Three-Dimensional Visible Light Indoor Localization Using AOA and RSS With Multiple Optical Receivers

Se-Hoon Yang, Hyun-Seung Kim, Yong-Hwan Son, and Sang-Kook Han, *Member, IEEE*

***Abstract*—A novel concept is proposed for integrating optical wireless visible light communications with 3-D indoor positioning using a single transmitter and multiple tilted optical receivers. We modeled a channel link, which was based on the transmitter and receiver characteristic data obtained in this experiment. The proposed 3-D positioning algorithm is based on gain difference, which is a function of the angle of arrival and the received signal strength. Our demonstration shows that the proposed algorithm can determine accurate positions, including height, without intercell interference.**

***Index Terms*—Angle of arrival (AOA), position measurement, received signal strength (RSS), visible light communication.**

I. Introduction

DEMANDS for location-based services (LBSs) in tracking, private services, autonomous robot control, position recognition, and emergency and navigation assistance are rapidly increasing. Positioning is an essential technique for developing LBS [1], [2]. Until recently, research into positioning systems for LBS has been concentrated in satellite global positioning systems (GPS), RF-ID, infrared, ultrasound, and WLAN. GPS has been regarded as an effective means of tracking various objects in outdoor environments; however, the GPS signal cannot reach dark zones such as tunnels or the interior areas of buildings. Accurate positioning is difficult in interior environments because of the influences of multi-path and radio disturbance [3]. Research into indoor positioning systems has been performed using radio frequency, infrared, ultrasound, and WLAN, though these systems are also limited due to factors such as the presence of additional infrastructure, large measurement error, narrow tracking range, electromagnetic interference, low security, long response time, and low scalability [2], [3].

For these reasons, indoor positioning systems using optical wireless visible light communication (OWVLC) have recently gained popularity as effective alternatives [4]–[9]. The OWVLC based on light-emitting diodes (LEDs) is suitable for indoor positioning because the received signal power is determined by photocurrent which is the generated by received optical power and it is greatly affected by the transmission distance and angle, thus, OWVLC can provide a more accurate estimate of position than existing systems. The white-LEDs used as transmitters in the OWVLC system are widely used for lighting due to their energy efficiency, lifetime, eco-friendliness, lighting efficiency, and fast frequency response. LEDs are semiconductors and can be easily modulated, making them suitable for optical wireless transmission [10]–[12]. High-speed wireless connectivity is implemented using a spectrally-efficient modulation method: orthogonal frequency division multiplexing or discrete multitone [13]–[16]. Thus, OWVLC is commensurate with indoor positioning and wireless communication systems.

In general, positioning systems based on OWVLC estimate transmission distance as a function of the received signal strength (RSS), which is based on intensity modulation and the direct detection method. In order to estimate position using trilateration through transmission distances, receiver need to know the positions of three or more reference nodes [17], [18]. Thus, this system is limited by the need of the optical receivers to receive signals from at least three different transmitters without interference. For this reason, previous research used the carrier allocation, or TDM technique. The positioning area is limited by the overlapped area of different transmitters as well as by additional information about characteristics of the transmitter. These have a decisive effect on signal strength, which is required even though the inter-cell interference problem can be solved based on characteristics of the transmitter, which vary as a function of the LEDs [4]–[6]. Multiple optical receiver structures are proposed for reducing the inter-cell interference; however, minimization of the device size and three-dimensional positioning still remain as limitations [7], [8].

In this paper, we propose a three-dimensional indoor positioning system using a single transmitter and multiple tilted optical receivers based on visible light communication. Inter-cell interference is no longer an issue, as the signal is transmitted via a single LED array. Two-dimensional positioning is possible using the incidence angle gain difference according to angle of arrival (AOA) only. Three-dimensional positioning is possible using RSS. As a result, positioning with less than 6 cm, including height, was demonstrated in a 2 m $\times$ 2 m $\times$ 2.5 m indoor optical wireless environment.

