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Indoor Localization Using Three dimensional Multi-PDs Receiver Based on RSS

Yinghao Liu, Ki-Hong Park, Boon S. Ooi and Mohamed-Slim Alouini

Abstract—A novel design of three dimensional optical receiver for visible light communication (VLC) indoor positioning system has been proposed in this paper. We model the optical wireless channel and utilize modified triangulation method to obtain more robust receiver position by using at least two LEDs and one receiver consisting of nine photodetectors (PDs). The main characteristics are as follows: (1) our design of multi-PDs receiver is fully expanded into three dimensions compared with the pyramid structure (PR); (2) based on Multiple-Photodiode-based Indoor Positioning algorithm [1], we improve the indoor positioning algorithm by redefining the optimization problem of obtaining the direction from receiver to LED and using weighted triangulation method to locate receiver position; (3) the improved algorithm is implemented and the simulation results are shown under our three dimensional multi-PDs structure receiver.

I. INTRODUCTION

In modern life, there are many applications where positioning plays an important role. People have developed the global positioning system (GPS) to locate world wide position with error in decimeter scales, which brings people much convenience. However, the accuracy of GPS is too low for indoor localization. The signal may drop down significantly since buildings can block the line of sight (LOS) connection. With the well-developed GPS being indispensable for outdoor activities, many researchers have been also devoted to seeking an indoor positioning system to realize indoor localization with acceptable error.

There are many research projects studying indoor localization using radio frequency (RF)-based, infrared (IR)-based and ultrasonic-based communication systems. Some systems conduct a Wi-Fi fingerprint localization method [2] using subsistent infrastructures, yet they need to build an environment-dependent database and can only get positioning accuracy with several meters. The RADAR system in [3] implements a location service within several meters error utilizing the existing RF data network. But indoor environments often contain substantial affecting the propagation of infrared RF signals and thus the accuracy of positioning due to multipath effects and interference. Others like [4] can achieve good precision with wide coverage in positioning a Mobile Robot within an infrared sensor system, yet with the requirement of a very accurate design and device selection. In [5], an ultrasonic-based indoor positioning system with centimeter level error is presented but at the price of high cost for extra hardware.

VLC using visible light instead of RF signals for communication has drawn much attention in recent years. The light-emitting diode (LED) has been widely deployed because of long lifespan, high power efficiency, low deployment cost and illumination functions. Besides, LEDs can be used to modulate electric signals into optical signals without introducing interference even at high rates, which turns LEDs into communication devices with the potential of transmitting high speed data streams. Therefore, positioning systems based on VLC have many merits such as no extra infrastructure, no electromagnetic interference and high accuracy.

Indoor localization based on received signal strength (RSS) of optical light has been studied in [6]–[8]. Centimeter-level errors can be achieved in [6] with the assumption of known height of the receiver. An array of PDs is mounted on the robot to obtain both RSS and angle of arrival (AOA) information in order to track the position of a moving robot in [7] with the assumption of known and fixed heights. Then another hybrid utilization of AOA and RSS in VLC systems for three dimensional localization is proposed in [8] and applies analytical learning rule to solve its non-linear and non-convex problems, which is pretty complex.

The Multiple-Photodiode-based Indoor Positioning algorithm [1] based on pyramid receiver is very original and effective, but there are some places to be improved, like the structure of the receiver and algorithm. This paper focuses on a novel design of three dimensional optical multi-PDs receiver and proposes an improved algorithm to enhance the performance of indoor localization based on [1]. In our indoor localization system, we assume that there are at least two LEDs on the ceiling with known positions in the room coordinate and then we use a three dimensional multi-PDs receiver to locate its position based on RSS. The main contributions are as follows.

(a) A novel receiver structure is proposed, which gives better performance when the height of the receiver is high, namely, 1.3m-1.7m. The new structure has nine PDs, which are distributed in three dimensions.

(b) We show a critical problem neglected by the existing work when the noise is comparable to the signal received
just gets more kinds of similar luminous power from a greater number of LEDs, which cannot contribute much to positioning accuracy.

