Dead-Zones Limitation in Visible Light Positioning Systems for Unmanned Aerial Vehicles

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***Abstract*—Visible Light Communication (VLC) has been gaining attention for many applications as a cost-effective and high bandwidth wireless technology. Visible light positioning (VLP) is often combined with VLC to offer multi-functionalities of illumination, communication, and localization. In this paper, we investigate coverage area and 'dead-zone' for the localization of an indoor flying receiver (e.g. drones). For accurate positioning, VLP requires a signal from more than two transmitters. However, the signal from the minimum number of transmitters may not always be available especially in the area close to the walls leading to inaccurate positioning (the dead-zone). The simulation for a typical industrial environment shows that the loss of a signal due to a dead-zone is highly dependent on the divergence angle of transmitters and the field of view of the receiver. The maximum height a drone can reach with a field of view of 85° for VLP systems is about 7.8 m for up to four transmitters without encountering any dead-zones.**

Keywords—Visible Light Positioning, Visible Light Communication, Indoor Localization, Industrial Environment, Indoor Positioning

I. INTRODUCTION

The developments of solid-state lighting and the subsequent advancements in light-emitting diodes (LEDs) have paved the way for many applications including visible light communication (VLC) and visible light positioning (VLP). VLC and VLP have great potential due to the wide availability of the illumination and signaling infrastructure. This is particularly promising as high power white LEDs are expected to replace the existing lighting infrastructure to achieve a low cost and energy efficient illumination. Besides illumination, these devices can offer a license-free spectrum for wireless communications without any electromagnetic inference. Furthermore, VLP systems can also be used for precise indoor and outdoor localizations.

VLC and VLP for industrial environments can be used for indoor positioning of forklifts and aerial drones to carry out autonomous tasks. For example, unmanned aerial vehicles (UAVs), also known as drones, offer a safe and cost-effective way for hard-to-reach areas for tasks such as visual inspections. The areas under inspection can range from offshore oil rigs to power plants. Currently, their use in warehouses for conducting physical inventory is gaining increasing attention. The challenge, however, is that the drone needs to determine its location in relation to its environment autonomously.

The VLP for two-dimensional (2-D) and three-dimensional (3-D) positioning uses trilateration, angle-of-arrival and angle difference of arrival (ADOA) algorithms which generally requires a signal from three or more spatially distributed transmitters [1-3]. Recently, it is demonstrated that positioning using a single transmitter is feasibly by exploiting angle diversity using multiple receivers [4]. A detailed survey of the aforementioned algorithms is presented in [2, 3].

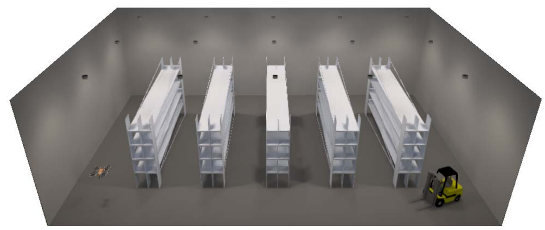

Fig. 1. A typical industrial environment with the LEDs configuration (dots).

Although VLP for stationary and slow-moving objects are well investigated, the possible failure of VLP for flying objects such as drones due to a signal loss has not been discussed. In this paper, for the first time, we consider the coverage area and localization precision for a drone in an industrial environment. For simplicity, we use a trilateration algorithm to demonstrate the coverage and dead-zones. Trilateration algorithms require distance measurements, so the received signal strength (RSS) is used to calculate the distance between the transmitters and the receiver. Then, the linear least square (LLS) method is used here to determine the position of the receiver. Afterward, the environment is evaluated to see where the systems cannot be properly implemented. While this paper uses a trilateration algorithm, the study can be extended to other positioning algorithms that require the use of more than one transmitter.

The remainder of the paper is organized as follows: Section II describes the system model of the VLC channel and the positioning algorithm. In Section III, simulation results and discussions are presented. Conclusions are finally drawn in Section IV.

II. SYSTEM MODEL

In this paper, a 20×15×6 m^3 warehouse is considered as shown in Fig.1. Uniformly distributed N light fixtures with 15 transmitters at the ceiling with a semi-angle of 45° and a power of 115 watts are used. The receiver, with a photodetector (PD) area A_r is located at the unknown location (x, y, z). The main parameters for the study are shown Table 1.

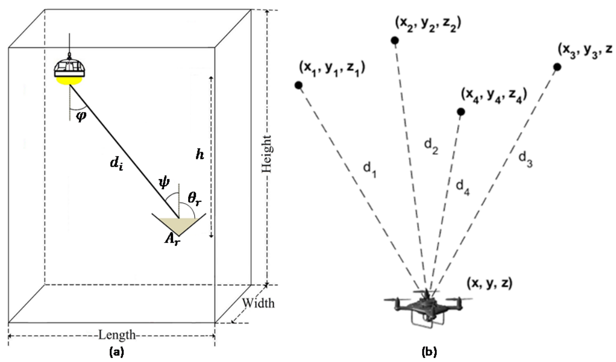

Fig. 2. (a) VLC system parameters and (b) Trilateration algorithm parameters.