II. Proposed System for Indoor Positioning

For indoor localization based on RSS, multiple transmitters or receivers are required. In order to determine position using the trilateration method, which is based on multiple transmitters, the user needs to know the transmission distance from each of the three or more different nodes, without inter-cell interference. Thus, additional interference reduction techniques are essential. The second approach is based on a single transmitter

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and multiple receivers. Inter-cell interference can be avoided; however, a minimum separation distance is required between receivers due to the induced RSS difference. This places a limitation on the allowable reduction in receiver size. The proposed system has a single transmitter and multiple tilted optical receivers. Since the RSS difference is induced by the incidence angle difference, the size reduction of the receiver becomes possible. Two-dimensional positioning is feasible without information regarding the transmitter, as the proposed system uses the expected incidence angle gain difference and the RSS difference only. Three-dimensional positioning is possible using RSS values.

The received signal power of the optical wireless channel in a line-of-sight environment is determined via radiation, incidence angle gain, transmission distance, transmitted signal power, and the characteristic constants of devices. This can be expressed as

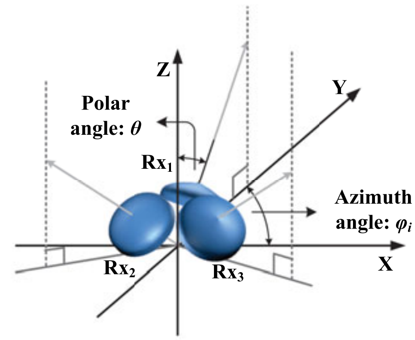
$$P_{iRF} = \left(P_t^2 / d^4\right) C_r \, G_t^2(\alpha) \, G_r^2(\beta_i) \tag{1}$$

where P_{iRF} and P_t represent received signal power and average transmitted optical power in dBm. d is the transmission distance in meter, and i is the ith optical receiver. $G_t(\alpha)$ is an angle gain according to the radiation pattern of the transmitter based on the lens shape for a radiation angle of α. $G_r(\beta_i)$ is the incidence angle gain of the optical receiver based on the effective area and internal refractive index of the lens with an incidence angle of β_i; the angle gain unit is normalized arbitrary unit. C_r is the RF power constant which includes the optical-to-electrical conversion efficiency at the optical receiver [4].

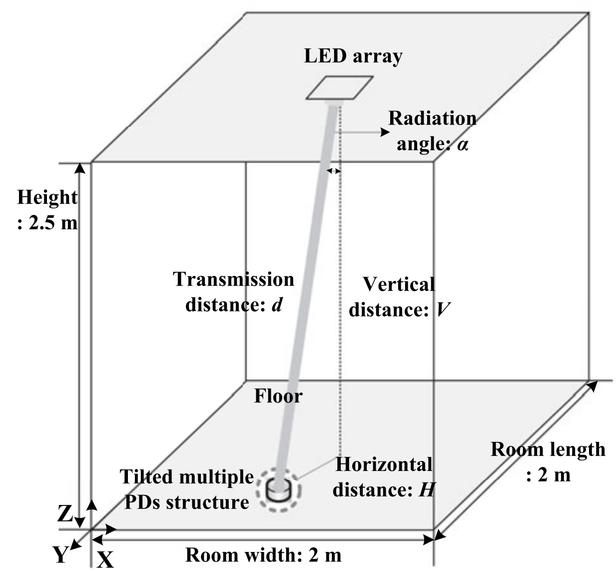
The radiation angle and incidence angle are the same when the transmitting plane and receiving plane are parallel; however, the incidence angle can be changed via the introduction of tilting. The proposed absolutely separated multiple optical receiver structure is described in Fig. 1(a). The incidence angle can be expressed as

$$\beta_i = \cos^{-1} \times \left(\frac{(x-a)\cos(\varphi_i)\sin(\theta) + (y-b)\sin(\varphi_i)\sin(\theta) + (z-c)\cos(\theta)}{\sqrt{(x-a)^2 + (y-b)^2 + (z-c)^2}} \right) \tag{2}$$

