Indoor Location Estimation Using Visible Light Communication and Image Sensors

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Abstract

High power white LEDs are expected to replace the existing lighting technologies in near future which are also suggested for visible light communication (VLC). We proposed an algorithm for high precision indoor positioning using lighting LEDs, VLC and image sensors. In the proposed algorithm, four LEDs transmitted their three-dimensional coordinate information which were received and demodulated by two image sensors near the unknown position. The unknown position was then calculated from the geometrical relations of the LED images created on the image sensors. We described the algorithm in details. Simulation of the proposed algorithm was done and presented in this paper. This technique did not require any angular measurement which was needed in contemporary positioning algorithms using LED and image sensor. Simulation results showed that the proposed system could estimate the unknown position within the accuracy of few centimeters. Positioning accuracy could be increased by using high resolution image sensors or by increasing the separation between the image sensors.

Keywords*: Indoor positioning, LED, Image sensor, VLC*

1. Introduction

Indoor positioning systems are becoming increasingly significant for pervasive and context-aware computing with location awareness, autonomous robot movement, sensor applications etc. During the last two decades, researchers have been trying to develop positioning techniques to provide precise location information using GPS, IR, RFID, Blutetooth, WLAN, Ultrasound, and so on [1]. GPS has been extensively used for positioning in outdoor environment such as in car navigation, mobile phones, ships, planes, surveying of public works etc. However, since GPS positioning depends on radio wave propagation, multipath fading and disturbances from other radio sources lead to large positioning error in indoor environment. The conventional indoor positioning systems such as WLAN, RFID, Bluetooth and Ultrasound system have problems due to system instability, long response time, low accuracy and low precision. Recently, visible light communication (VLC) is emerging as an attractive technology for indoor positioning system [2-6]. Together with illumination, lighting equipments serve the purpose of data communication in VLC system. This system is regarded as one of the most promising alternatives to band limited radio wave communication since it does not cause or suffer from radio or electromagnetic interference. VLC can be used in buildings, underground and even in hospitals where radio frequency is prohibited. Compared to conventional lighting devices such as incandescent and fluorescent lamps, LED is more advantageous in terms of long life expectancy, high tolerance to environmental hazards, low operating voltage, low power consumption and nominal heat dissipation lighting.

Hence, high power white LEDs are considered to be a strong candidate for the future illumination technology [7-9]. Therefore, we focus on developing VLC based positioning system. In this paper, we propose an algorithm for high precision indoor positioning using LED based VLC and image sensors. The proposed scheme utilizes LED lighting array as VLC transmitter that transmits the three-dimensional (3D) coordinate information of some reference LEDs. Two image sensors receive the information from all the reference LED lights through lenses and demodulate the position information. The required unknown position is then calculated using the position information of the reference LEDs and the geometric relationship of the images on the two image sensors.

2. Background

VLC based positioning research is still at a preliminary stage. Rigorous works are yet to be published. However, some significant VLC based positioning techniques and algorithms can be found in [2-6]. [2] and [3] describe the VLC based positioning system using visible light communication identification (VLID), photo detector and 6-axes sensor. These works describe that three different estimated receiver positions (ERP) are created due to the effect of the receiver's field-of-view (FOV). In the conventional positioning scheme, a single ERP is used where the only way to reduce the estimation error is by decreasing the FOV of the receiver [2]. The authors in [3] proposed switching estimated receiver position scheme where the ERP is switched depending on the receiver's tilt angle, to limit the estimated error distance. Root mean square of error distances were found to be 46.3 cm, 33.6 cm and 29.8 cm for receiver FOV angles of 25°, 17.5° and 10°, respectively. The scheme estimates two-dimensional (2D) positions. However, the accuracy of the estimated positions is unavoidably dependent on accuracy of angulations data from 6-axes sensor. A VLC guidance system using fluorescent lamps and photo sensor has been proposed in [4], which can also estimate the 2D location with accuracy between 10 to 30 cm ranges. The system is designed to assist the visually impaired persons by providing them the necessary information inside the building. Location estimation in this system requires at least three fluorescent lamps to be detected by the photo sensor which implies some limitations on positioning everywhere inside the room due to the geometry of the lighting installation. Positioning accuracy of this system obviously depends on the accuracy of measuring the tilt angle of the photo sensor. VLC based positioning using LED lights and image sensor has been proposed in [5] and [6]. This system performs the optical intensity modulation of the LED illumination for data transmission and receives the light by using image sensor. Data from various light sources can be received at the same time by using image sensor as receiver. This is done by spatially separating the light rays from different LEDs by a lens provided that the receiver is directed towards the light source. In [5], at least three LEDs from the LED lighting array transmit the 3D coordinate information. The 2D image sensor receives the lights separated spatially by a lens and demodulates the 3D coordinate information of each LED. The position of the receiver is then calculated by solving two sets of quadratic equations which may leave some possibilities of computational error. In [6], 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 3D coordinates of the LEDs to the 2D coordinates of the image sensor. Simulation results show that the receiver's position can be estimated with accuracy of within 1.5 meters if the pixel size is 36×10^{-6} m. Analysis of the previous works reveals that positioning error of the previously proposed schemes may occur from the precise angular measurements and solution of quadratic equations for position estimation. Hence, we propose a new algorithm for positioning in VLC system based on lighting LEDs and two image sensors which does not require any angular measurement and can overcome the limitations of the existing schemes.