B. Channel Model

Our indoor localization system assumes that there are at least two LEDs within the LOS link to one multi-PDs receiver, because only the direction (or the distance) from the receiver to the LED can be known if there is only one LED. The system takes irradiated LED optical signal at the LEDs and optical signal received by PDs as transmitted signal and received signal, respectively. Then there are $K$ transmitters (LEDs) and $L = 9$ PDs. Suppose $d_{ji}$ is the distance between the $j$-th photodetector and the $i$-th transmitter, $\phi_{ji}$ is the irradiation angle of optical signal from the $i$-th LED to the $j$-th PD with respect to the normal of the $i$-th LED (defined as the vector perpendicular to the LED plane), $\psi_{ji}$ is the incidence angle of optical signal from the $i$-th LED to the $j$-th PD with respect to the normal of the $j$-th PD (defined as the vector perpendicular to the PD plane), and the effective area of PD is denoted as $A$. Then, the channel gain from the $i$-th LED to the $j$-th PD through the LOS optical channel in the luminous domain is \[ H_{ji} = A(m + 1) \frac{\cos^m(\phi_{ji}) \cos^M(\psi_{ji})}{2\pi d_{ji}^2}. \] (1)

Note that the Lambertian emission order $m$ is \[ m = \frac{-\ln 2}{\ln(\cos(\phi_{1/2}))}, \] (2)
where $\phi_{1/2}$ is the LED semi-angle at half-power and \[ M = \frac{-\ln 2}{\ln(\cos(\psi_{1/2}))}, \] (3)
where $\psi_{1/2}$ is the half power angle of incidence of a PD. $\phi_{1/2}$ and $\psi_{1/2}$ are determined by the properties of LEDs and PDs. Besides, channel gain $H_{ji}$ in (1) holds only if the optical LOS signal arrives within the field of view (FOV) of the PD. Otherwise, the PD detects no luminous power beyond its FOV.

Therefore, suppose the optical luminous flux $\Phi_i$ (in lm) of the $i$-th LED is the transmitted luminous power, the luminous power $P_{ji}$ received from the $i$-th LED received by the $j$-th PD is: \[ P_{ji} = \Phi_i H_{ji} = \Phi_i A(m + 1) \frac{\cos^m(\phi_{ji}) \cos^M(\psi_{ji})}{2\pi d_{ji}^2}. \] (4)

Here we give Fig. 2 to demonstrate the geometrical relationship of parameters in the LOS channel.

C. Coordinate Transformation

Through the accelerometer, the normal or orientation $N$ of the receiver can be obtained shown as in Fig. 3(a), which we assume is the $Z$-axis of the receiver coordinate. Now consider the coordinate $O_a$ is aligned with the room coordinate $O_r$, then coordinate $O_a$ can be known by shifting coordinate $O_r$ with a vector $\psi_{r\rightarrow a}$. The angle between $N$ and $Z_a$-axis is $\theta_N$ and the angle between the projection of $N$ and $X_a$-axis is $\phi_N$. 

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Fig. 1: (a) shows the top view of the receiver. (b) shows the front view of the receiver.

by PDs in the luminous flux domain and then the solution is provided considering the practical environment.

(c) The previous existing algorithm proposed in [1] is revised in terms of modifying triangulation with weights in order to earn more accurate results. This can greatly lessen the error.

This paper is organized as follows. Section II describes the indoor localization system including some related knowledge. The proposed improved algorithm is explained in Section III, which is introduced in detail step by step. The simulation results are presented in Section IV, where the positioning error of our novel receiver and improved algorithm are compared with those of previous work. Then several typical points are picked to demonstrate the localization error and the paper is concluded in Section V.

II. INDOOR LOCALIZATION SYSTEM MODEL

A. Novel three-dimensional receiver structure

The existing typical angle diversity receivers can be separated into pyramid receiver (PR) and hemispheric receiver (HR) proposed in [9]. Inspired by this, we propose a novel angle diversity receiver with nine PDs. There are three titled PDs uniformly distributed with the same elevation angle in the horizontal plane and six PDs vertically distributed, where two PDs are placed vertically (like PD$_2$ and PD$_3$) in Fig. 1(b) around each PD (like PD$_1$) in Fig. 1(a). Note that there are another PD on the other side of PD$_1$ and same for PD$_5$.