where φ is the azimuth angle which is an angle between the X-axis and the orthogonal projection of the normal vector of the receiver–XY plane and θ is the polar angle which is an angle between the normal vector of receiver and the normal vector of the XY plane. The coordinates of the LED (x, y, z) are fixed, and the coordinates of the receivers are set as (a, b, c), as the receivers are close enough to have the same coordinates. The radiation angle difference has a zero value and the incidence angle differences between the various different optical receivers are determined based on θ and φ. Consequently, the angle gain difference occurs as a function of the incidence angle. From Fig. 1(b), the difference in transmission distance between LED and each receiver can be ignored because the receivers are close enough. Therefore, d is determined based on the vertical distance V and horizontal distance H. P_t, and G_t are also the same, because these factors are characteristics of the transmitter, and the proposed system uses a single LED array. In addition, C_r is the same because proposed system is composed with the same optical receivers; thus, the difference in received signal power is determined by $G_r(\beta_i)$.



(a)



(b)

Fig. 1. (a) Proposed multiple tilted and separated optical receiver structure and (b) experimental environment of the three-dimensional positioning system.

The incidence angle at the receiver can be calculated based on φ, θ, and the coordinates of the LED and receiver. Thus, if we know $G_r(\beta_i)$, we can obtain the gain distribution according to indoor position. From (1), $G_t(\alpha)$ and $G_r(\beta_i)$ are transmitter and receiver gain according to radiation angle α and incidence angle β_i, respectively. In order to measure the radiation and incidence angle gains, the received RF powers were measured using RF spectrum analyzer; transmission distance is fixed and rotating the transmitter and receiver, respectively. Fig. 2 shows the measured and modeled normalized angle gain profile of the used LED and optical receiver as a function of the radiation and incidence angles. In general, lambertian model is suitable for OWVLC channel [10]. However, in our experimental results, exponential model is more suitable than lambertian model and it can be expressed as

$$G_t(\alpha) = \exp(-\alpha^{s_t}/k_t), \; G_r(\beta_i) = \exp(-\beta_i^{s_r}/k_r). \tag{3}$$

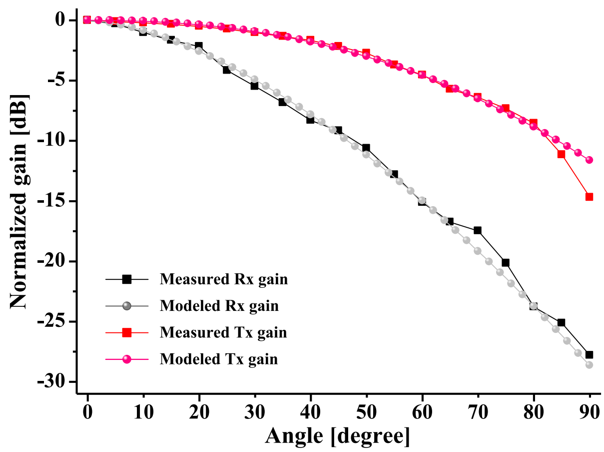


Fig. 2. The normalized radiation and incidence angle gain profile of the used LED and optical receiver.

S_t and S_r are slope constants as lens shape of LED and receiver. k_t and k_r are related to semi-angle at half power of LED and optical receiver; $k_t = (\alpha_{1/2})S_t/ln(1/2)$ and $k_r = (\beta_{i1/2})S_r/ln(1/2)$ [4]. Fig. 3 shows the reference gain distribution according to the indoor position, based on the incidence angle gain profile of the optical receiver when the indoor environment was 2 m × 2 m × 2.5 m, the LED coordinates where (100, 100, 250), the position of the receivers are on the floor, θ is 10°, and the φ of the optical receivers are 90°, 210°, and 330°, respectively. These values are fixed at the structure design stage; thus, if user wants to change these angles according to experimental environments, user can obtain the values using a gyro-sensor.

III. Indoor Positioning Algorithm

A. Two-Dimensional Positioning

Every optical receiver obtains a different P_{iRF} according to β_i from (2). A position estimation using the trilateration method based on the transmission distance from (1) is not possible because the characteristics of the LED are unknown except location information. However, other factors, for example, P_t, d, C_r, and $G_t(\alpha)$, are the same at each P_{iRF}. Thus, the expected incidence angle gain difference can be obtained from two separate receivers using the P_{iRF} difference, which can be expressed as

$$\Delta P_{ij} = P_{iRF} - P_{jRF} \approx \Delta G_{ij} = G_{ir}(\beta_i) - G_{jr}(\beta_j). \quad (4)$$

$G_{ir}(\beta_i)$ is the receiver gain, which is a function of β_i at the ith receiver and unit is dB. The expected gain difference distribution according to the indoor position can be mathematically obtained from Fig. 3 and it can be expressed as in Fig. 4; thus, the measurements of P_{iRF} and Fig. 4 enable indoor positioning.