3. Proposed Algorithm

In the proposed system, LED arrays used for illumination are also used for positioning. At least four LEDs from the array transmit their 3D coordinate information which are received and demodulated by two image sensors through two optical lenses. In choosing the LEDs, we have to make sure that they are not collinear. Let us consider that A, B, C and D in Fig. 1 represent four LEDs which transmit their known 3D coordinates (x_1, y_1, z_1) , (x_2, y_2, z_2) , (x_3, y_3, z_3) and (x_4, y_4, z_4) respectively. The image sensors used for receiving the light signals consist of a 2D array of photosensitive elements. Hence, each element or pixel can act as an individual photo sensor and multiple LED signals can be detected and demodulated simultaneously by the single image sensor. Two image sensors receive the intensity modulated lights from the four LEDs separated spatially by using two separate lenses and demodulate the 3D coordinate information of the LEDs. The image sensors are installed in the same plane at a known lateral distance with their major axis in the same line pp' . Lens, having identical properties and focal length, is installed above the center of each image sensor. The axis of each lens, normal to the image sensor plane, intersects the center of the corresponding image sensor. The physical arrangement of the system can be understood from Figure 1. 'U' is the mid point of the straight line joining the centers of the two lenses. The unknown 3D coordinate of the point $U(x, y, z)$ is estimated in this scheme. The distances of the point U from the four reference LEDs A, B, C and D are denoted by d_1, d_2 , d_3 and d_4 , respectively. These distances are calculated from the geometric relationship between the distance and the position difference of the LED images on the two image sensors.

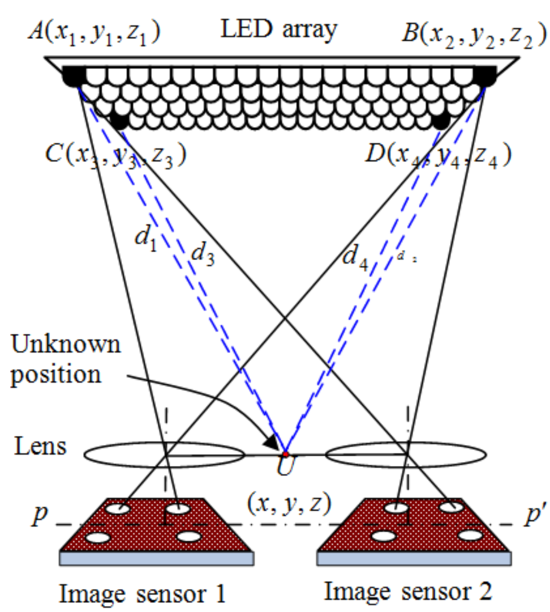

Figure 1. Proposed VLC Positioning System

Geometric relationship of the proposed positioning scheme is detailed in Figure 2. This figure explains the procedure for determining the distance of the point U from an LED. Here, the focal length of the lenses, f and the distance between the centers of the lenses, L are known. If the distances of the image centers from the center of the image sensors are i_1 and i_2, and their projection on the major axis of the image sensors are Pi_1 and Pi_2, the distance d_1 can be calculated as follows.

$$di = |Pi_2 - Pi_1| \tag{1}$$

$$h = \frac{f \times L}{di} \tag{2}$$

$$c = \sqrt{f^2 + i_1^2} \tag{3}$$

$$d = \sqrt{f^2 + i_2^2} \tag{4}$$

$$a = \frac{h \times c}{f} \tag{5}$$

$$b = \frac{h \times d}{f} \tag{6}$$

$$\theta = \cos^{-1}\left(\frac{a^2 + L^2 - b^2}{2aL}\right) \tag{7}$$

$$d_1 = \sqrt{a^2 + \left(L/2\right)^2 - 2a\frac{L}{2}\cos\theta} \tag{8}$$

Similarly, d_2, d_3 and d_4 can be obtained from the other three LEDs. Hence, we obtain a set of four quadratic equations as follows:

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = d_1^2 \tag{9}$$

$$(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 = d_2^2 \tag{10}$$

$$(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 = d_3^2 \tag{11}$$

$$(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2 = d_4^2 \tag{12}$$

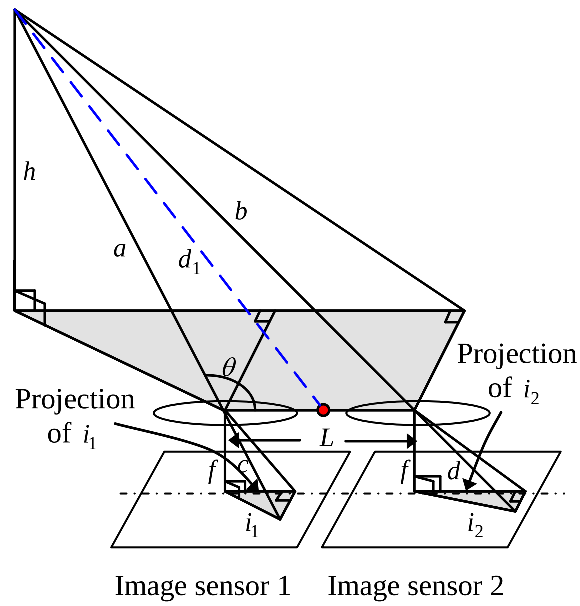

Figure 2. Positioning Technique

4. Position Estimation

4.1 Least Square Estimation

To estimate the 3D unknown positions, a set of three equations are sufficient if the distances could be estimated accurately. However, due to quantization error in the pixels, exact distance between the LED and the unknown position can not be estimated. The intuitive solution to this problem is to use more than three references. Mathematically, this turns the above equations into an over-determined system of equations, termed as linear least square (LS) problem. We can estimate the unknown position by solving the following equation for $\mathbf{X}$.

$$2\mathbf{M}^T\mathbf{M}\mathbf{X} = \mathbf{M}^T\mathbf{D} \qquad (13)$$

$$\text{where, } \mathbf{M} = \begin{bmatrix} x_4 - x_1 & y_4 - y_1 & z_4 - z_1 \\ x_4 - x_2 & y_4 - y_2 & z_4 - z_2 \\ x_4 - x_3 & y_4 - y_3 & z_4 - z_2 \end{bmatrix},$$

$$\mathbf{D} = \begin{bmatrix} (d_1^2 - d_4^2) - (x_1^2 - x_4^2) - (y_1^2 - y_4^2) - (z_1^2 - z_4^2) \\ (d_2^2 - d_4^2) - (x_2^2 - x_4^2) - (y_2^2 - y_4^2) - (z_2^2 - z_4^2) \\ (d_3^2 - d_4^2) - (x_3^2 - x_4^2) - (y_3^2 - y_4^2) - (z_3^2 - z_4^2) \end{bmatrix} \text{ and } \mathbf{X} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

Condition for linear LS solution is that matrix M should have full rank. However, since the reference LEDs are in the same plane (ie. all have same z coordinate value), this condition does not satisfy. Hence, we add a small value with the z axis value of the fourth reference LED. Even though this technique solves the singularity problem of matrix $\mathbf{M}$, we obtain an erroneous estimation for z axis. To estimate the z axis value, we further use vector estimation. Three reference LEDs, A, B and C are used for this estimation.

4.2 Vector Estimation

If $\overline{\mathbf{A}}$, $\overline{\mathbf{B}}$ and $\overline{\mathbf{C}}$ represent the vectors that correspond to the coordinates of A, B and C, respectively, two intersecting points can be calculated using the following equations (14 to 23).

$$\overline{\mathbf{BA}} = \overline{\mathbf{B}} - \overline{\mathbf{A}} \tag{14}$$

$$\overline{\mathbf{CA}} = \overline{\mathbf{C}} - \overline{\mathbf{A}} \tag{15}$$

$$\overline{\mathbf{D}} = cross(\overline{\mathbf{BA}}, \overline{\mathbf{CA}}) \tag{16}$$

$$E = \sum_{I=1}^{3} D(i)^2 \tag{17}$$

$$\overline{\mathbf{X}} = \left(\sum_{i=1}^{3} \overline{BA}(i)^2 + d_1{}^2 - d_2{}^2 \right) * \overline{\mathbf{CA}} \tag{18}$$

