A RSS/AOA based indoor positioning system with a single LED lamp

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***Abstract*—Indoor positioning using visible light has attracted great attentions in the world. The reported indoor positioning schemes based on visible light are limited by installing multiple LED lamps in the environments. In order to overcome this limitation, we propose a novel indoor positioning system using only one LED lamp, in which a smartphone is used to be receiver to estimate the three-dimension (3-D) position by using the received-signal-strength (RSS) and angle-of-arrival (AOA) positioning algorithm. The proposed system is demonstrated by experiment and the results show that ~10.2-cm average positioning error is achieved in a 2 m × 2 m × 2.5 m indoor environment.**

Keywords—Visible light; indoor positioning; RSS; AOA

I. Introduction

Due to the great demands for indoor location-based services, the indoor positioning system (IPS) has developed rapidly in recent years. As a widely used outdoor positioning system, global positioning system (GPS) [1] cannot be applied in indoor environments, because GPS signals can't reach to the interior areas of buildings. Infrared radiation (IR)- [2], ultrasound- [3], or radio frequency (RF)- [4] based IPSs have been proposed to be used in indoor environments. However, these systems are not the ideal candidates due to the disadvantages of high cost, low positioning accuracy, and electromagnetic interference.

Currently, visible light communication (VLC) [5] has become an attractive research topic due to the development of solid state lighting technology. The IPS based on VLC, namely as a "light positioning system (LPS)" [6], is considered one of the most attractive solutions [7] due to its unique advantages of high positioning accuracy, no RF interference, etc.

Moreover, positioning algorithms used in LPSs are very important for achieving the high location accuracy. The received-signal-strength (RSS) and the angle-of-arrival (AOA) are the two popular positioning algorithms in the reported LPSs. In [8], three-dimension (3-D) positioning is achieved using RSS algorithm by estimating the distances from at least 3 LED lamps to a receiver. In this system, ~0.4 m position error is achieved. In [9], by means of AOA algorithm in which the angles of arrived light signals from at least 2 LED lamps are measured, 3-D positioning with ~4 cm average position error is demonstrated by experiment. As observed above, in the reported LPSs, signals from multiple LED lamps are required to be received by the receiver. That requirement limits the performance of these systems in the environments of installing only one LED lamp, such as bedroom, compartment, etc.

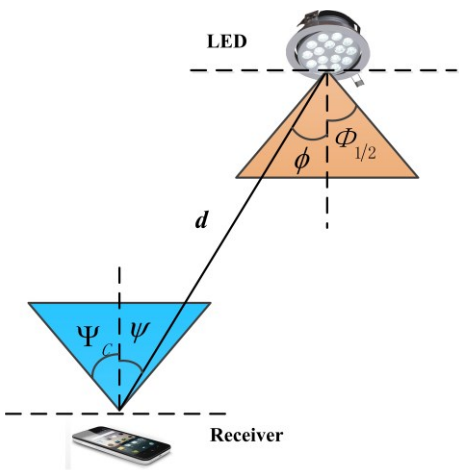

Fig. 1.The proposed positioning system model

In order to overcome these issues, a RSS/AOA-based indoor positioning system with a single LED lamp is proposed in this paper. In the proposed system, a commercial smartphone is used to be a receiver to receive signals and estimate 3-D positions. In comparison with the reported LPSs, our system can achieve the following advantages. Firstly, our system can work in the environments of installing a single LED lamp. This means our system has the greater adaptability. Secondly, a commercial smartphone is used to be a receiver in the proposed system, so the cost can be dramatically reduced. The system is demonstrated by experiment and the results indicate that ~10.2 cm average position error can be achieved in a 2 m × 2 m × 2.5 m indoor environment.

II. System Model

Fig. 1 illustrates the proposed system model. Only one LED lamp deployed on the ceiling emits white light which is modulated by signals. In the receiver end, a smartphone which is integrated with an image sensor, a photodetector (PD) and a magnetic field sensor, demodulates signals and estimates the locations.

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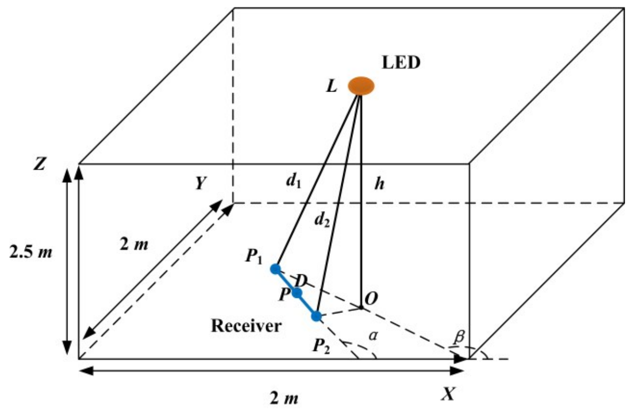