In two-dimensional positioning, the height component, c, is given, and the position of the receiver can be expressed as *(a, b)*. From the measured P_{iRF} and angle gain differences distribution, a matched line which is minimum difference between ΔP_{ij} and Fig. 4 can be estimated. The position of the receivers can be estimated by determining the cross point of each line.

B. Three-Dimensional Positioning

The incidence angle gain distribution and gain difference can be obtained by assuming the position of the receivers in an indoor space using (2); however, considering the height component, positioning is not possible when using the proposed two-dimensional positioning algorithm, because variables such as d and $G_t(\alpha)$ can affect how the received signal power is added. Three-dimensional positioning is composed of two steps: positioning in the *XY* plane using a two-dimensional positioning algorithm that assumes a height and compensates for the height component by using the information from the transmitter. Fig. 5 shows a graphical schematic of how the three-dimensional positioning system is working. The assumed height is divided into spacing 10 cm from the floor to 150 cm. The estimated position, obtained via two-dimensional positioning, can be expressed as $E_l(a_l, b_l, l)$ at the lth layer. The expected received signal power can be obtained using (1) at the E_l, which is the estimated spatial coordinates of the receivers. The height can be estimated using the minimum difference between the expected and measured signal power, because the small difference at a specific layer means the existence probability is higher there than for other layers. Thus, the difference in power according to layer F_l can be expressed as

$$F_l = \sum_{i=1}^{3} |E_l P_{iRF} - P_{iRF}|. \quad (5)$$

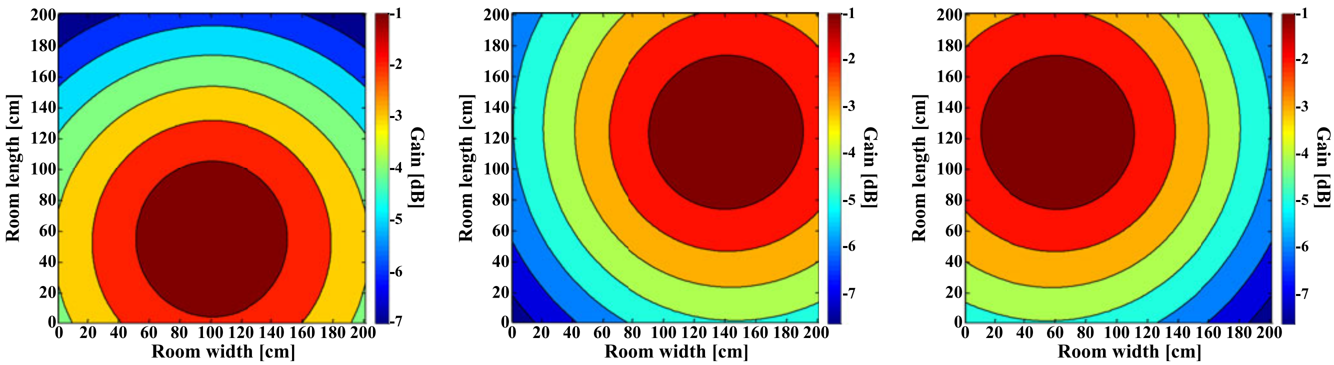
$E_l P_{iRF}$ is the expected received signal power of the estimated position at the lth layer and ith receiver, and P_{iRF} is the measured signal power from the ith receiver. Three-dimensional positioning is enabled by selecting the pair of layers with the smallest F_l and it can be expressed as

$$\mathrm{POS} = \frac{(F_{l2}E_{l1}) + (F_{l1}E_{l2})}{(F_{l1} + F_{l2})}. \quad (6)$$

POS is the final estimated position and includes height. F_{l1} and F_{l2} are the first and second smallest difference value, respectively and E_{l1} and E_{l2} are the estimated positions at the lth layer, respectively.