$$\overline{\mathbf{Y}} = \left(\sum_{i=1}^{3} \overline{CA}(i)^2 + d_1{}^2 - d_3{}^2 \right) * \overline{\mathbf{BA}} \tag{19}$$

$$\overline{\mathbf{U}} = \frac{cross\left(\frac{\left(\overline{\mathbf{X}} - \overline{\mathbf{Y}}\right)}{2}, \overline{\mathbf{D}} \right)}{E} \tag{20}$$

$$\overline{\mathbf{V}} = \sqrt{\frac{\left(d_1{}^2 - \sum_{i=1}^{3} \overline{U}(i)^2 \right) * \overline{\mathbf{D}}}{E}} \tag{21}$$

$$\overline{\mathbf{P_1}} = \overline{\mathbf{A}} + \overline{\mathbf{U}} + \overline{\mathbf{V}} \tag{22}$$

$$\overline{\mathbf{P_2}} = \overline{\mathbf{A}} + \overline{\mathbf{U}} - \overline{\mathbf{V}} \tag{23}$$

Vectors $\overline{\mathbf{P_1}}$ and $\overline{\mathbf{P_2}}$ represent the two intersecting points from which z axis value of one is selected depending on the geometry of the room.

5. Simulations and Results

5.1. Simulation Setup

Performance of the proposed algorithm is evaluated by simulation using Matlab. One important issue of this scheme is the area within which the position can be determined under an LED array. If the four reference LEDs are seen by both the image sensors, the system can make the estimation. The positioning area is reduced to the minimum when the image sensors' are parallel to the LED array. Figure 3 describes the geometric dimensions for calculating the working area. Assuming that the image sensors are parallel to the LED array, we can calculate the positioning area from the following equations.

$$p = h * \tan\varphi \tag{24}$$

$$r = p + (p - q) \quad (25)$$

where, φ is the half of FOV of the image sensors, q is the length of a side of the LED array, h is the vertical distance between the LED array and image sensors, r is the length of a side of the positioning area. In our simulation model, an LED array of 1×1 m^2 area is assumed. We consider the FOV of the image sensors to be 45^{o} and the vertical distance between the LED array and the image sensor to be 3.5 m. Therefore, the proposed scheme will be able to estimate position within an area of approximately 1.8×1.8 m^2, 3.5 m below the LED array. Hence, keeping distance between two adjacent positions to 1 cm on both the horizontal axes, we assume $181\times181=32761$ experimental positions on the horizontal plane. In our simulation, the major axis of the image sensors is assumed to be parallel to the x-axis of the positioning area. We choose APS-C type 6 Mega pixel image sensor, which is used commercially in Nikon D40, D50, D70, D70s, Pentax K100D, etc. The simulation parameters are listed in Table 1.

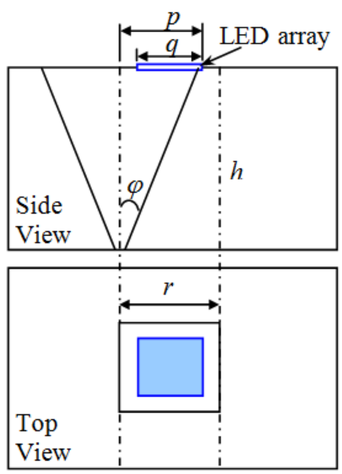

Figure 3. Positioning Area under an LED Array

Table 1. Simulation Parameters

Parameter	Value
Image sensor dimension	23.7×15.8 mm^2
Number of pixels	3008×2000
FOV	45^{o}
Focal length of lens	2.5 cm
Distance between center of two lenses	10 cm
Vertical distance of image sensor and LED array	3.5 m
Positioning area	1.8×1.8 m^2
Distance between adjacent positions in x-axis	1 cm
Distance between adjacent positions in y-axis	1 cm
Total estimating positions	32761

The pixels on the image sensor are arranged in 2D arrays. LED images can be constructed by multiple pixels. For this reason, we need to determine the center of each image prior to other measurements. Let, N pixels constitute the image of a particular LED. The center of the image is then calculated in terms of row and column number of image matrix by calculating the centroid.

$$(N_r, N_c) = \frac{1}{N}\sum_{j=1}^{N}(N_{rj}, N_{cj}), \quad j = 1,2,3\cdots\cdots, N \quad (26)$$

where, (N_r, N_c) is the center of the image in terms of row and column number of the image matrix, (N_{rj}, N_{cj}) are the row-column number of the pixels that construct the corresponding LED image, and j is the number of pixels.

