

# Optical Engineering

[SPIDigitalLibrary.org/oe](http://SPIDigitalLibrary.org/oe)

## **Indoor location awareness based on received signal strength ratio and time division multiplexing using light-emitting diode light**

Soo-Yong Jung  
Seong Ro Lee  
Chang-Soo Park

# Indoor location awareness based on received signal strength ratio and time division multiplexing using light-emitting diode light

Soo-Yong Jung,<sup>a</sup> Seong Ro Lee,<sup>b</sup> and Chang-Soo Park<sup>c,\*</sup>

<sup>a</sup>Honam Research Center, Electronics and Telecommunications Research Institute, 176-11 Cheomdan Gwagi-ro, Buk-gu, Gwangju 500-480, South Korea

<sup>b</sup>Mokpo National University, Department of Information and Electronics Engineering, Yeonsan-ro, Cheonggye-myeon, Jeollanam-do, Muan-gun 1666, South Korea

<sup>c</sup>Gwangju Institute of Science and Technology, Department of Information and Communications, 261 Cheomdan-gwagi-ro, Buk-gu, Gwangju 500-712, South Korea

**Abstract.** We propose and demonstrate an indoor location awareness method for an autonomous robot vehicle using light-emitting diodes (LEDs). The location is estimated by measuring received signal strength ratio (RSSR), which is the relative ratio of optical powers detected between each LED and optical receiver. In this method, multiple LED lamps on the indoor ceiling are used, which can radiate light only during the individual time slot assigned to each of them. Using the RSSRs, circle or straight line equations are obtained and the crossing point among those equations determines the location of the object. In the experiment, four LED lamps are identified by time-division multiplexing with room dimensions of  $1.0 \times 1.0 \times 1.3 \text{ m}^3$ , and the results show that the mean of the location error is 3.24 cm in the entire floor area. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.OE.53.1.016106]

Keywords: location awareness; indoor positioning system; light emitting diode; visible light communications; optical wireless.

Paper 131610L received Oct. 23, 2013; revised manuscript received Nov. 22, 2013; accepted for publication Dec. 4, 2013; published online Jan. 6, 2014.

## 1 Introduction

Indoor positioning systems using light-emitting diodes (LEDs) have recently been introduced. The LEDs are expected to play an increasingly important role in the lighting industry in the near future. Moreover, because the LEDs can easily switch and modulate electrical signals into light-wave signals at high speed, they can be used for visible light communication<sup>1,2</sup> and head-tracking techniques.<sup>3</sup> Numerous LED-based positioning systems have been reported by using image sensors,<sup>4</sup> fingerprinting,<sup>5</sup> correlation,<sup>6</sup> and time difference of arrival (TDOA)<sup>7,8</sup> so far. However, the image-sensor-based systems require LEDs of different colors in order to distinguish each one among all of them. Fingerprinting- and correlation-based systems are based on a training stage to obtain a fingerprint map and correlation-sum-ratio equations, respectively. The TDOA-based systems utilize precise delay control to adjust initial phase.

In this article, the LED-based indoor location awareness method for an autonomous robot vehicle has been proposed and demonstrated. The location of an object is estimated by measuring received signal strength ratio (RSSR), which is the relative ratio of optical powers detected between each LED and optical receiver. This method reduces errors due to the difference in device parameters because it could be cancelled out. Using the RSSRs, circle or straight line equations are obtained and the crossing point of the equations indicates the location.

## 2 Location Estimation

For location estimation, we use four LED lamps for illumination as access points. Each LED lamp radiates at its assigned time slot. This is for identification of which LED is being illuminated at a particular time. The power from each LED is measured when it radiates. Figure 1 illustrates the light path from the LED to the object. The detector is mounted on top of the moving object. Therefore, the detected area is parallel to the ground floor. The received power,  $P_R$ , is expressed as<sup>9</sup>

$$P_R = H(0) \cdot P_T \\ = \frac{n+1}{2\pi d^2} A_R \cdot \cos \theta \cdot \cos^n \phi \cdot \text{rect}\left(\frac{\theta}{\text{FOV}}\right) \cdot P_T, \quad (1)$$

where  $H(0)$  is channel DC gain,  $P_T$  is the source power,  $A_R$  is the detector effective area,  $d$  is the distance between LED and the object,  $n$  is the mode number of the radiation lobe,  $\phi$  is the angle of irradiance with respect to the transmitter perpendicular axis,  $\theta$  is the angle of incidence with respect to the object perpendicular axis,  $\text{rect}(\cdot)$  is a rectangular function, and FOV is the field of view of the object.

