions because (9) is a quadratic equation set, and only one solution is valid. Thus, with the aid of the roughly estimated height by (5), the invalid solution of (9) is eliminated. It is worth to mention that if the size of used light sources are different, (5) will become invalid. In that case, we can use the distance between different light sources' centroid as D, and use the distance between the projective light spots' centroid of different light sources as $\bar{d}$. Then, the new equation (5) can still achieve the height estimation.

Without loss of generality, we assume that the vector from the centroid of light source A to that of light source B is parallel to the axis x. Thus, the vector from the projective spot of B′ to that of A′ is also parallel to axis x, and the orientation φ of the receiver can be estimated by calculating the angle between the vector of B′A′ and the axis x' by $\varphi = \arctan(\frac{y_1'-y_2'}{x_1'-x_2'})$ as Fig. 3 shows. Thus, the error of the estimated orientation can be expressed by

$$\Delta\varphi = |\varphi - \varphi_R| \quad (11)$$

where φ_R is the practical orientation of the receiver.

3. Proof-Of-Concept Experiments And Results

Fig. 4 is the proof-of-concept experimental setup of the proposed indoor visible light positioning scheme with metameric light sources and image sensor, Fig. 5 is the hardware of a lied down positioning cell. For simplify, only one positioning cell is demonstrated. By placing more positioning cells evenly, the positioning service can be achieved in practical scenarios. At the transmit end, 3 bulb LED lamps marked as A, B, and C, each with four-color LED chips (red, green, blue, and white), are driven by a spectral mapping module, and work as metameric reference light sources. The measured spectral power distributions of the used LED chips are shown in Fig. 6, respectively. The white lights with same color coordinate are transmitted with different intensity ratios of 4 colors

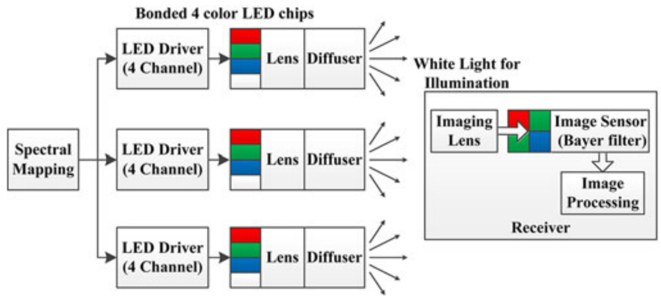

Fig. 4. Experimental setup of metameric imaging indoor visible light positioning system.

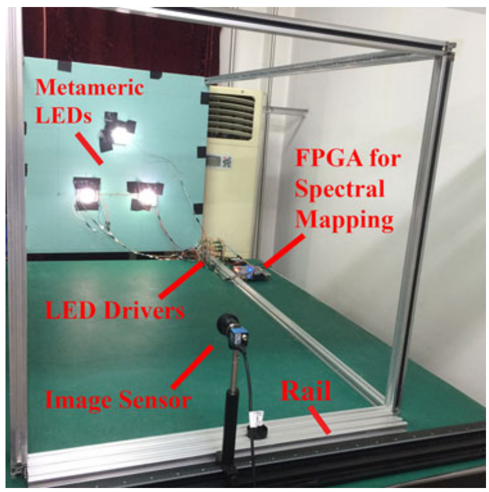

Fig. 5. Hardware of the visible light positioning system.