5.2. Least Square Estimation Results

The performance of the proposed algorithm with least square estimation is first evaluated for a fixed unknown position. Keeping the other factors constant, the number of pixels per line of the image sensor is increased from 600 to 3000 with a step of 200 pixels. Simulation result is shown in Figure 4. Horizontal axis represents pixels per line and vertical axis represents the positioning error in meter. It is observed that the positioning error is decreased with increasing the pixel number. The error has a fluctuating behavior which is occurred due to the quantization error of the pixel. The reason is that the image center is assumed to be at the center of the pixel which is obtained from image center estimation using Eq. (26). However, the actual center of the LED image is not always at the pixel center. As a result, we get the quantization error. It is observed that the positioning error is decreased with increasing the pixel number. From the Figure 4, it is seen that the mean of the absolute estimation error is 0.064, 0.003 and 0.6 m along the x, y and z axes, respectively, when pixels per line is 3000. Mean of the total positioning error at this case is 0.81 m. Errors along x and y axes are much lower than that along z axis. To avoid the singularity problem in the least square estimation, discussed in Section 4.1, we added a small length to the z coordinate of the reference LED, 'D'. For that reason, we obtain large error along z axis. As a result, estimation error is increased in LS estimation. To solve that problem, we further estimated the unknown z axis using the vector estimation and the three reference LEDs A, B and C.

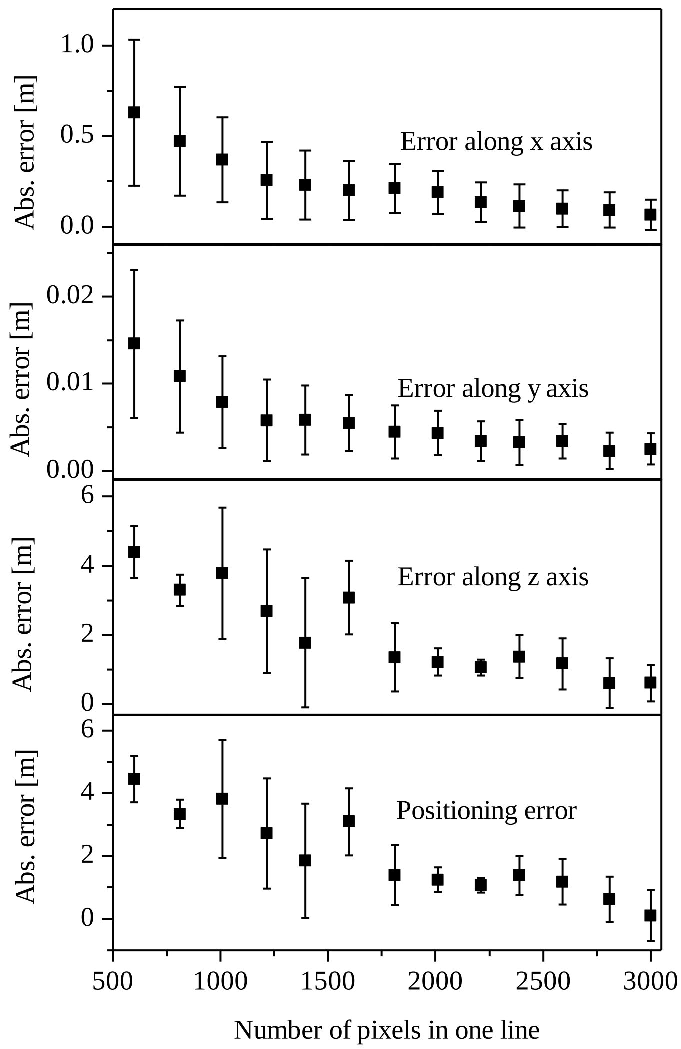

Figure 4. Mean and Standard Deviation of the Absolute Positioning Error using Least Square Estimation. Error along z axis is higher than that of x and y axes.

5.3. Vector Estimation Results

For vector estimation of the 3D unknown position, we need only three reference LEDs. Hence, data corresponding to reference LEDs A, B and C are used. As before, the pixel per line is increased from 600 to 3000 with the step of 200 pixels to understand the effect of pixel size on estimation error. All other parameters are kept unchanged as LS estimation. Results are shown in Figure 5. Horizontal and vertical axes indicate number of pixels per line and estimation error, respectively. Mean of the absolute errors along x, y and z axes are found to be 0.063, 0.003 and 0.017 m, respectively, when the pixel number is 3000 per line. Mean of the overall error is 0.076 m. Also, it is seen in Figure 5 that the vector estimation gives lower error along z axis than that of LS estimation. On the other hand, error along x and y axes are similar to the LS estimation. However, in case of random error that might take place during the estimation of distances of the reference LEDs from the unknown position, LS estimation would give better estimation result for x and y axes than that of vector estimation. Summarizing these two sets of results, we suggest the use of LS estimation for x and y axes, and vector estimation for z axis that can give us a better overall estimation of unknown position. Mean of the estimation error from the combination of LS and vector estimation along the different axes and the overall estimation error are shown in Figure 6. Mean estimation error is 0.156 m as the number of pixels per line is 3000.