In the proposed system, the receiver angle  $\theta$  is smaller than the FOV at each measured point. Also,  $\theta$  is equal to  $\phi$  because the perpendicular axes of the LED lamp and the detector window of the object are parallel. Thus, we can rewrite the received power as

$$P_R = \frac{n+1}{2\pi d^2} A_R \cdot \cos^{n+1} \theta \cdot P_T = K \frac{1}{d^{n+3}}, \quad (2)$$

\*Address all correspondence to: Chang-Soo Park, E-mail: [csp@gist.ac.kr](mailto:csp@gist.ac.kr)

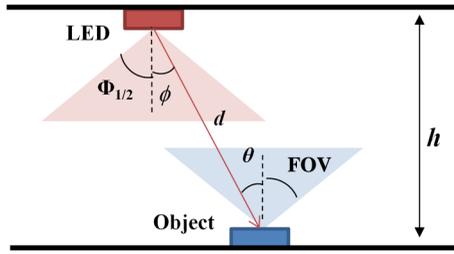


Fig. 1 Geometrical parameters for light-emitting diode light path.

where  $h$  is the height of the room and  $K$  is a common value for each LED, expressed as  $K = (n + 1)A_R h^{n+1} P_T / 2\pi$ . Therefore, the received power can be expressed as a function of distance. Using Eq. (2), the RSSR between two LEDs,  $RSSR_{1,2}$ , is calculated by taking the relative ratio  $P_{R1}/P_{R2}$  and is given by

$$RSSR_{1,2} = \frac{P_{R1}}{P_{R2}} = \frac{K/d_1^{n+3}}{K/d_2^{n+3}} = \left(\frac{d_2}{d_1}\right)^{n+3}. \quad (3)$$

Figure 2 shows the possible trace of the object having the same value in the ratio of  $d_2/d_1$  from LED1 and LED2. When the distance ratio ( $d_2/d_1$ ) is  $C_{1,2}$ ,  $(LED_x, LED_y, h)$  are the coordinates of each LED lamp in the ceiling, and  $(x, y, 0)$  are the object coordinates at a random position on the floor, so we can obtain the following equation,

$$\frac{\sqrt{(x - LED2_x)^2 + (y - LED2_y)^2 + h^2}}{\sqrt{(x - LED1_x)^2 + (y - LED1_y)^2 + h^2}} = \frac{d_2}{d_1} = C_{1,2}. \quad (4)$$

From Eq. (4), for the given ratio of  $d_2/d_1$ , we can draw either a circle or a straight line. Analytical derivation of this equation is summarized in Appendix. In case of  $C_{1,2} \neq 1$ , Eq. (4) is simplified into a circle and expressed as

$$\begin{aligned} & \left(x - \frac{LED2_x - C_{1,2}^2 LED1_x}{1 - C_{1,2}^2}\right)^2 + \left(y - \frac{LED2_y - C_{1,2}^2 LED1_y}{1 - C_{1,2}^2}\right)^2 \\ &= \frac{C_{1,2}^2}{(1 - C_{1,2}^2)^2} \{ (LED1_x - LED2_x)^2 \\ &+ (LED1_y - LED2_y)^2 \} - h^2. \end{aligned} \quad (5)$$

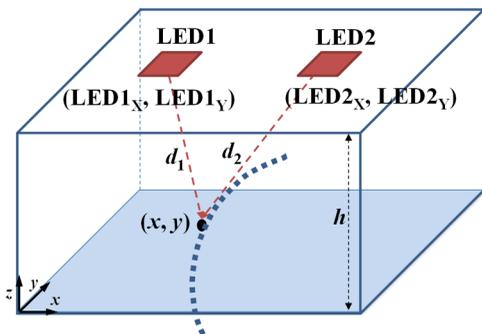


Fig. 2 Position trace of the detector satisfying received signal strength ratio (RSSR).

As a special case of  $C_{1,2} = 1$ , the trace of  $(x, y)$  is more simplified to a straight line and is expressed as

$$\begin{aligned} & 2(LED1_x - LED2_x)x + 2(LED1_y - LED2_y)y \\ & - LED1_x^2 + LED2_x^2 - LED1_y^2 + LED2_y^2 = 0. \end{aligned} \quad (6)$$

This RSSR method can be applied to the case of four LED lamps, and three equations can be obtained from the relations between LED1 and LED2, between LED1 and LED3, and between LED1 and LED4. The location of the object can be found by obtaining a solution of these simultaneous equations.