For typical LEDs with Lambertian radiation order m, the received power P_{ri} from i^{th} transmitter is given by:

$$P_{ri} = \begin{cases} P_{ti} \frac{(m+1)A_r}{2\pi d_i^2} \cos^m(\varphi)\cos(\psi), & \psi \leq \theta_r \\ 0, & \psi > \theta_r \end{cases} \quad (1)$$

where P_t is the transmitter's power for i^{th} transmitter, d_i is the distance between the transmitter and the receiver, ψ is the angle of incidence, φ is the angle of irradiance, and θ_r is the field-of-view (FOV) of the receiver, as shown in Fig. 2 (a). The distance between the transmitter and receiver d_i can be estimated using the RSS. Assuming $\cos(\varphi) = \cos(\psi) = \frac{z_i - z}{d_i} = \frac{h}{d_i}$ for horizontally oriented transmitters and receiver, the d_i can be estimated using received signal power P_{ri} for a known value of P_{ti} as:

$$d_i = \sqrt[m+3]{\frac{(m+1)\, A_r\, P_{ti}\, h^{m+1}}{2\,\pi\, P_{ri}}} \quad (2)$$

where $h = z_i - z$ is the vertical height difference between the transmitter and receiver.

The 2-D position of the receiver can be calculated using three reference points. However, for a 3-D localization, a minimum of four-reference points and its corresponding distances are needed. It can be obtained through quadratic equations:

$$\begin{cases} d_1^2 = (x_1 - x)^2 + (y_1 - y)^2 + (z_1 - z)^2 \\ d_2^2 = (x_2 - x)^2 + (y_2 - y)^2 + (z_2 - z)^2 \\ \vdots \\ d_n^2 = (x_n - x)^2 + (y_n - y)^2 + (z_n - z)^2 \end{cases} \quad (3)$$

where $x_n, y_n, z_n,\ (n = 1, 2, \ldots, N)$ are the positions of the of transmitters as shown in Fig. 2 (b). The receiver's position (x, y, z) can be calculated using linear equation as follows [5]

$$\mathbf{AX} = \mathbf{b} \quad (4)$$

where

$$\mathbf{A} = \begin{bmatrix} x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\ x_3 - x_1 & y_3 - y_2 & z_3 - z_1 \\ & \vdots & \\ x_n - x_1 & y_n - y_1 & z_n - z_1 \end{bmatrix}, \quad \mathbf{X} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Width × Length × Height	25m × 15m × 8m
Transmitter's Power - P_t	115 W
Number of transmitters	15
Transmitter separation	5 m
Transmitter's Beam Angle (half)	45°
Photodetector Area - A_r	1 cm^2
Receiver's FOV (half angle) - θ_r	75°- 80°- 85°

$$\mathbf{b} = \frac{1}{2}\begin{bmatrix} (d_1^2 - d_2^2) + (x_2^2 + y_2^2 + z_2^2) - (x_1^2 + y_1^2 + z_1^2) \\ (d_1^2 - d_3^2) + (x_3^2 + y_3^2 + z_3^2) - (x_1^2 + y_1^2 + z_1^2) \\ \vdots \\ (d_1^2 - d_n^2) + (x_n^2 + y_n^2 + z_n^2) - (x_1^2 + y_1^2 + z_1^2) \end{bmatrix}$$

where **A** is described as the coordinates of transmitters, **b** is represented by the distances to the transmitters together with the coordinates, and **X** is the estimated location of the receiver. Thus, the estimated location of the receiver is solved by using the linear least square method given by:

$$\mathbf{X} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T \mathrm{b} \quad (5)$$

where $()^T$ is the transpose operation.

With these equations, it is possible to calculate the position of a receiver with respect to known transmitter coordinates.

III. RESULTS AND DISCUSSION

The performance of the proposed algorithm is evaluated for a warehouse with a storage rack area (see Fig. 1). Osram's 2nd generation Compact High Bay light fixtures with a semi-angle of 45° and optical power of 115 watts are selected here as they are intended for high-bay applications. Illumination simulation using DIALux software demonstrates an average illumination of 282 lx at a working plane of 0.8 meters as shown in Fig. 3 which is higher than the European standards of a minimum of 200 lx for visual tasks [6].

As discussed in Section II, the 3-D localization requires signals from 4 spatially distributed transmitter. The loss of a signal from one or more the transmitters due to the signal being outside the FOV is a risk that can happen for mobile receivers. This occurs here when the drone flies closer to the light fixtures or an area outside the light's beam angle. In order to establish a relationship between the coverage area/dead-zone and FOV, the simulation was performed in an industrial environment with the dimensions given in Table I.

