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Angle of light arrival estimation for non-line-of-sight optical camera communications

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Abstract– Optical camera communication (OCC) has been considered as an alternate solution to spectrum congested radio frequency (RF) based short-range wireless communications. OCC depends largely on the line of sight (LOS) path in which the angle of arrival (AOA) plays an important role. This paper presents a new formula for the AOA that can be useful to design an efficient non-line-of-sight OCC. Unlike the conventional formula having double dependency of distance and displacement, the proposed formula is contingent upon the received illuminance only. To verify the proposed formula, the AOAs for three different light paths are measured on a reference surface located near to the receiver. It is found that the measured AOAs from the proposed formula show good agreement with the conventional formula.

1. Introduction

The rapid increase of wireless users and their demand for wide bandwidth has caused radio frequency (RF) communication to face a problem of spectrum congestion. The spectrum congestion has become a serious issue in present wireless communications. To overcome the spectrum congestion in existing RF bands, visible light communication (VLC) has become a useful alternative [1].

For the past decade, the VLC, which is based on a light emitting diode (LED) as the transmitter, has been one of the interesting alternative solutions for the spectrum problem. A high switching rate of LED, which is less than few nanoseconds, is significantly higher than a critical flicker frequency, thus allowing data transmission to be supported [2]. In addition, the VLC offers built-in security because the light does not pass through walls, thus keeping the VLC data confined in a pre-defined coverage area [3]. However, the VLC has some unavoidable disadvantages such as short communication distance and the significant drop in signal strength for non-line-of-sight (NLOS) configurations.

Optical camera communication (OCC) is a variant of the VLC. The camera is used as the receiver in OCC. The OCC has attracted much interest in academia as well as industry [4]. Similar to the VLC, signal transmission in the OCC depends on LOS path. Therefore, it is essential to combat NLOS conditions to recover the transmitted signal. In this view, an analysis of light angle, which is AOA, plays an important role in OCC for effective signal transmission from the LED transmitter to the camera receiver. The analysis of AOA for static transmitter-receiver configuration is relatively simple, since the displacement between the transmitter and the receiver is fixed. However, this analysis of AOA becomes more challenging, when both the transmitter and receiver are dynamic as the direction of incident light and the distance between the transmitter and the receiver vary continuously. To overcome this problem, a novel formula for the AOA calculation is proposed in this paper. Unlike the conventional formula, this formula is independent of both the displacement and the distance between the transmitter and receiver. In this paper, a reference surface has been considered at the receiver end for the ease of the AOA calculation. The in-depth calculation is based on the received illuminance on the reference surface, while the transmitter and receiver are in a dynamic mode. Simulations are conducted to verify the proposed AOA. Section 2 presents the proposed formula, while Section 3 shows simulation results and discussions. Section 4 draws conclusions.

2. Reference Surface Based AOA

In a practical scenario where both the transmitter and the receiver are moving, it becomes challenging to measure the AOA of light from the LED transmitter in an OCC link. We propose a formula to analyze the AOA on a reference surface located near the receiver.

2.1. Proposed Model

In the proposed model, an LED is used as the transmitter and a camera as the receiver. Figure 1 shows a static model for the calculation of AOA. θ denotes an AOA of a light, d_1 denotes the distance between the LED source and the reference surface, and r_1 is the displacement of light from the LED axis. Figure 2 represents a dynamic model where the transmitter has moved. d_2 denotes a distance, which could be either longer or shorter than d_1. The displacement is represented by r_2 that could be either longer or shorter than r_1. Due to the movement of the transmitter, the distance of light displacement (r_1 and r_2) changes.

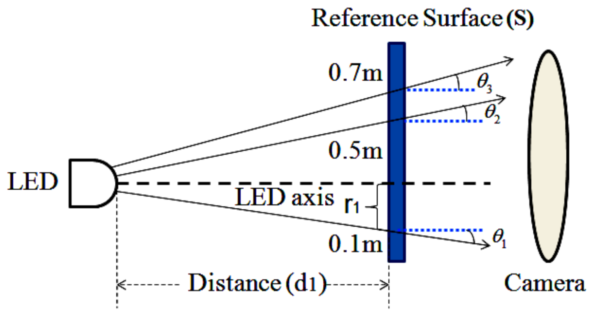

Figure 1. Static model for LED and camera

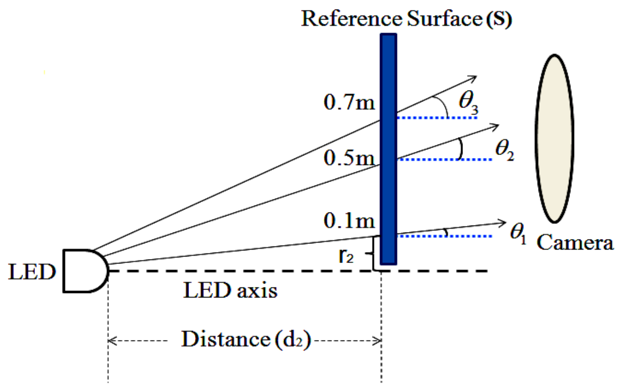

Figure 2. Dynamic model for moved LED and camera

Figures 1 and 2 depict two possible positions of the transmitter due to its movement. Received illuminance is measured at three different positions on the reference surface.