### 3 Performance Evaluation using Simulation

To verify the validity of the proposed method, a simulation has been performed using four LED lamps. The dimension of the system model is considered to be  $3.0 \times 3.0 \times 3.0 \text{ m}^3$  for typical indoor environment. Four LED lamps are placed on the ceiling at  $(0.75 \text{ m}, 0.75 \text{ m})$ ,  $(0.75 \text{ m}, 2.25 \text{ m})$ ,  $(2.25 \text{ m}, 0.75 \text{ m})$ , and  $(2.25 \text{ m}, 2.25 \text{ m})$ . Each LED lamp is composed of 81 ( $9 \times 9$ ) LED chips, with a chip interval of 3 cm. Figure 3 depicts the system model, with  $L = 3 \text{ m}$ . The LED lamp is modulated by different addresses of  $[1 \ 0 \ 0 \ 0]$ ,  $[0 \ 1 \ 0 \ 0]$ ,  $[0 \ 0 \ 1 \ 0]$ , and  $[0 \ 0 \ 0 \ 1]$ , respectively, in order to utilize the time division multiplexing technique. This technique indicates that only one LED transmits a pulse signal at the assigned time slot. This is how each signal is

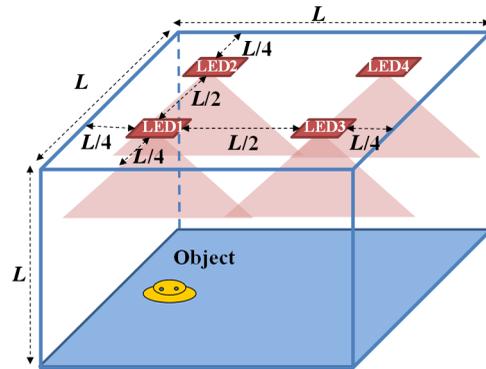


Fig. 3 Simulation model.

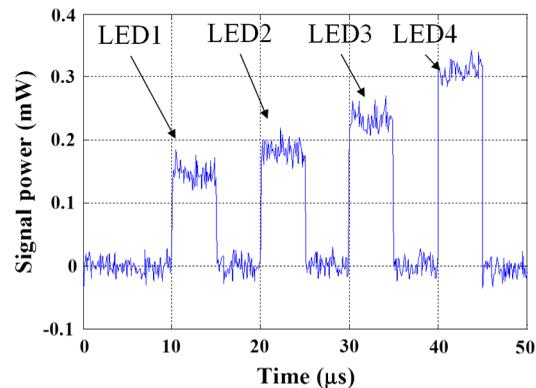


Fig. 4 Received data stream at (2.5 m and 2 m) in the simulation model.

distinguished among others. The transmitted light signal has the return-to-zero data format at 100 Kb/s and signal-to-noise ratio of 20 dB, which is given by additive white Gaussian noise.

The received signal at point (2.5 m, 2 m) on the floor is shown in Fig. 4. The first pulse signal comes from LED1 with the largest distance-dependent loss. In practical systems, all LEDs are synchronized with a preamble signal,

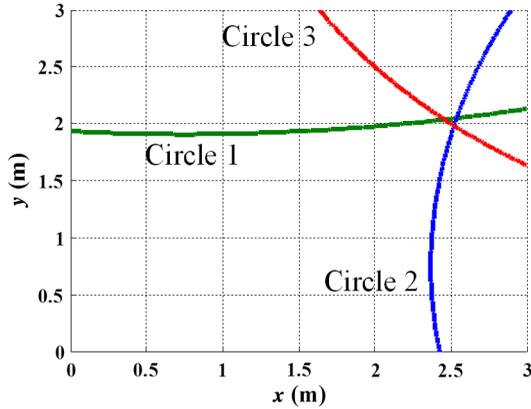


Fig. 5 The obtained circles using the RSSR at (2.5 m and 2 m) in the simulation model.