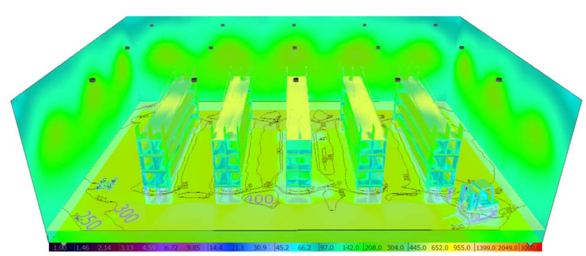

Fig. 3. Illumination levels obtained using DIALux.

Fig. 4 shows 3-D coverage area/dead-zone for a drone with receiver FOV of 75°, 80° and 85°. Note that the white area is the coverage area and the dark area is the dead-zone. The dead-zone occurs due to the unavailability of the signals from a second, third, and fourth transmitter LEDs. As can be seen in the figure, there is full room coverage up to a certain height. For a receiver with FOV of 75°, 80° and 85° the maximum heights the drone can fly are 5.2 m, 6.2 m and 7.1 m, respectively. Above these heights, the dead-zones start appearing at the corners of the room. The drone can reach a maximum height of 7.1 m, 7.4 m and 7.7 m for the FOVs of 75°, 80° and 85°, respectively, in most parts of the room except at the corners and the edges. The results of the coverage simulation are summarized in Table II. The results clearly indicate the impact of small changes in the FOV and the range of the drone. To enable a drone to function in these problematic areas, the positioning algorithm can be used with a sensor such as an altimeter or a gyroscope. Alternatively, an FOV of 90° can be used such as the one researched in [7].

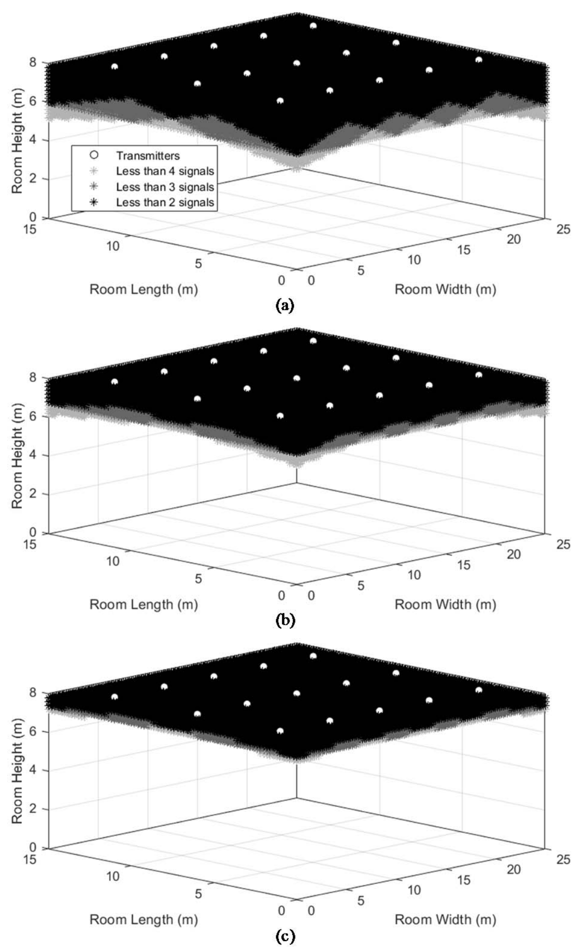

Fig. 4. Dead-zones for a flying receiver: a) for a receiver FOV = 75°, b) for a receiver with FOV = 80°, and c) for a receiver with FOV = 85°.

TABLE II
THE MAXIMUM HEIGHT A DRONE CAN REACH

No. of Txs \ FOV		75°	80°	85°
Less than 4	Corners (m)	5.2	6.2	7.1
	Edges (m)	6.0	6.7	7.4
	Between (m)	7.1	7.4	7.7
Less than 3	Corners (m)	5.9	6.7	7.4
	Edges (m)	6.5	7	7.6
	Between (m)	7.1	7.4	7.7
Less than 2	Corners (m)	5.9	6.7	7.4
	Edges (m)	7.1	7.4	7.7
	Between (m)	7.4	7.6	7.8

IV. CONCLUSION

In this paper, coverage area and dead-zone area for a drone in an industrial environment is studied using VLP. An illumination simulation was performed to verify that the environment meets the levels specified by European standards. Dead-zones for positioning algorithms that require the use of two, three, and four transmitters has been simulated for a receiver with different angles. The results demonstrated that the maximum height a drone can reach with an FOV of 85° for VLP systems that requires three and four transmitters is 7.7 m, and 7.8 m when requiring two transmitters. The simulations aimed to demonstrate the limitations that flying objects such as drones might encounter based on the receiver's FOV. As mentioned before, this limitation is not exclusive to trilateration methods, as positioning algorithms generally require a certain number of signals to estimate the position. Future work includes experimental work and evaluating dead-zones with reflections.

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