2.2. Calculation of AOA

For the calculation of AOA, the values of θ (θ_1, θ_2, and θ_3) are considered. We first consider the solid angle for light and derive an expression for AOA.

2.2.1. Solid Angle for Light

According to the geometrical concept, a solid angle (dΩ) can be defined as a two dimensional angle in the three dimensional space on a surface. Figure 3 shows the solid angle [5].

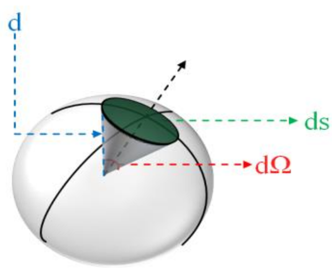

Figure 3. Solid angle

$$d\Omega = \frac{ds}{d^2} \tag{1}$$

ds represents an elementary surface where the light path intersects and d denotes the distance.

In this paper, the following parameters were considered. I(θ, r) denotes the intensity of an LED, while the I(θ, r) value at θ = 0 and r = 0 denotes the intensity of an LED at the source. Then, ψ(θ, r) denotes the flux of the LED and L(θ, r) as the illuminance.

2.2.2. Transmitter and Receiver on Horizontal Axis

The elementary flux received by the solid angle is given by [5].

$$[d\psi(\theta,r)]_{\theta=0,r=0} = [I(\theta,r)]_{\theta=0,r=0} \times d\Omega$$

$$[d\psi(\theta,r)]_{\theta=0,r=0} = \left[I(\theta,r)_{\theta=0,r=0}\right] \times \frac{ds}{d^2} \tag{2}$$

Therefore, the received illuminance through the solid angle can be expressed by

$$[L(\theta,r)]_{\theta=0,r=0} = \frac{\left[[d\psi(\theta,r)]_{\theta=0,r=0}\right]}{ds}$$

$$= \left[[I(\theta,r)]_{\theta=0,r=0}\right] \times \frac{ds}{d^2} \times \frac{1}{ds}$$

$$[L(\theta,r)]_{\theta=0,r=0} = \frac{[I(\theta,r)]_{\theta=0,r=0}}{d^2} \tag{3}$$

To simplify the notation, for the I(θ, r) value at θ = 0 and r = 0, the intensity of the LED transmitter is denoted by I(0). That is,

$$[I(\theta,r)]_{\theta=0,r=0} = I(0,0) = I(0) \tag{4}$$

2.2.3. Moving Transmitter

The calculation for L(θ, r) is extended to accommodate a new position on the surface. Figure 4 depicts the two possible positions, A and B, falling on the reference surface. These new positions are in *r* displacement distance either above the LED axis or below the LED axis and create an angle of θ with the LED axis [5]. This change in θ occurs when the transmitter-receiver configuration is moving. Because of this movement, the incident position of the light on the reference surface is changed either above or below the LED axis. This dynamic situation is shown in Fig. 4.

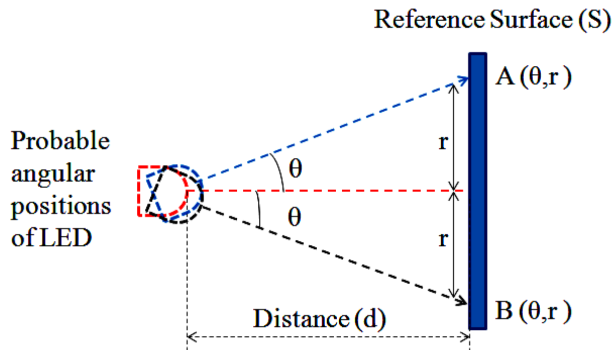

Figure 4. Light arriving on the reference surface.

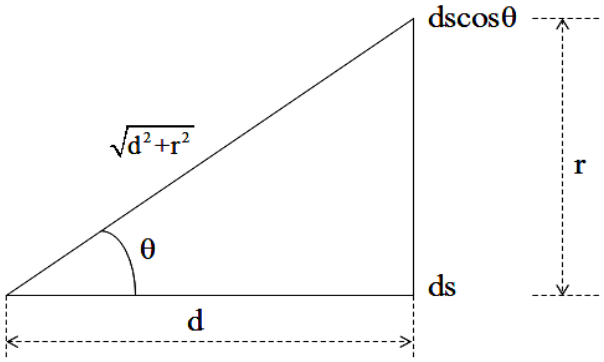

Figure 5. Path of light arriving to the reference surface with displacement r.