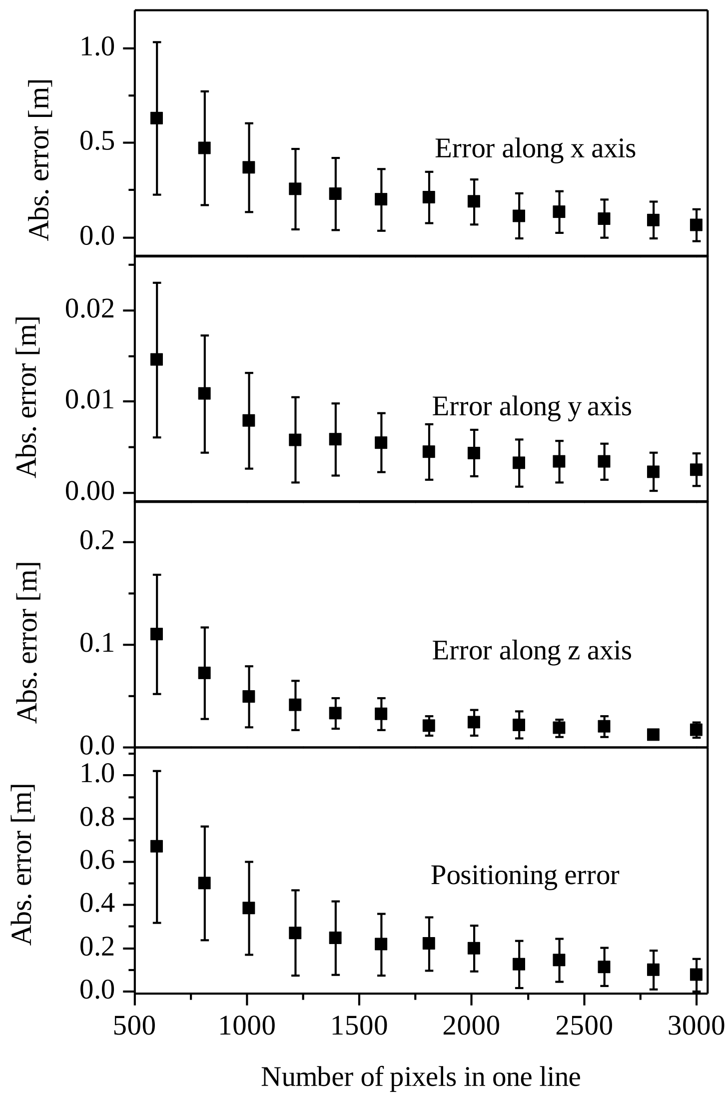

Figure 5. Mean and Standard Deviation of the Absolute Positioning Error along the Three Different Axes. The positioning is done using vector estimation. Error along z axis is much lower than that of least square estimation.