Fig. 2.Schematic of the proposed positioning algorithm

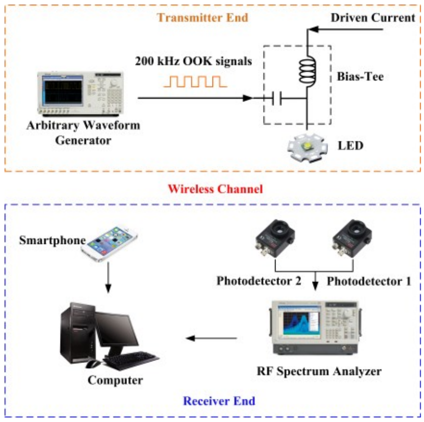

Fig. 3.The experimental setup

In general, a commercial LED lamp follows a Lambertian radiation pattern, so the channel gain can be given by [10]:

$$H = \begin{cases} \frac{(m+1)A}{2\pi d^2}\cos^m(\phi)\cos(\psi)T_S(\psi)G(\psi), & 0 \le \psi \le \Psi_C \\ 0, & \psi > \Psi_C \end{cases}, \quad (1)$$

where m is the Lambertian order, which is relative to the semi-angle at half illuminance of a LED. A is the area of an optical detector, d is the distance between a transmitter and a receiver, ϕ is the irradiant angle, ψ is the incident angle, and Ψ_C is the field-of-view of a receiver. $T_s(\psi)$ is the gain of an optical filter, and $G(\psi)$ is the gain of an optical concentrator. In our system, there are no optical concentrator and filter, so the received electrical power P_{er} can be given by:

$$P_{er} = \frac{c}{d^4}\cos^{2m}(\phi)\cos^2(\psi), \quad (2)$$

where c is a constant and defined as follows:

$$c = \frac{kR^2P_{ot}^2(m+1)^2}{4\pi^2}, \quad (3)$$

where k is the conversion coefficient of the optical-to-electrical power, R is the optical detector responsivity, and P_{ot} is the emitted optical power.

In order to obtain the values of c and m, we fix the vertical distance between the LED lamp and the receiver. The perpendicular axes of LED lamp and receiver are assumed to be parallel. Then, we move the receiver on the xy-plane and measure the received electrical powers on different positions using a RF spectrum analyzer. Fitting the measurement points with the function of $(c\cos^{2(m+1)}(\phi))/d^4$, we can get $c = 0.76 \times 10^{-4}$ and $m = 0.8815$. From m, the semi-angle at half illuminance of the LED is calculated to be 62.9°, which is approximate to 62.5° provided in the datasheet.

III. Positioning Algorithm

In order to estimate 3-D positions using the proposed positioning algorithm, the receiver needs to know the received electrical power, the incident light azimuth angle, and the receiver orientation. The incident light azimuth angle which is defined as an angle between x-axis and the orthogonal projection of incident light to the xy-plane, is measured by an image sensor [11]. The receiver orientation which can be represented by an angle between the x-axis and the orthogonal projection of the receiver pointing direction to the xy-plane, is measured by a magnetic field sensor.

The schematic of the proposed 3-D positioning algorithm is illustrated in Fig. 2. We assume that a LED lamp with coordinates of (a, b, c) is deployed in the environment. The image sensor and the PD with coordinates of (x_1, y_1, z_1) and (x_2, y_2, z_2) are respectively deployed on the position P_1 and P_2, which are separated by a distance D. As the midpoint between P_1 and P_2, the position P with coordinates of (x, y, z) is assumed to be the estimation position. If the receiver orientation is assumed to be α, the coordinates of P_1 and P_2 can be defined as

$$\begin{cases} x_1 = x - \frac{D}{2}\cos(\alpha) \\ y_1 = y - \frac{D}{2}\sin(\alpha) \\ z_1 = z \end{cases}, \quad \begin{cases} x_2 = x + \frac{D}{2}\cos(\alpha) \\ y_2 = y + \frac{D}{2}\sin(\alpha) \\ z_2 = z \end{cases}. \quad (4)$$

Because the received electrical powers on the positions P_1 and P_2 are independent, from Eq. (2), we can get

$$\begin{cases} P_{er1} = \frac{c}{d_1^4}\cos^{2m}(\phi_1)\cos^2(\psi_1) \\ P_{er2} = \frac{c}{d_2^4}\cos^{2m}(\phi_2)\cos^2(\psi_2) \end{cases}. \quad (5)$$