The solid angle at the new position is given by [6]

$$d\Omega = \frac{ds\cos\theta}{\left(\sqrt{d^2+r^2}\right)^2} = \frac{ds\cos\theta}{d^2+r^2} \qquad (5)$$

Then, the received flux is given by

$$d\Psi(\theta, r) = I(\theta, r) \times d\Omega$$

$$= I(\theta, r)\cos\theta \times \frac{ds}{d^2+r^2} \qquad (6)$$

By using the Lambert's cosine law, it is evident that if the source intensity is I(0), then the intensity at any point at an angle of θ to the source will be equal to I(0)cosθ. Thus, the flux can be rewritten as

$$d\Psi(\theta, r) = I(0,0)\cos\theta \times \cos\theta \times \frac{ds}{d^2+r^2}$$

$$= I(0)\cos^2\theta \times \frac{ds}{d^2+r^2} \qquad (7)$$

Then, the illuminance at the point, which is at θ angle to the source, can be measured as [7]

$$L(\theta, r) = \frac{d\Psi(\theta, r)}{ds} = I(0) \times \cos^2\theta \times \frac{ds}{d^2+r^2} \times \frac{1}{ds}$$

$$L(\theta, r) = \frac{I(0) \times \cos^2\theta}{d^2+r^2} \qquad (8)$$

Eq. (8) provides the illuminance at θ angle to the source, but this expression depends on the values of distance and displacement. Therefore, for the calculation of θ, when the transmitter-receiver path is not on the same axis, it is necessary to modify it by eliminating the unknown parameters, i.e., distance (d) and displacement (r).

2.2.4. Estimation of AOA

Using the geometrical concept depicted in Fig. 5, it can be said that

$$\cos\theta = \frac{d}{\sqrt{d^2+r^2}} \qquad (9)$$

Eq. (8) can then be modified to

$$L(\theta, r) = I(0) \times \cos^2\theta \times \frac{1}{d^2+r^2} \times \frac{d^2}{d^2} \qquad (10)$$

By rearranging this, L can be obtained as

$$L(\theta, r) = \frac{I(0)}{d^2} \times \cos^2\theta \times \frac{d^2}{d^2+r^2}$$

$$= L(0,0) \times \cos^2\theta \times \cos^2\theta \qquad (11)$$

That is, the AOA is given by

$$\theta = \cos^{-1}\left[\frac{L(\theta, r)}{L(0)}\right]^{\frac{1}{4}} \qquad (12)$$

In other words, the AOA is described as

$$\theta = \cos^{-1}\left[\frac{\text{Illumination received at the desired location}}{\text{source illumination at a distance d}}\right]^{\frac{1}{4}}$$

3. Results and Discussion

Parameters used for simulations are provided in Table 1.

Table 1. Simulation parameters.

Intensity (W/m^2)	Distance (meter)	Displacement (meter)
24	1	1

The simulations were first performed to compare the results obtained from the reference formula (Eq.(8)) and the proposed formula (Eq. (12)). Table 2 shows a comparison between reference formula and proposed formula in terms of the measured illuminance. r_1 denotes the displacement of light path due to the change in angle, when using reference formula and L_1 is the measured illuminance. Displacement (r_2) of light path is due to the change in angle, when using the proposed formula and L_2 is the measured illuminance.

It is shown that reference formula provides the measured illuminances of 6.0000 lx, 6.1212 lx, and 6.2448 lx at three different positions, respectively. These measured values are almost similar to those values obtained from the proposed formula. Hence, the proposed formula (Eq. (12)) shows good agreement with the conventional formula.

Table 2. Comparison for verification.

Reference formula(Eq.(8))		**Proposed formula(Eq.(12))**	
$\lvert r_1 \rvert$ (m)	**L1 (lx)**	**$\lvert r_2 \rvert$ (m)**	**L2 (lx)**
1	6.0000	1.0000	6.000
0.9900	6.1212	0.9900	6.1212
0.9800	6.2448	0.9801	6.2437

Table 3 shows the measured AOAs at different positions on the reference surface. The measured AOAs from the conventional formula are found to be 6.2515°, 26.6565°, and 35.0469° at 0.1m, 0.5m, and 0.7m positions, respectively. The measured AOAs from the proposed formula are 5.7106°, 26.5651°, and 34.9920° at 0.1m, 0.5m, and 0.7m positions, respectively. Therefore, the two formulas yield nearly identical estimation of the AOAs.

Table 3. Measured AOA at different positions on reference surface.

Positions on the reference surface (m)	Estimated AOAs	
	Conventional (degree)	Proposed (degree)
0.1	$\theta_1 = 6.2515$	$\theta_1 = 5.7106$
0.5	$\theta_2 = 26.6565$	$\theta_2 = 26.5651$
0.7	$\theta_3 = 35.0469$	$\theta_3 = 34.9920$

4. Conclusion

A new AOA formula has been proposed, based on the fundamental concept of light. The proposed AOA is a function of the illuminance received on the reference surface, given the LED illuminance. As opposed to the conventional AOA estimation, the proposed formula offers a convenient and less complex solution to the estimation of AOA in an OCC environment. In addition, the proposed formula has the benefit of measuring the AOAs in a moving transmitter condition. Simulation results show that the proposed estimation is accurate and in good agreement with the conventional estimation. Therefore, the proposed formula can be useful to effectively adjust the received light intensity, while reducing or eliminating light noise present in a non-line-of-sight OCC environment.

Acknowledgments

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