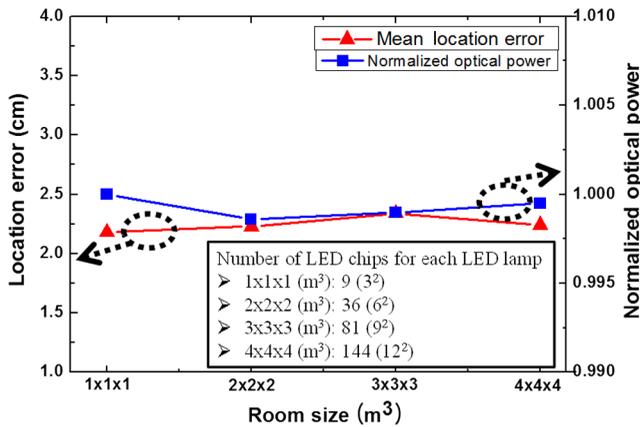


Fig. 6 Variation of mean location error along with increased room size.

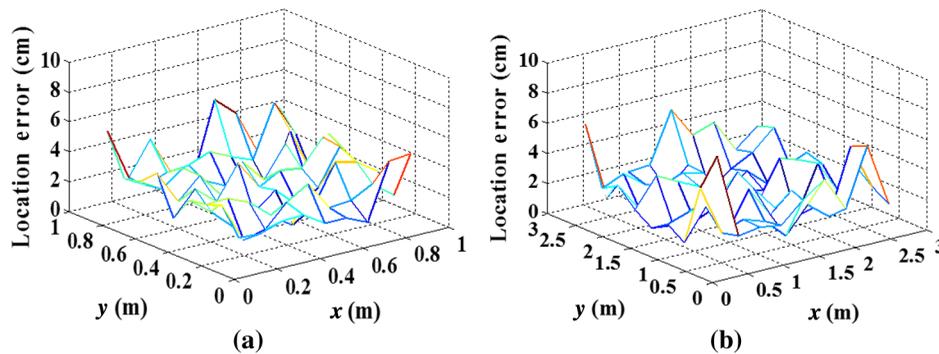


Fig. 7 The location errors at 100 points on the floor in the dimensions of (a) 1 × 1 × 1 m<sup>3</sup> and (b) 3 × 3 × 3 m<sup>3</sup>.

and we can easily identify each LED by reading pulse positions after the preamble signal. The detected powers,  $RSSR_{1,2}$ ,  $RSSR_{1,3}$ , and  $RSSR_{1,4}$  are calculated as 0.7869, 0.6165, and 0.4663, respectively, with the corresponding distance ratios of 0.9390, 0.8806, and 0.8183 for  $C_{1,2}$ ,  $C_{1,3}$ , and  $C_{1,4}$ . Using these ratios and Eq. (5), equations for “Circle1,” “Circle2,” and “Circle3” in Fig. 5 are obtained from the relations between LED1 and LED2, between LED1 and LED3, and between LED1 and LED4, respectively. Because of the added noise, the three circles do not meet at one point. Therefore, the final location can be calculated by taking an average of these three crossing points to be (2.507 m, 2.022 m) with the location error of 2.29 cm.

To investigate the influence of dimension on the performance, we simulated by changing  $L = 3$  m to  $L = 2$  m and  $L = 1$  m. The positioning accuracy of the proposed method was hardly affected by the room size as long as the average optical power on the floor is maintained by increasing the number of LED chips of each LED lamp as shown in Fig. 6. In the simulation, to maintain the optical power, 9, 36, 81, and 144 LED chips were used for each LED lamp with dimensions of  $1 \times 1 \times 1$  m<sup>3</sup> ( $L = 1$  m),  $2 \times 2 \times 2$  m<sup>3</sup> ( $L = 2$  m),  $3 \times 3 \times 3$  m<sup>3</sup> ( $L = 3$  m), and  $4 \times 4 \times 4$  m<sup>3</sup> ( $L = 4$  m), respectively. Figures 7(a) and 7(b) show the location errors at 100 points on the floor when  $L$  is equal to 1 and 3 m, respectively.