In order to estimate the position P uniquely, the incident light azimuth angle which is assumed to be β, is also used. From Fig.2, we can get

$$(y_1 - b) - \tan(\beta)(x_1 - a) = 0. \quad (6)$$

Moreover, the 2-D coordinates of the LED lamp and P_1 follow

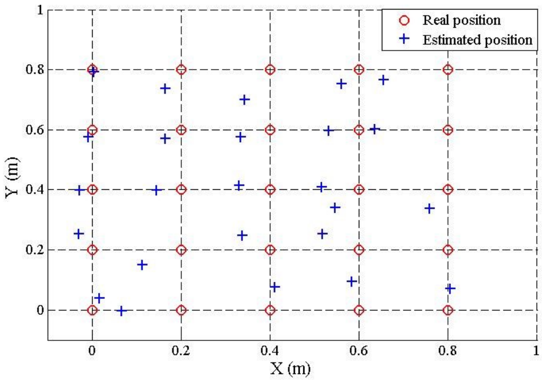

Fig. 4.The 2-D position estimation of the proposed system

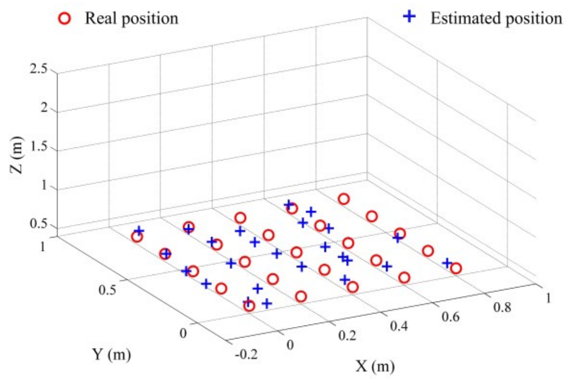

Fig. 5.The 3-D position estimation of the proposed system

$$\begin{cases} x_1 > a, y_1 > b, & \text{if } 0 < \beta \le \dfrac{\pi}{2}, \\ x_1 < a, y_1 > b, & \text{if } \dfrac{\pi}{2} < \beta \le \pi, \\ x_1 < a, y_1 < b, & \text{if } \pi < \beta \le \dfrac{3\pi}{2}, \\ x_1 > a, y_1 < b, & \text{if } \dfrac{3\pi}{2} < \beta \le 2\pi. \end{cases} \quad (7)$$

Therefore, the 3-D coordinates of receiver can be estimated uniquely from Eqs. (4-7).

IV. Results

Following the experimental setup shown in Fig. 3, a Cree Xlamp XM-L LED with coordinates of (0 m, 0 m, 2.5 m) is deployed in a 2 m × 2 m × 2.5 m indoor environment. 200 kHz OOK signals which are generated by an arbitrary waveform generator (AWG), are used to modulate the LED with drive current by a bias-tee circuit. Due to only one LED used, the multiple access, such as time division multiplexing (TDM) [12] or RF carrier allocation [13], is not concerned in this paper. At the receiver end, 25 reference points are evenly distributed on the xy-plane in the simplified room model. At each point, two identical PDs (Thorlabs PDA100A silicon photodetector) which are separated by 10 cm (according to size of a commercial smartphone), are used to receive the optical signals. In addition, a smartphone is used to measure the incident light azimuth angle and the receiver orientation. By all the measurements, the 3-D positions are estimated using Matlab in a computer.

Due to space symmetry, the room model in Fig. 2 can be simplified to a model with size of 1 m × 1 m × 2.5 m. The real receiver height is set to 0.5 m. The 2-D position estimation results of the proposed system are shown in Fig. 4. The maximum positioning error of 26 cm is achieved on the position (0.8 m, 0.6 m) and the minimum positioning error of 0.8 cm is achieved on the position (0 m, 0.8 m). ~8.8 cm 2-D average positioning error is achieved in the simplified room model. In theory, the minimum positioning error happens at the position with the maximum SNR. In other words, the best position estimation should be achieved on the position which is nearest to the LED lamp. However, Fig. 2 illustrates a different result. It can be explained that the positioning error in our system is not only influenced by the received electrical power, but also influenced by the incident light azimuth angle and the receiver orientation. So the performance of our proposed system is not totally depended on SNR. In addition, due to the impossibility to match the real LED position to the assumed LED position precisely, the positioning error induced by the mismatch of the LED position cannot be avoided.

The 3-D position estimation results of the proposed system are shown in Fig. 5. The average positioning error is ~10.2 cm. Note that, the room size in Fig. 5 can be extended to 2 m × 2 m × 2.5 m. Therefore, the proposed system with ~10.2 cm average 3-D positioning error in a 2 m × 2 m × 2.5 m room environment is verified by the experiment.

V. Conclusions

In this paper, an indoor positioning system using one single LED lamp is proposed. In our system, a commercial smartphone which is integrated with an image sensor, a PD, and a magnetic field sensor, is used to be receiver. The 3-D position estimation is achieved using RSS/AOA algorithm. The performance of the proposed system is demonstrated by experiment and the results indicate ~10 cm average position error is achieved in a 2 m × 2 m × 2.5 m room environment. Therefore, our proposed system can be a promising candidate in indoor positioning field.

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