Compared with PR and HR, our design is more robust to higher and corner positions. For example, when the receiver is moved approximately with height from 0 m to 1.5 m, the number of PDs in PR that can receive signals from a certain LED may decrease. Besides, these PDs in PR receive similar power since the PDs have similar orientation. Intuitively, we can see that our three dimensional receiver (TDR) will perform better considering the structure and application environment. The main reasons are: (1) it has more chance to receive optical signals from at least two or even more LEDs for our indoor positioning system; (2) the more discrepancies the received signals from different LEDs hold, the less error the positioning system will produce. As for PR structures shown in [2], when the number of PDs is increased from three or four to nine, PR
We can get $O_h$ by rotating $O_a$ through $\phi_N$ angle along $Z_a$-axis, and then get $O_b$ by rotating $O_h$ through $\theta_N$ angle along new $Y_h$-axis. For any point $Q_a$ in coordinate $O_a$, if coordinate $O_a$ is rotated through $\phi_N$ along $Z_a$-axis, $O_b$ coordinate can be acquired. Let $Q_b$ denote the corresponding position in $O_b$ coordinate of fixed $Q_a$ point. According to linear algebra, we know the relation among $Q_a$, $Q_b$, and rotation matrix $\Omega_z(\phi_N)$

$$Q_a = \Omega_z(\phi_N)Q_b = \begin{bmatrix} \cos(\phi_N) & -\sin(\phi_N) & 0 \\ \sin(\phi_N) & \cos(\phi_N) & 0 \\ 0 & 0 & 1 \end{bmatrix} Q_b. \quad (5)$$

Then we know the position of $Q_a$ in room coordinate is

$$Q_r = v_{r-a} + Q_a = v_{r-a} + \Omega_z(\phi_N)\Omega_y(\theta_N)Q_c,$$

where $Q_c$ comes from the corresponding point $Q_d$ in coordinate $O_d$. The point $Q_d$, central point of a PD, is known in the receiver coordinate $O_d$ because the distribution of PD is defined by us. But we do not know the misalignment angle $\psi_N$ between $O_d$ and $O_c$, which can help us obtain the positions of any points that are known in $O_d$ and unknown in $O_c$ (or $O_h$) coordinate, in order to calculate positions of these points in room coordinate. Suppose the misalignment angle between $O_d$ and $O_c$ is $\psi_N$, then the receiver coordinate $O_d$ can be acquired by rotating through $v_{r-a}$ along Z-axis in $O_c$. Applying the same rule above, there is a known point $Q_d$ in $O_d$ receiver coordinate, the position $Q_r$ in room coordinate $O_r$ is

$$Q_r = v_{r-a} + \Omega_z(\phi_N)\Omega_y(\theta_N)\Omega_z(\psi_N)Q_d. \quad (7)$$

The geometric relation is shown in Fig. 3.

If we know the discrepancy vector $v_{r-a}$, we can easily get the position of every PDs in the room coordinate since we know PDs positions $Q_d$ in receiver coordinate $O_d$. As for $v_{r-a}$, we let it traverse from 0 to $2\pi$ to find the most appropriate value, which is explained in our algorithm in Section III.

III. PROPOSED POSITIONING ALGORITHM

Our algorithm improves the main approach proposed in [1] by solving the underlying problem and modifying triangulation with reasonable weights. The algorithm can be separated into two steps.

(1) Calculating the direction from receiver towards the $i$-th LED: Through power matrix $P$, where the element $P_{ji}$ represents the luminous power of the optical signal received by the $j$-th PD from the $i$-th LED, we estimate the direction $V_i$ from receiver towards the $i$-th LED.

(2) Modifying triangulation: Inspired by weighted centroid localization (WCL) in [10], we use weighted triangulation to estimate the optimized receiver position based on $V_i$ and positions of LEDs.