### 4 Experiments and Results

For experimental demonstration, we structured a simple case of  $L = 1$  m. Figure 8 shows the experimental setup. In the experiment, the LED chips with a viewing angle of  $\pm 65$  deg and a PIN photodiode (PD) with a FOV of  $\pm 30$  deg are used. Each LED lamp was composed of 16 white LED chips with  $4 \times 4$  arrangements; the line distance between LED chips was 3.3 cm. The object is composed of a PD, a trans-impedance amplifier, and an operational amplifier. Because the PD has an embedded lens, with consideration of the directivity,  $\cos^2 \theta$  needs to be multiplied to the channel DC gain. Then, Eq. (2) is modified as,

$$P_R = \frac{n + 1}{2\pi d^2} A_R \cdot \cos^{n+3} \theta \cdot P_T = K' \frac{1}{d^{n+5}}, \tag{7}$$

where  $K' = (n + 1)A_R h^{n+3} P_T / 2\pi$ . The indoor size is  $1 \times 1 \times 1.3$  m<sup>3</sup>. Four LED lamps were placed at (0.25 m, 0.25 m), (0.25 m, 0.75 m), (0.75 m, 0.25 m), and (0.75 m, 0.75 m) corresponding to LED1, LED2, LED3,

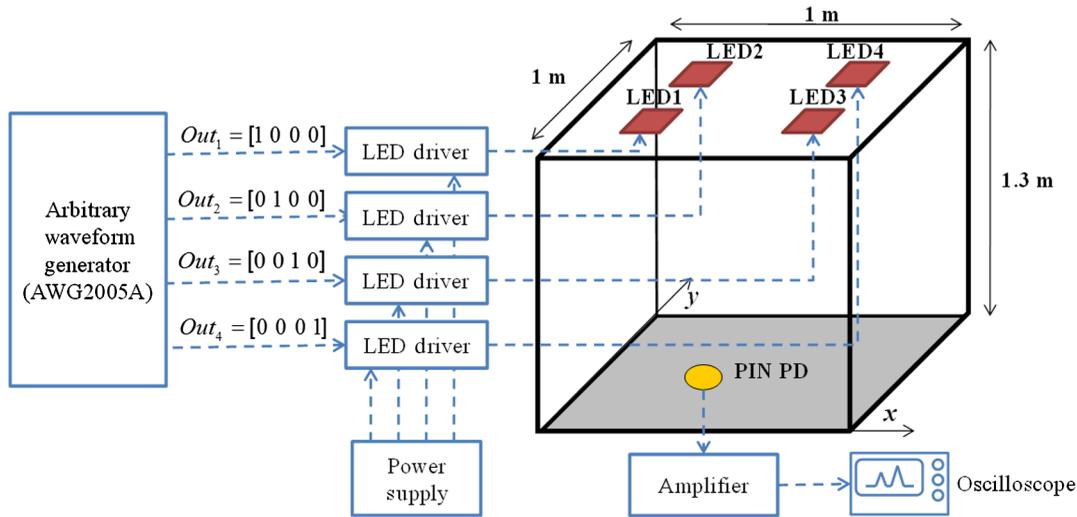


Fig. 8 Experimental setup.

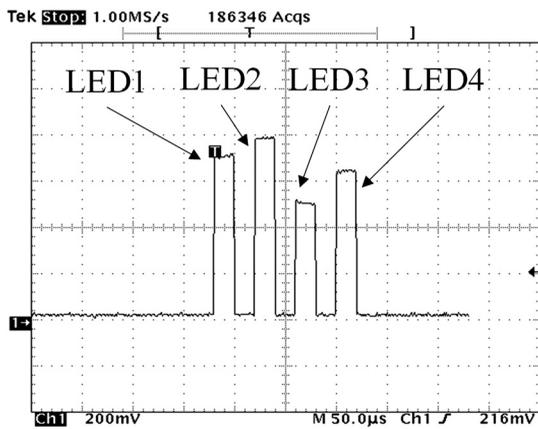


Fig. 9 Received data stream at (0.3 m, 0.6 m).

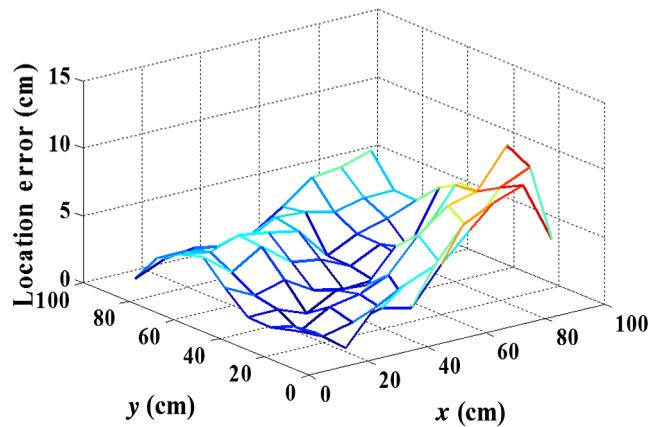


Fig. 11 Location error at 81 points on the floor.

and LED4. Using an arbitrary waveform generator with four output ports, each LED lamp was synchronously modulated by different addresses of [1 0 0 0], [0 1 0 0], [0 0 1 0], and [0 0 0 1] with a data rate of 100 Kb/s.