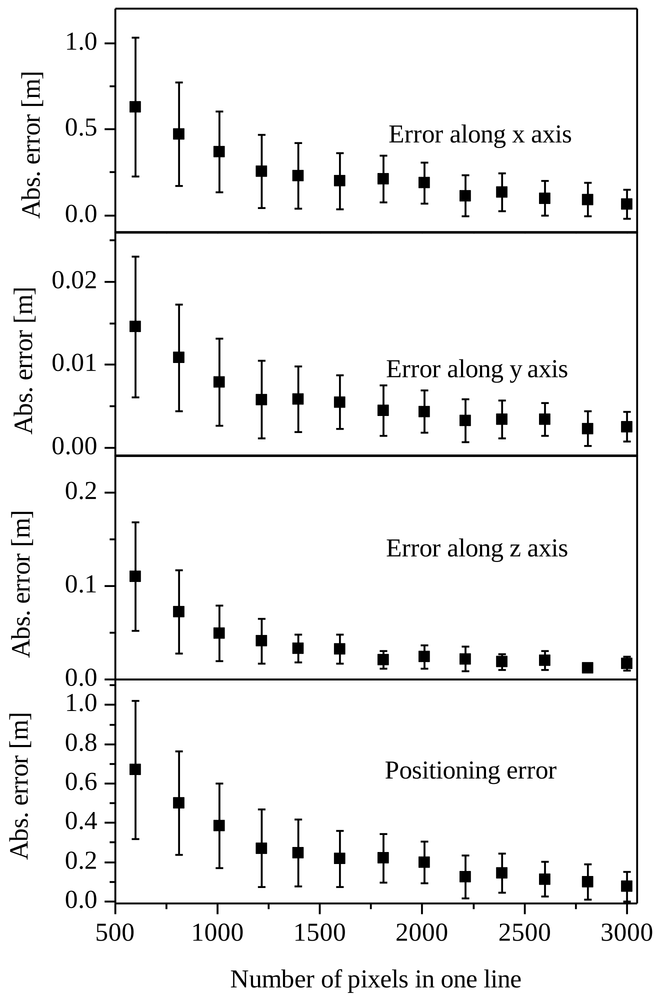

Figure 6. Mean of the Absolute Positioning Error Obtained from Least Square and Vector Estimation Together, LS Estimation is for x and y Axes Value Estimation and Vector Estimation is for z Axis Value Estimation

5.4. Influence of Lens Distance on Positioning Error

Distance between the centers of the lenses certainly has some effect on positioning error. To find out the relationship between lens distance and position error, we vary the distance between the centers of the lenses from 4 cm to 20 cm with step of 2 cm and calculate the root mean square of error distance (E_{rms}) of the 32761 experimental positions described in Section 4.1, using the following equation.

$$E_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} Err_n^{\ 2}} \tag{27}$$

where, n is the number of position to be estimated and Err_n is the estimation error of n th position. Results shown in Figure 7(a) indicate that the RMS positioning error decreases both for vector estimation and LS-vector estimation as we increase the distance between the two lenses. The improvement of the positioning performance is significant up to the distance of approximately 10 cm. At 10 cm distance, the RMS errors for vector and LS-vector estimation are found 0.1239 and 0.09333, respectively. It is also found that the RMS error of LS-vector estimation is lower than that of vector estimation if the lens distance is increased beyond 7.2 cm. Since there is a trade-off between the positioning area and distance of the image sensors, so, we can keep the distance as low as possible. To establish a relationship between the RMS error and lens distance, we further performed second order exponential decay fitting on the LS-vector estimation RMS error results as shown in Figure 7(b). The relation is given below.

$$E_{rms} = -34.40693 + 2.30423e^{-L/0.01959} + 34.52329e^{-L/100.65857} \quad (28)$$

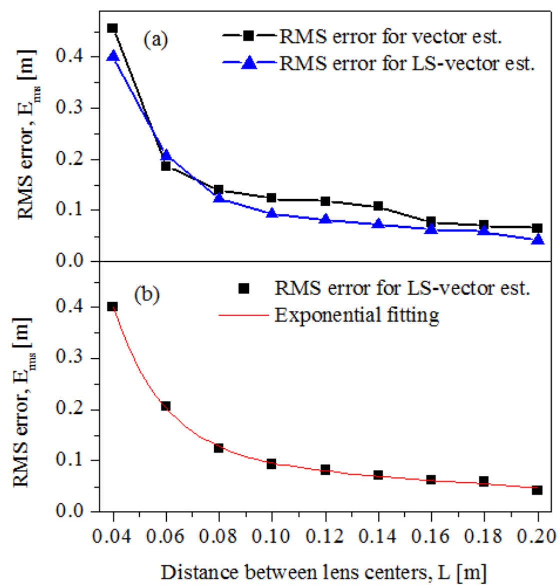

Figure 7. (a) RMS Positioning Error for Vector and LS-vector Estimation at Different Lens Distances (b) Second Order Exponential Decay Fitting of RMS Error for LS-vector Estimation

5.5. Influence of Focal Length on Positioning Error

Focal length of the lens also has the effect on the positioning error. To observe this effect, we have done another simulation experiment varying the focal length of the lenses from 1 to 2 cm with an increment of 0.1 cm and using LS-vector estimation technique. Number of pixel per centimeter and distance between the centers of two lenses are assumed to be 1000 and 15 cm, respectively. Result is shown in Figure 8 which indicates that positioning error can be decreased by using lenses of longer focal length. However, there is some fluctuating nature due to the quantization error from the pixel count.