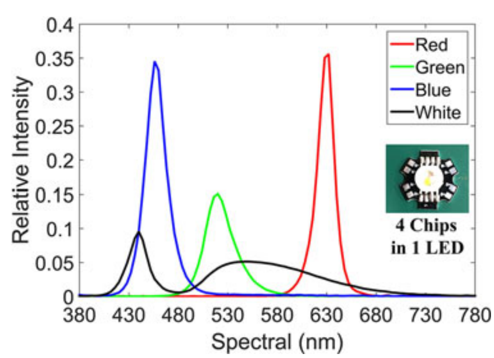

Fig. 6. Measured spectral power distributions of used four-color bonded LED chips.

by respective LED lamps. In the experiment, light diffusers (lampshades) are installed following the LED lamps to redistribute the light from LEDs and achieve uniform light illumination. At the receiver, a color image sensor (Sony ICX 445) integrated with imaging lens (Computar H0514-MP2) and Bayer filter detects the image of the LED lamps, and a rail is used to fix the image sensor. To avoid pixels are saturated and the reference light sources cannot be identified [20], the exposure time of the image sensor is set according to the illuminance. When the output of any pixel of the image sensor is 255 (namely saturated), a shorter exposure time will be used, and an image will

TABLE I
Key Parameters of Positioning System

Parameter	Value
LED A's average current ratio	R:G:B:W = 21.3:30.6:11.5:50
LED B's average current ratio	R:G:B:W = 0:0:0:100
LED C's average current ratio	R:G:B:W = 42.6:61.2:22.9:0
LED A's space coordinate (m)	(0.3, 0.3, 0)
LED B's space coordinate (m)	(0.45, 0.6, 0)
LED C's space coordinate (m)	(0.6, 0.3, 0)
Diffusers' diameter (mm)	62
Lens's equivalent focal length (mm)	5
Lens's field of view (degree)	51.4 × 39.5
Pixel number of image sensor	1292 × 964
Pixel size of image sensor (μm)	3.75 × 3.75
Objective color coordinate (CIE1931)	(0.3279, 0.3459)

be re-captured. Key parameters of the transmitter and the receiver are listed in Table I. The dimension of the prototype positioning system is 0.9 m × 0.9 m × 1.8 m. In the experiments, the color coordinates of the used LED chips are measured by a colorimeter (Photo Research, PR715) and shown as Fig. 7. It is worth to notice that the "white" point is not only the color coordinate of the used white LED chip, but also the objective color coordinate of the merged LED lamps. The color coordinates of the merged LED lamps are also measured by the colorimeter, and the color coordinates of LED lamps A/B/C are (0.3266, 0.3423), (0.3279, 0.3459), and (0.3276, 0.3392), respectively. It is noticed that the difference in color coordinates of LED lamps A/B/C is nearly negligible for human eyes, so the LED lamps can be viewed as metameric.

Fig. 8(a) shows three projective light spots on the image plane of the three metameric LED lamps. The enlarged details of the spots are shown in Fig. 8(b)–(d). The centroid of each spot is calculated with the aid of its circumscribed square of each spot. The average output intensity ratio of sub-pixels in a spot is calculated with its inscribed square as shown in Fig. 8(b)–(d), and the metameric LED lamps that have the projective spots can be identified accordingly with only one captured image. After the metameric LED lamps are identified, the 2-D and 3-D coordinates of the image sensor can be obtained with the proposed positioning algorithm in Section 2.

In Fig. 8(a), it can be observed that the intensity levels of the pixels out of the light spots are zero due to short exposure time of the image sensor, indicating that the proposed imaging positioning algorithm is not sensitive to diffuse light and the background on the ceiling.

The error of 2-D positioning and its distribution probability are shown in Fig. 9. The average error of 2-D positioning is 1.50 cm. The errors are largely less than 2.5 cm, and the error of 95% confidence level is about 5 cm. Generally, the space distribution of 2-D positioning error in the cell is even, so centimeter-magnitude 2-D positioning can be kept in whole indoor space by evenly placing more cells with metameric light sources at the ceiling.