Figure 9 shows the data stream measured at (0.3 m, 0.6 m) by using an oscilloscope. The fluctuation in the received

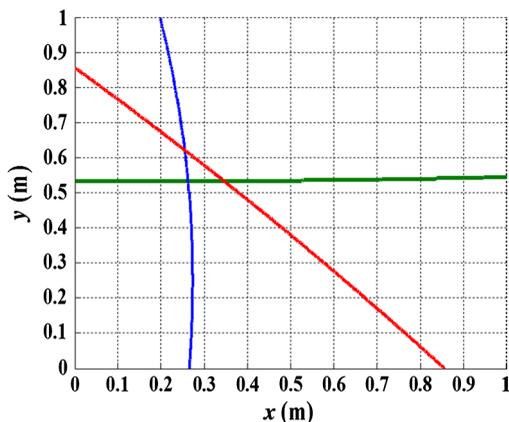


Fig. 10 The obtained circles using the RSSR at (0.3 m, 0.6 m).

signal powers reflects the distance between each LED and the detector. Using the powers detected, circle equations could be drawn based on Eq. (5) as depicted in Fig. 10. The crossing point points the location of the object. Due to noise and measurement errors, the three circles did not meet at a single point; instead, there existed three crossing points. The final location is determined at the average of the three crossing points. It showed the location error of 3.89 cm at (0.3 m, 0.6 m).

The location error was evaluated at several points on the floor. Figure 11 shows the result of the location error. Among 81 points on the floor, the maximum location error was 10.29 cm and the mean of location error was 3.24 cm. The location error was mainly caused by performance difference between LED lamps, measurement error, noises, and reflections from the wall.

## 5 Conclusions

We proposed the RSSR-based indoor positioning method using LED ceiling lamps. Using the RSSRs, circle or straight line equations are obtained and the crossing point of the equations indicates the location. Differently from the conventional method using only detected powers, the proposed method using the RSSR has an advantage of cancelling out

the noises due to the difference in optical device parameters. Identification of each LED lamp was achieved by using time division multiplexing technique. The positioning accuracy of the proposed method was hardly affected by the room size as long as the average optical power on the floor is maintained. The experimental results using four LED lamps with dimensions of  $1.0 \times 1.0 \times 1.3 \text{ m}^3$  showed the mean of the location error of 3.24 cm in the entire floor.

The proposed location awareness method uses the LEDs for illumination without additional installation of the LEDs with high accuracy. Therefore, it can be utilized as an effective indoor positioning system in the future.

## Appendix A: Derivation of Equations from RSSR method

Referring to Fig. 2, it should be noted that the distance ratio ( $d_2/d_1$ ) between LED1 and LED2, is  $C_{1,2}$ , ( $\text{LED}_X, \text{LED}_Y, h$ ) are the coordinates of each LED lamp in the ceiling, and  $(x, y, 0)$  are the object coordinates at random position on the floor. Therefore

$$\frac{\sqrt{(x - \text{LED}2_X)^2 + (y - \text{LED}2_Y)^2 + h^2}}{\sqrt{(x - \text{LED}1_X)^2 + (y - \text{LED}1_Y)^2 + h^2}} = \frac{d_2}{d_1} = C_{1,2}. \quad (4)$$

After squaring both sides of Eq. (4), it can be expressed as

$$(x - \text{LED}2_X)^2 + (y - \text{LED}2_Y)^2 + h^2 = C_{1,2}^2 [(x - \text{LED}1_X)^2 + (y - \text{LED}1_Y)^2 + h^2]. \quad (8)$$

Equation (8) immediately results in

$$\begin{aligned} & (1 - C_{1,2}^2)x^2 - 2(\text{LED}2_X - C_{1,2}^2\text{LED}1_X)x + \text{LED}2_X^2 \\ & - C_{1,2}^2\text{LED}1_X^2 + (1 - C_{1,2}^2)y^2 - 2(\text{LED}2_Y \\ & - C_{1,2}^2\text{LED}1_Y)y + \text{LED}2_Y^2 - C_{1,2}^2\text{LED}1_Y^2 \\ & + (1 - C_{1,2}^2)h^2 = 0. \end{aligned} \quad (9)$$