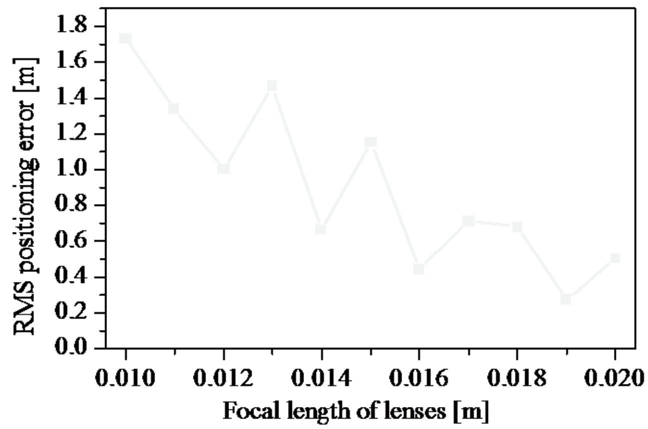

Figure 8. RMS Positioning Error for Different Focal Length of the Lenses

6. Discussion

In this section, we discuss about some limitations of the proposed algorithm and compare it with other previously proposed positioning algorithms based on VLC.

6.1. Limitations

Distance estimation in the proposed algorithm depends on the image distance measurements on the image sensors. For the accuracy of the estimation, each component needs to be installed with high measurements accuracy. Image sensors should be installed in the same plane and the lenses should have identical properties. Otherwise the positioning accuracy would be degraded largely. One major limitation of the VLC based positioning is the positioning area of the system. Since the positioning process solely depends on the reference coordinate information from the lighting source, the proposed scheme can not calculate the position if all the reference LEDs can not be seen by both the image sensors. The lighting arrangement bears much importance for positioning since there should not be any shadowed region inside the positioning area. Another important limitation originates from the quantization error of the pixels. The LED rays can be projected to any part of the pixel of an image sensor; it is not always projected to the center of the pixel. Since the desired position is calculated assuming that the center of the LED image is in the center of a pixel, it causes the quantization error. The proposed algorithm is applicable for stationary or slowly moving targets. To apply this system for moving targets, data transmission rate of the VLC system should be sufficiently high.

6.2. Comparison with Other Technologies

In this section, we follow-up and discuss about the advantages of our proposed algorithm. Some previous VLC based positioning algorithms [2-6] are briefly discussed in Section 2. We tried to solve some major challenges by our proposed algorithm. In [2] and [3], photo detector is used as receiver which can receive signal from a single light source at a time. In the proposed algorithm, use of image sensor facilitates to receive signals from several light sources simultaneously. In case of positioning error, switching estimated receiver position scheme [3] reports the 2D RMS positioning error to be 46.3 cm, 33.6 cm and 29.8 cm for receiver FOV angles of 25°, 17.5° and 10°, respectively. The VLC guidance system using fluorescent lights and photo sensor [4] estimates the location with accuracy within 10 to 30cm. However, the positioning is 2D. Positioning algorithm using LEDs, image sensor and 6-axes sensor [6] estimates the receiver's position with accuracy of within 1.5 m provided that pixel size is 36×10^{-6} m. In our proposed scheme, 3D positions can be estimated with an RMS error of about few centimeters. In addition, positioning accuracy of the systems described in [2, 3, 4, 6] obviously depends on the accuracy of angular measurements. Our proposed algorithm does not need any kind of angular measurement. Rather, the position is calculated from the difference of the image distances in two image sensors. Hence, the measurement error is significantly reduced since we do not need any angular measurement.

Table 2. Comparison of the Proposed Algorithm with Earlier VLC based Positioning Algorithms

Ref No.	Transmitter	Receiver	Positioning type	Accuracy	Angular measurement
2	LED	Photo detector	2D	1~2m	Needed
3	LED	Photo detector	2D	0.298~0.463m	Needed
4	Fluorescent lamp	Photo detector	2D	0.1~0.3m	Needed
5	LED	Image sensor	3D		Not needed
6	LED	Image sensor	3D	1.5m	Needed
Proposed algorithm	LED	Image sensor	3D	0~0.15m	Not needed

Some major features of the proposed algorithm are compared with the previous VLC based positioning systems and are listed in Table 2. Comparison of the properties listed in Table 2 depicts that the proposed system would be advantageous due to high accuracy and angular measurement-less 3D positioning.

7. Conclusion

In this paper, we propose an algorithm for indoor positioning using lighting LED array and image sensors. White LEDs are used as optical transmitters in which at least four spatially separated non-collinear LEDs send their known position information. The image sensors located at the unknown position receive and demodulate the light signal through lenses. The unknown position is then calculated using the geometric relations of the LED image distances. Mathematical formulations for the proposed algorithm are discussed in details. A series of simulations are explained to understand the positioning error characteristics. Simulation results indicate that by using the proposed algorithm, the positioning error can be minimized within the range of a few centimeters. The proposed technique has the benefits of device simplicity.

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