A. Calculation of the direction from receiver towards the $i$-th LED

In (4), assuming that all LEDs have the same optical luminous power $\Phi$, we can let $\phi_{ji} = \phi_i$ and $d_{ji} = d_i$ for $\forall j \in \{1, 2, ..., L\}$ since the small distance, $\Delta_j$, between the centers of the receiver and the $j$-th PD, is negligible with respect to the distance between the $i$-th LED and the receiver center, $d_i$. Therefore, considering the $i$-th LED for $i \in \{1, 2, ..., K\}$ and the $j$-th PD for $j \in \{1, 2, ..., L\}$, we have

$$P_{ji} = \Phi \frac{A(m+1)}{2\pi d_i^2} \cos^m(\phi_{ji}) \cos^M(\psi_{ji}) \quad (8)$$

$$\approx \frac{C}{d_i} \cos^m(\phi_i) \cos^M(\psi_{ji}), \quad (9)$$

where $C$ is defined as $\Phi \frac{A(m+1)}{2\pi}$ and is known and constant. Considering just the $i$-th LED, we can see $\cos(\psi_{ji}) \propto P_{ji}^{\frac{1}{M}}$. Hence, without noise, the planes perpendicular to the normal...
vectors with length of $P_{ji}^T$ will intersect at a line (two PDs within LOS of the $i$-th LED) or a point (three or more PDs within LOS of the $i$-th LED), and the vector $V_i$ from the receiver to its projection on the line or the intersection point is pointing to the $i$-th LED. The geometric figure is shown in Fig. 4. Note $N_j$ is a vector with a certain length for the rest context, rather than a vector with length of one unit.

When the noise exists, we need to find a point $\omega$ which minimizes summation of all the distances from $\omega$ to the projection of $\omega$ into the planes that are perpendicular to normals of PDs with length $P_{ji}^T$. Lemma 1 in [11] gives a method to find the point $\omega$. However, they neglect a critical problem as shown in Fig. 5, where the error would be unreasonable if $N_j$ is large and small $N_j$ is comparable to noise.

Therefore, $N_j$ with greater magnitude should be given more emphasis when we define the optimization problem, which helps obtain $\omega$ through minimizing summation of all the distances from $\omega$ to the projection points $\omega_j$ on the $j$-th plane. Suppose the misalignment angle between coordinate $O_c$ and coordinate $O_d$ is $\psi$, for the $i$-th LED, the normals of PDs with length $P_{ji}^T$ are known, denoted as $N_j$, then we have

$$\omega_j - \omega = tN_j,$$

$$\omega_j^TN_j = N_j^TN_j.$$  

Multiplying (10) by $N_j^T$ on the left side and substituting $N_j^T\omega_j$ with $N_j^TN_j$, we can get

$$t = 1 - \frac{N_j^T\omega}{N_j^TN_j},$$

$$\omega_j - \omega = -\frac{N_j^TN_j}{N_j^TN_j}\omega + N_j.$$  

Let $E_j$ and $F_j$ denote $-\frac{N_jN_j^T}{N_j^TN_j}$ and $N_j$, we have

$$\omega_j - \omega = E_j\omega + F_j.$$  

Let $W_j^i = \|N_j\|^2$ denote weight put on the $j$-th plane since greater $N_j$ will produce greater $W_j$. It means that we lay higher emphasis on the error resulting from $(\omega_j - \omega)$ part and the optimization problem in order to obtain $\omega$ or $V_i$ is defined as

$$\omega^* = \arg\min_{\omega} f(\omega)$$

$$= \arg\min_{\omega} \sum_{j=1}^{L} (\|E_j\omega + F_j\|^2W_j),$$

which gives us

$$\omega^* = -\left(\sum_{j=1}^{L} E_j^T E_j W_j^1\right)^{-1} \sum_{j=1}^{L} E_j^T F_j W_j^1.$$  

Denote $\sum_{j=1}^{L} E_j^T E_j W_j^1$ as matrix $D$ with rank $r$, we get $V_i$ as following.

1) $r = 1$: This means there is just one $N_j$ that is none zero, hence $\omega^* = N_j$;
2) $r = 2$: This problem is similar as $\omega = \min \|\omega\|^2$, subject to $D\omega = b$, where $b$ is $-\sum_{j=1}^{L} E_j^T F_j W_j^1$. The optimal solution is $\omega^* = D^T(DD^T)^{-1}b$;
3) $r = 3$: We use matrix inverse operation in (16).

Finally, the estimated direction from the receiver to the $i$-th LED is $V_i = \omega^*$.