Here, we have to consider two cases,  $C_{1,2} \neq 1$  and  $C_{1,2} = 1$ . Let us first consider the case when  $C_{1,2} \neq 1$ , Eq. (9) can be modified as

$$\begin{aligned} & \left(x - \frac{\text{LED}2_X - C_{1,2}^2\text{LED}1_X}{1 - C_{1,2}^2}\right)^2 + \frac{1}{(1 - C_{1,2}^2)^2} (-C_{1,2}^2\text{LED}1_X^2 + 2C_{1,2}^2\text{LED}1_X\text{LED}2_X - C_{1,2}^2\text{LED}2_X^2) \\ & + \left(y - \frac{\text{LED}2_Y - C_{1,2}^2\text{LED}1_Y}{1 - C_{1,2}^2}\right)^2 + \frac{1}{(1 - C_{1,2}^2)^2} (-C_{1,2}^2\text{LED}1_Y^2 + 2C_{1,2}^2\text{LED}1_Y\text{LED}2_Y - C_{1,2}^2\text{LED}2_Y^2) + h^2 = 0. \end{aligned} \quad (10)$$

And can be simplified as

$$\left(x - \frac{\text{LED}2_X - C_{1,2}^2\text{LED}1_X}{1 - C_{1,2}^2}\right)^2 + \left(y - \frac{\text{LED}2_Y - C_{1,2}^2\text{LED}1_Y}{1 - C_{1,2}^2}\right)^2 = \left(\frac{C_{1,2}}{1 - C_{1,2}^2}\right)^2 [(\text{LED}1_X - \text{LED}2_X)^2 + (\text{LED}1_Y - \text{LED}2_Y)^2] - h^2. \quad (5)$$

We can finally obtain the equation of a circle. In the other case, when  $C_{1,2} = 1$ , Eq. (9) has been simplified as Eq. (6), this straightforwardly leads to the straight line equation and expressed as

$$\begin{aligned} & 2(\text{LED}1_X - \text{LED}2_X)x + 2(\text{LED}1_Y - \text{LED}2_Y)y \\ & - \text{LED}1_X^2 + \text{LED}2_X^2 - \text{LED}1_Y^2 + \text{LED}2_Y^2 = 0. \end{aligned} \quad (6)$$

## Acknowledgments

This work was supported by Priority Research Centers Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2009-0093828), and by Green IT Convergence Technology Development Program funded by the Ministry of Science, ICT, and Future Planning.

## References

1. C. G. Lee, C. S. Park, and J.-H. Kim, "Experimental verification of optical wireless communication link using high-brightness illumination light-emitting diodes," *Opt. Eng.* **46**(12), 125005 (2007).
2. S.-M. Kim and S.-M. Kim, "Wireless visible light communication technology using optical beamforming," *Opt. Eng.* **52**(10), 106101 (2013).
3. C. W. Cho et al., "Gaze detection by wearable eye-tracking and NIR LED-based head-tracking device based on SVR," *ETRI J.* **34**(4), 542–552 (2012).
4. T. Tanaka and S. Haruyama, "New position detection method using image sensor and visible light LEDs," in *Second Int. Conf. Mach. Vision*, pp. 150–153, IEEE Computer Society (2009).
5. J. Vongkulbhisal et al., "A fingerprinting-based indoor localization system using intensity modulation of light emitting diodes," *Microw. Opt. Technol. Lett.* **54**(5), 1218–1227 (2012).
6. S.-Y. Jung et al., "Optical wireless indoor positioning system using light emitting diode ceiling lights," *Microw. Opt. Technol. Lett.* **54**(7), 1622–1626 (2012).
7. S.-Y. Jung, S. Hann, and C.-S. Park, "TDOA-based optical wireless indoor localization using LED ceiling lamps," *IEEE Trans. Consum. Electron.* **57**(4), 1592–1596, (2011).
8. K. Panta and J. Armstrong, "Indoor localisation using white LEDs," *IEEE Electron. Lett.* **48**(4), 228–230 (2012).
9. J. M. Kahn and J. R. Barry, "Wireless infrared communications," *Proc. IEEE* **85**(2), 265–298 (1997).