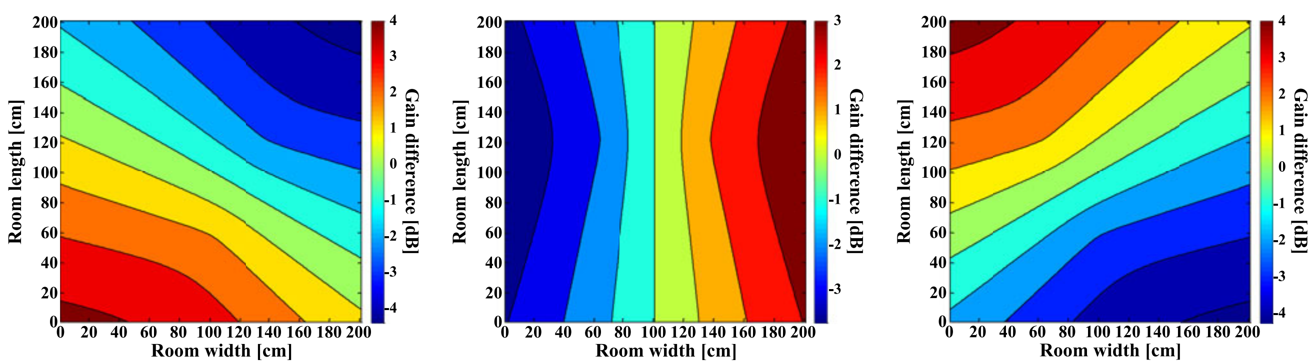
IV. Experiments and Results

The plan for the experimental environment is shown in Fig. 1(b) where an OSRAM LE-UW-S2W LED array is used to illuminate an indoor environment of dimensions 2 m by 2 m and a height of 2.5 m. Constant bias voltage and QPSK signal, which include the coordinates of the LED, were applied to the LED array using a bias-tee. A 250-K symbol per second QPSK signal with a 2.0 MHz subcarrier was generated via a vector signal generator. An optical wireless signal was detected at separated multiple tilted HAMAMATSU S6801 optical receivers, and the size of device with multiple optical receivers is reduced within a circle of 3 cm diameter. The received signal power was analyzed using an RF spectrum analyzer. The error distance is determined by comparing the known position with the estimated position based on a positioning algorithm mentioned in Section III, using the measured signal power at a known position.



(a) (b) (c)

Fig. 3. Incidence angle gain profile on the floor when polar angle is 10° and azimuth angles are (a) 90°, (b) 210°, and (c) 330°, respectively.



(a) (b) (c)

Fig. 4. Incidence angle gain difference in proposed environment on the floor between (a) Rx1 and Rx2, (b) Rx2 and Rx3, and (c) Rx3 and Rx1 when the polar angle is 10° and azimuth angle of Rx1, Rx2, and Rx3 are 90°, 210°, and 330°, respectively.

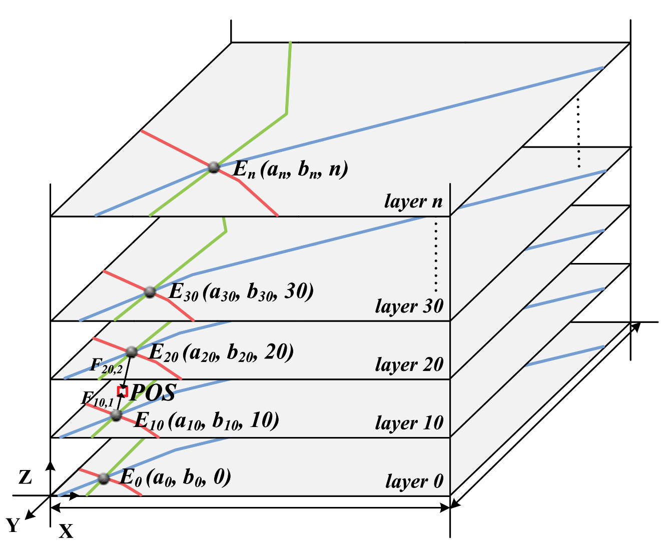


Fig. 5. Graphical schematic of three-dimensional positioning using proposed positioning algorithm.