B. Improved Triangulation

Now directions from receiver position to LEDs, $V_i$ for $i \in \{1, 2, \ldots, K\}$, and the positions of LEDs are both known. We can use triangulation to estimate the position of receiver. According to $V_i$, when there is no noise receiver position $s$ will be the intersection point of lines, where the $i$-th line is defined as $r_i = h_i + t_sV_i$, $\{i : 1 \leq i \leq K\}$ and $h_i$ denotes the position of the $i$-th LED. In practical scenario, these $K$ lines may not intersect at one point due to the additive noise and the negligible small distance between the centers of receiver and PD. Therefore, we need to find the point $s$ that minimizes the summations of $L_2$ norm squares of the vectors from $s$ to $s_i$, where $s_i$ is the point in line $L_i$ and most closest to point $s$.

The fact that $s$ is within line $L_i$ gives us $(s_i - s) \bot V_i$, which can be written as $s_i^TV_i = s^TV_i$. From the expression of line, we know

$$s^TV_i = (t_iV_i^T+h_i^2)V_i.$$  

Or equivalently,

$$t_i = \frac{s^TV_i - h_i^2V_i}{V_i^TV_i}.$$  

Substituting (19) into the line equation, we can get

$$s_i - s = \left(\frac{V_iV_i^T}{V_i^TV_i} - I\right)s + (I - \frac{V_iV_i^T}{V_i^TV_i})h_i,$$

where matrix $I$ represents appropriate identity matrix.
Inspired by weighted centroid localization (WCL) in [10], here we define $W^2$ as $L_2$ norm of $V_i$. Greater $||V_i||^2$ indicates stronger received luminous power or smaller distance $d_i$ between the $i$-th LED and the receiver, where we regard error coming from smaller distance as important. Let $B_i = \frac{V_iV_i^T}{V_i^TV_i} - I$, the revised optimization problem can be transformed into

$$s^* = \text{argmin}_s \sum_{i=1}^{K} (||s_i - s||^2 W_i^2) \triangleq g(s)$$

$$= \text{argmin}_s \sum_{i=1}^{K} (||B_i s - B_i h_i||^2 W_i^2).$$

Then we have the optimal $s^*$ is:

$$s^* = (\sum_{i=1}^{K} B_i^T B_i W_i^2)^{-1} \sum_{i=1}^{K} B_i^T B_i h_i W_i^2.$$ (21)

If matrix $\sum_{i=1}^{K} B_i^T B_i W_i^2$ is not full rank, we consider this problem as shown in the analysis of (16). Meanwhile, we calculate $s^*$ and the corresponding $g(s^*)$ for each assumed $\nu$ changing from 0 to $2\pi$ and record the pair of values. Then the desired receiver position is estimated as $s^*$ corresponding with the minimum $g(s^*)$ over $\nu \in [0, 2\pi]$. 

IV. SIMULATION RESULTS

Before the results are given, the environment for the simulation should be noted. We model the wireless optical communication system in a room of size $5\text{m} \times 5\text{m} \times 3\text{m}$. There are four LEDs uniformly distributed in the ceiling considered as transmitters, that is, $(\frac{5}{10}, \frac{5}{10}, 3)\text{m}$, $(\frac{5}{10}, \frac{10}{10}, 3)\text{m}$, $(\frac{10}{10}, \frac{5}{10}, 3)\text{m}$, $(\frac{10}{10}, \frac{10}{10}, 3)\text{m}$. The propagation of optical signal from LEDs follows Lambertian pattern, and we take the Lambertian parameters $m$ and $M$ as 1 and 1.4, respectively, based on the experiments provided by [1]. At the receiver side, there are nine PDs spreading into three dimensions as our design. Three PDs at the bottom have the same elevation angle of 23°, and the PD responsivity ($R_0$), effective area ($A$) and FOV of each PD are 22nm-lux$^{-1}$, 15mm$^2$ and 1.22rad, respectively [1]. Eight typical points at two kinds of heights are picked up to observe the positioning error under different noise variance, receiver structures and algorithms. As we know, the total noises include shot noise, thermal noise and the accelerometer noise, among which the shot noise has dominating effects on the error in practical measurements [11]. It is also mentioned that the shot noise is approximately $\sigma_n^2 = 10^{-17}$ (in $A^2$) when the luminous flux of the LED is $P_{\text{LED}} = \Phi = 6000\text{lm}$ and the electric current is around $P_{\text{LED}} = 10^{-6}$ (in $A$) [11]. Then we know $\sigma_n^2 = \sigma_e^2 + \sigma_i^2 = 10^{-17} \times (\frac{10}{22} \times 10^{-4})^2 = 225 \times 10^{-11}\text{lm}^2$. which implies that we could assume that the total noise variance is approximately $10^{-12}\text{lm}^2$. In the simulation, we assume that the ambient noise is dominating the noise from the PD and accelerometer which are negligible in the simulation. Then we investigate the positioning performance when the luminous power of transmitted optical signal is 1000lm and noise variance is ranged as $[-160, -100] \text{dB lm}^2$. Higher noise will undermine the effectiveness of algorithms under each receiver structure since positioning error in meters level is not acceptable in a room of size $5\text{m} \times 5\text{m} \times 3\text{m}$.