Fig. 10 presents the error of 3-D positioning and its distribution probability. The average error of 3-D positioning is 3.58 cm, and the error of 95% confidence level is about 10 cm. It should be pointed out that the positioning errors of some points at the central area are relatively large, which is caused by the deviation of the reference positions of LED lamps, the random tilt of LED lamps and the image sensor. In general, however, the 3-D positioning error is centimeter-magnitude, and

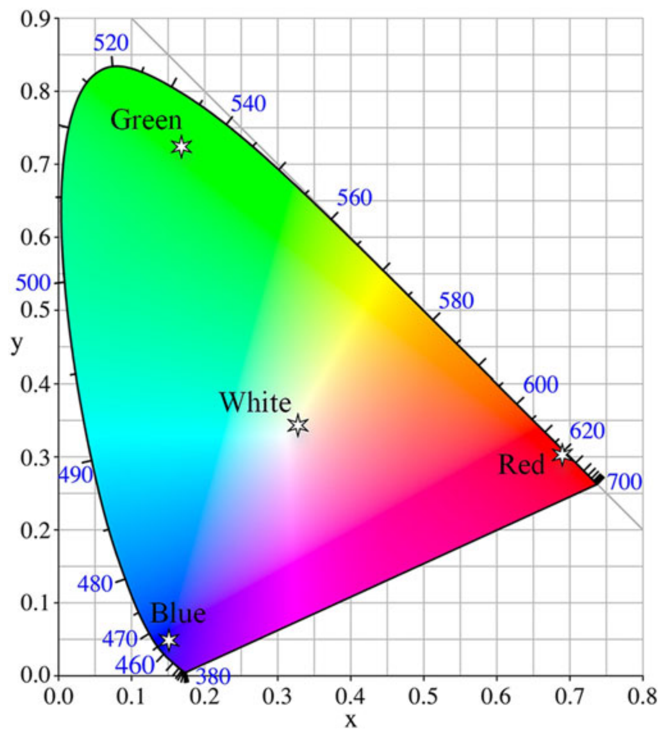

Fig. 7. Measured color coordinates of the used LED chips.

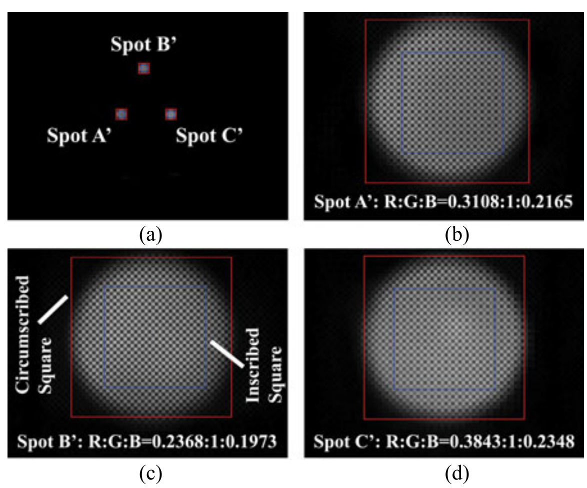

Fig. 8. Identification of different metameric light sources (a) three spots, (b) spot A', (c) spot B', and (d) spot C'.

it is accurate enough to provide indoor location-based service with an image sensor in currently available mobile devices.

Finally, the orientation of the image sensor is also estimated. The pointing error is evaluated with various directions of image sensor, which is introduced by the random slight tilt and quantization error from pixels of the image sensor in the experiments. Its distribution probability is presented in Fig. 11, with the average error of 0.48 degree and the maximum measured orientation error about 1 degree. Generally speaking, the average pointing error of less than 1 degree is good enough for indoor positioning and navigation.

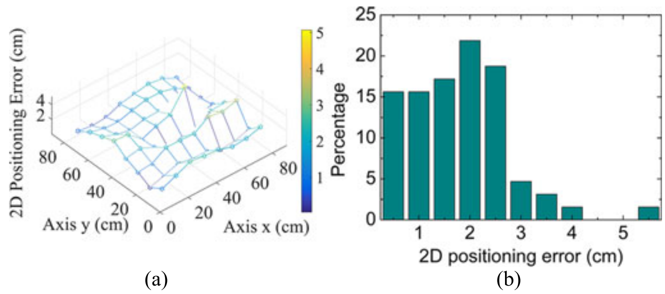

Fig. 9. (a) Two-dimensional positioning error and its space distribution (b) histogram of 2-D positioning error.