A. Two-Dimensional Positioning Based on AOA

Positioning is possible without the additional information on characteristics of the transmitter except absolute position of LED array when the receiver is on the floor and the height of the indoor area is given. For example, the measured P_{iRF} values were −56.66, −59.47, and −57.5 dBm when the real position of the receiver was (50, 50, 0); then ΔP_{12}, ΔP_{23}, and ΔP_{31} were 2.81, −1.97, and −0.84 dB, respectively. The measured signal power difference is defined by the incidence angle gain difference only; thus, matched lines are obtained using the measured signal power difference, ΔP_{ij}, and the gain difference distribution in Fig. 4. The red, green, and blue lines in Fig. 6 indicate the analogous difference between different ΔP_{ij} and ΔG_{ij}, respectively. Thus, line pattern is similar with that in Fig. 4. From the result, the position of the receiver can be estimated based on the center of the cross area for the three different lines, in this case (51, 51). The error distance was 1.4 cm when the receivers were on the floor.

B. Three-Dimensional Positioning Using RSS

The location information of the transmitter is additionally required for three-dimensional positioning when the height is unknown. If the real position is (50, 50, 0), as in the previous example, then the estimated *XY*-plane position at each layer can be obtained using a two-dimensional positioning algorithm. The F_l can be obtained from $E_l P_{iRF}$ and P_{iRF}, and is shown in Table I. In this example, *layer* 0 and *layer* 10 have the smallest F_l, 0.21

TABLE I
ESTIMATED POSITION AND RECEIVED SIGNAL POWER DIFFERENCE AT EACH LAYER WHEN REAL POSITION IS (50, 50, 0)

Layer	Estimated position	Power difference [dB]	Layer	Estimated position	Power difference [dB]
0	(51, 51)	0.21	80	(68, 67)	23.65
10	(53, 53)	1.21	90	(69, 69)	15.2
20	(55, 55)	2.23	100	(71, 71)	18.25
30	(57, 57)	3.44	110	(73, 73)	21.62
40	(59, 59)	4.83	120	(75, 75)	25.5
50	(61, 61)	6.41	130	(77, 77)	29.93
60	(63, 63)	8.2	140	(79, 79)	34.96
70	(65, 65)	10.23	150	(81, 81)	40.7

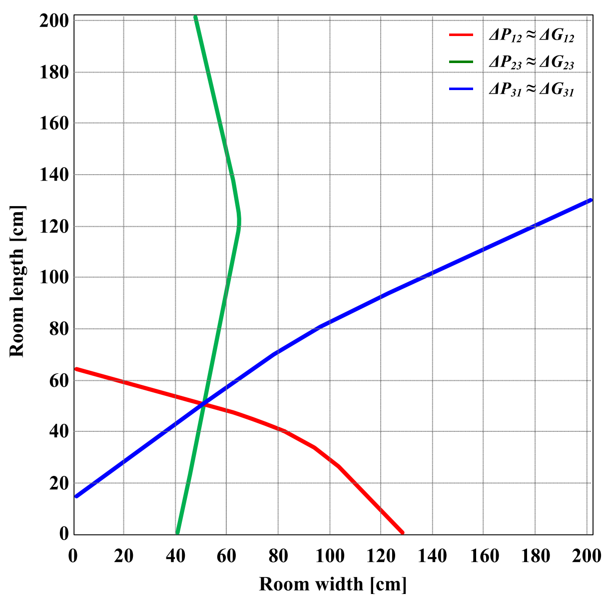


Fig. 6. Matched lines distribution between ΔP_{ij} and gain difference when the real position is (50, 50, 0).

and 1.21, respectively, and the estimated position of each layer is (51, 51) and (53, 53), respectively. The final estimated position of the receiver is (51.3, 51.3, 1.5) with an error distance of approximately 2.3 cm, using (6).