The results under TDR and improved algorithm are still promising when the noise variance is lower than $-120\text{dB lm}^2$. Note that the error is averaged by 2000 times and the typical testing points $P_1$, $P_2$, $P_3$, $P_4$ and $P_5$, $P_6$, $P_7$, $P_8$ represent $(2.5, 0, 1.5)\text{m}$, $(2.5, 2.5, 1.5)\text{m}$, $(1.25, 1.25, 1.5)\text{m}$, $(0, 0, 1.5)\text{m}$ and $(2.5, 0, 0)\text{m}$, $(2.5, 2.5, 0)\text{m}$, $(1.25, 1.25, 0)\text{m}$, $(0, 0, 0)\text{m}$, respectively.

Under TDR structure, we pick up some typical points to demonstrate the effect of weight $W^1_j$ in the optimization problem (15). As shown in Fig. 6, reasonable weight $W^1_j$ can greatly reduce the error as a result of attenuating the disturbance of noise when we calculate the directions from the receiver towards LEDs. Therefore, we have verified the importance of weight $W^1_j$ in our redefined optimization problem (15). When the receiver position is at some typical points with height of 1.5m in the room, our revised algorithm referring as $W^3_j$ performs better than that without $W^1_j$ and $W^2$. When $W^1_j$ exists but $W^2$ does not exist, the error magnitudes of corner points, $P_1$ and $P_4$, indicate that the neglected problem in previous work, as we mentioned in Fig. 5, can be solved with appropriate weights $W^1_j$. Here $W^1_j$ and $W^2$ denote the vectors composed of $W^1_j$ and $W^2_j$ for simplicity.

We want to know the influence of weight $W^2$, which works well especially when the receiver is near to one of the LEDs while far away from the others. Therefore, position $P_1$ is selected to show that $W^2$ can help make our improved algorithm more robust. $W^2$ can help rectify the mistake coming from the deflected directions calculated from the receiver to the LEDs due to noise, which is verified in Fig. 7. As for position like $P_2$, $P_3$ and $P_4$, it will not make much difference between triangulation and weighted triangulation.

Fig. 8 shows that our receiver structure is almost always better than PR when the height is 1.5m. The superiority is more obvious especially when the noise variance is low. To demonstrate this more clearly, Fig. 9 contains three point $P_5$, ...
Fig. 7: Comparison of the algorithms between with $W^2$ and without $W^2$ under TDR.

Fig. 8: Comparison of PR and TDR when $z = 1.5m$.

Fig. 9: Comparison of PR and TDR when $z = 0m$.

$P_7$ and $P_8$ to illustrate that the errors coming from our receiver structure are also smaller than that from PR using the same improved algorithm at 0m, which shows that our receiver is better than PR. Note that the number of PDs in PR should also be nine when we compare these two different structures.

V. CONCLUSION

We design a novel three dimensional structure receiver including nine PDs expanded into three dimensions. Using the accelerometer and the received optical signals detected by the PDs through coordinate transformation and the Lambertian equation, the receiver position is estimated by traversing the unknown misalignment angle $\psi$ from 0 to $2\pi$. We propose the improved algorithm based on [1] with reasonable weights to reduce the positioning error, which can also solve the practical problem when the noise is comparable to some received signals within the FOV of PDs. The weighted triangulation can decrease the localization error when the receiver is placed at some edge positions. Simulation results reveal that our three dimensional receiver performs better than PR angle diversity receiver. In addition, the comparison shows that our revised algorithm under three dimensional structure receiver is more robust to the noise.

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