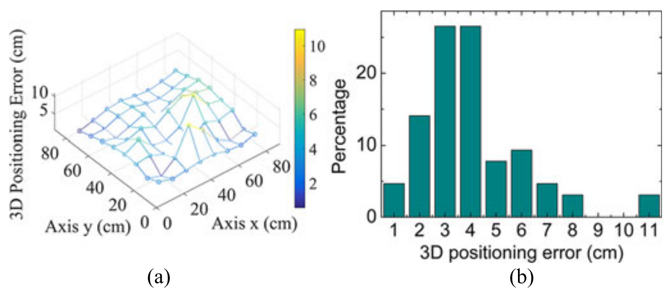

Fig. 10. (a) Three-dimensional positioning error and its space distribution (b) histogram of 3-D positioning error.

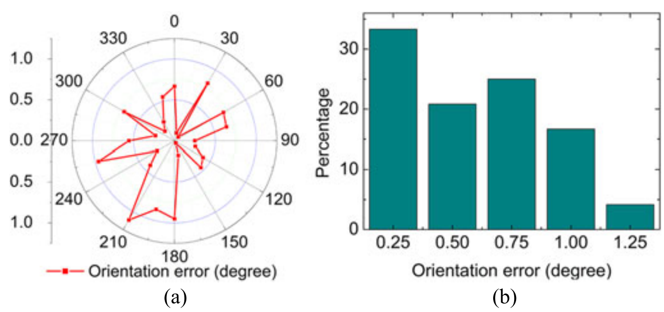

Fig. 11. (a) Orientation error and its space distribution (b) histogram of orientation error.

It is noted in Fig. 8 that the range of measured average output intensity ratio of R:G is from 0.2368:1 to 0.3843:1 in the experiments. If we assume the intensity level of green channel is 250 (the maximum output intensity level of the used image sensor is 255), the corresponding intensity levels of red channel are from 59 to 96. Thus, if the SNR of received visible light is high enough, there are 38 color combinations to realize metameric light sources with considering different reference light sources discernible at the receiver. If light sources with bonded N ($N > 4$) kinds of LED chips are used, there will be more degrees of freedom to vary the intensity ratio of different kinds of LED chips, and the number of color combinations to realize metamerism will be increased exponentially. To assume there are three metameric light sources in a positioning cell and there are K ($K \geq 38$) color combinations to realize metamerism, there will be C_K^3 different kinds of positioning cells to employ the proposed positioning scheme.

IV. Conclusion

An indoor visible light positioning method based on metameric white light sources and color image sensor is proposed and demonstrated in this paper. At the transmitter, multiple color LED chips with different intensity ratios are utilized to merge metameric white light sources. At the receiver, the output intensity ratios of sub-pixels in projective light spots on the image sensor are employed to identify the respective metameric light sources in the positioning system. In a dimension of 0.9 m $\times$ 0.9 m $\times$ 1.8 m (i.e., the image sensor is 1.8 m below the light sources), the results of the prototype positioning system demonstrate that, the average error of 2-D positioning is 1.5 cm, the average error of 3-D positioning is 3.6 cm, and the average error of orientation measurement is less than 1.0 degree. If more white light sources merged with color-LED chips are evenly placed in a larger dimension, such positioning accuracy will be kept, which is good enough for indoor positioning and navigation, and foresees many potential applications in various scenarios such as supermarkets, warehouses, offices, and parking lots. The method proposed in this paper is cost effective and convenient for user since a commercial color image sensor is used as receiver, which is available in currently mobile device. Moreover, the proposed method can be utilized to achieve high accuracy indoor positioning with only one captured image and has no requirement on frame rate.

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