In order to verify the performance of the position estimation at the proposed structure and algorithm, we estimate the position of 49 points when the height was set to 15, 50 and 85 cm. The average error distance was less than 3 cm and maximum error was less than 6 cm, as shown in Fig. 7. From our experiments, main causes of positioning error are as follows: Firstly, modeled gain profile which is not perfectly matched with real values. Secondly, experimentally obtained θ and φ can be slightly different from ideal values. Thirdly, received signal power which can be fluctuated by external conditions. Thus, positioning error can be improved by adding more parameters in modeling process and using gyro-sensor in receiver for obtain the accurate θ and φ values.

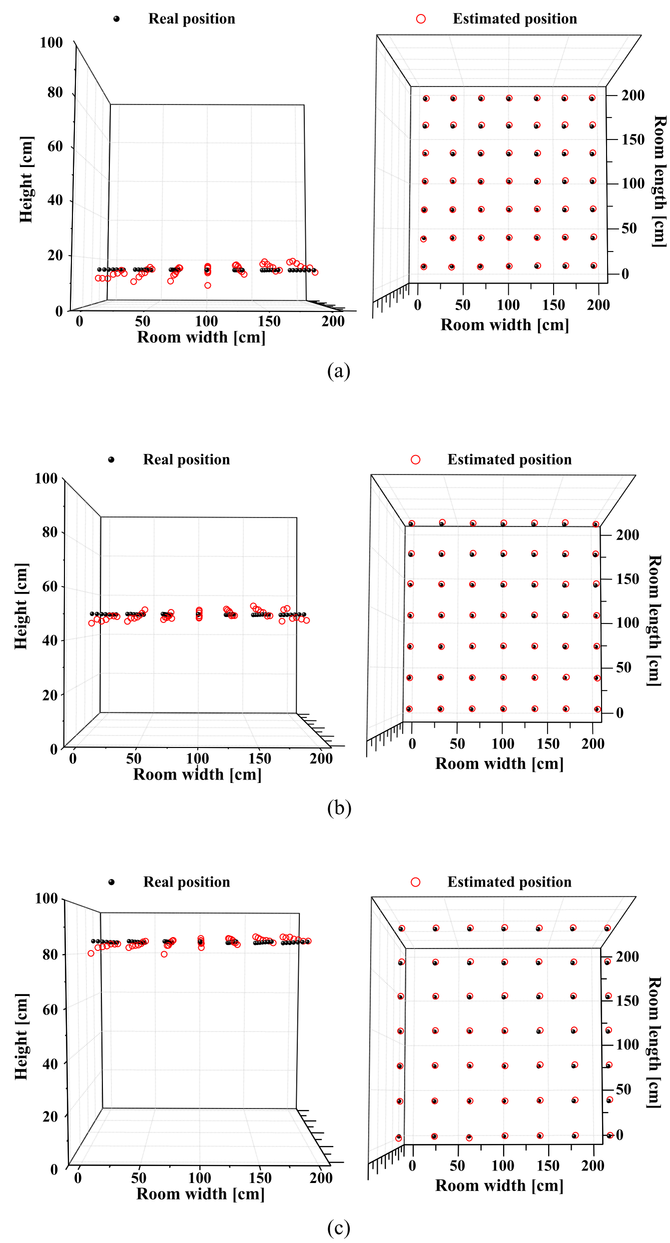


Fig. 7. Three-dimensional positioning results at 49 points with real user heights of (a) 15 cm, (b) 50 cm, and (c) 85 cm, respectively.

V. Conclusion

In summary, we propose a highly accurate indoor positioning system that uses a single LED array and multiple tilted optical receivers. Inter-cell interference is fundamentally removed using a single transmitter and receiver miniaturization is possible due to the tilted structure. Two-dimensional positioning is possible due to an angle-gain profile according to AOA only. Three-dimensional positioning is achieved using RSS. Proposed system requires information on the angle gain profile a priori for the positioning which is unique characteristics of transmitter and receiver. Hence, we have used experimentally measured angle gain profile. We were able to obtain the estimated position with less than 6 cm of error when θ was 10°; thus, the proposed indoor positioning technique, which is based on optical wireless visible light, could be useful for indoor navigation, autonomous machine control systems, and LBS applications.

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