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Feasibility Study of Reverse Trilateration Strategy with a single Tx for VLP

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Abstract— This paper describes a visible light position system relying on a single transmitter to infer position information. The system adopts a reverse trilateration scheme, where a set of three photodiodes is employed to estimate the position. The reverse trilateration scheme adopted for this system, yields to a very simple mathematical framework, suitable for low power and low complexity systems. The position information is inferred through Rx signal strength, without the need for sophisticated angle measurements or precise synchronization as is the case in angle of arrival and time difference of arrival systems. Simulation results show that the proposed system shows high susceptibility to noise, thus requiring high signal to noise ratios in order to achieve low positioning errors.

Keywords—Visible light positioning, Photodiode, RSS, Reverse Trilateration.

I INTRODUCTION

The global positioning system (GPS) is an unquestionable reference when discussing positioning systems, which is widely and effectively used in outdoor environments. However, it lacks accuracy in indoor environments, mostly due to poor coverage and high signal attenuation of the radio waves propagating through solid objects. Thus, the need for a more reliable and accurate positioning technologies for indoor applications, which has seen a grown of research activity in recent years [1], [2]. Several positioning systems based on different technologies have been proposed, such as, wireless local area networks (WLAN), ultrasounds, ultra wide band (UWB), radio frequency identification (RFID) and Bluetooth. However, most of these systems have limited positioning accuracies [3-8]. System based on radio waves are affected by multipath fading [9], whereas ultrasound based systems are influenced by the ambient temperature [10]. UWB and RFID schemes have a limited range of action [11]. Finally, Bluetooth demands user association, a feature which is not always desirable [12].

Recently, visible light communications (VLC) has become an interesting and complementary communications technology to the radio frequency wireless systems [13]. Motivated by the availability of solid-state lighting devices, VLC systems explore synergies between illumination and data communications, using the same light emitting diode (LED) based lights. Visible light positioning (VLP), has emerged quite obviously as a special application of VLC, which is more suited for indoor scenarios. Given that, lighting systems come with a spatial distribution feature, using these sources as beacons (or base-stations) for positioning provides a fertile ground for research. Traditional indoor positioning techniques

using LED includes, received signal strength (RSS), angle of arrival (AOA), time of arrival (TOA) and time difference of arrival (TDOA), as well as proximity and fingerprinting [14]. TOA is a well-known method for localization, which is complex requiring accurate synchronization between the transmitter (Tx) and the receiver (Rx) [15]. In TDOA systems the requirement for synchronization is not so stringent as for TOA, but still requires an accurate clock reference at the Tx side. AOA systems require Rx diversity in order to extract the angle information [16]. Image based systems use image sensors as a means to achieve the Rx diversity [17]. RSS systems estimate the position based on the received signal power, thus being sensitive to the noise. Nevertheless, RSS systems have higher accuracy compared to proximity and fingerprinting techniques [18], as well as being simpler and cost-effective.

One common requirement for these methods is the need to have measurements based on 3 different sources, which is a mathematical imposition, where each measurement produces a locus of possible positions. Note that, the ambiguity is removed using other measurements. Therefore, considering these constraints, a minimal set up could be achieved using a single photosensitive sensor (e.g., a photodiode (PD)), and at least three reference Tx's. There have been several contributions exploring minimal configurations, which are based on different set of configurations, or combination of multiple schemes. In [19], the authors described a VLP system using two LEDs. The proposed approach carried out two RSS measurements, which were sufficient to estimate the position to the right (or left) of the line defined by the Tx's. The system achieved a positioning accuracy lower 20 cm under moderate SNR of 13 dB, despite having lower system complexity. In [20], a three dimensional (3D) indoor VLP system was proposed based on single Tx and a single tilted Rx as well as using RSS and AOA to improve positioning accuracy. The tilted Rx was mounted on a spinning platform, and the 3D space representation was distributed into several two-dimensional (2D) planes, which were handled by lifting the Rx's platform. The proposed VLP system offered an average position error (PE) of < 35mm. In [21], a compact VLP system with a single Tx and single tilted Rx was proposed for an indoor environment of 0.6×0.6×1.1 m with an average PE of < 25 mm. In [22], a reverse trilateration scheme employing three Rx's in the ceiling and one Tx in the ground was reported with a PE of < 0.2 m. The proposed system was relevant for applications where the network needs to know the position of the user.

This paper focuses on the reverse trilateration scheme where the position sensor uses three PDs and relies on a single

Fig. 1. Reverse trilateration concept

Tx to determine the location. The system employs RSS, which makes this approach suitable for low power and low complexity applications. The paper shows theoretical analysis supported by simulation to investigate the system performance. We show that, the system's performance is highly influenced by noise. We show also, that, performance improvements can be achieved using averaging techniques.

The rest of the paper is organized as follows: Section II details the system design and modeling. Section III develops the system error performance analysis. Section IV presents the simulation set up and the achieved results. Finally section V gives the concluding remarks.

II SYSTEM DESIGN AND MODELING

The schematic of the proposed reversed trilateration strategy is illustrated in Fig. 1. The VLP sensor comprises 3 PDs positioned on a circle of radius R_s . The projection of the distances between each PDs and the Tx are given by r_k , where $k = 1, 2$ and 3 . Using r_k it is possible to form a well posed system of two equations for the center position of the sensor. These three distances provide the radius of three circles, centered at each PD, with common intercept at the Tx's position.

Let the positions of k^{th} PD be $\mathbf{X}_k^o = (x_k^o, y_k^o)^T$ with $\mathbf{X}_1^o = (-R_s, 0)^T$, $\mathbf{X}_2^o = (R_s/2, R_s\sqrt{3}/2)^T$ and $\mathbf{X}_3^o = (R_s/2, -R_s\sqrt{3}/2)^T$. The Tx projection on the x - y plane is $\mathbf{X}_T = (x_T, y_T)^T$. The position of the VLP sensor in the x - y plane as a function of an arbitrary translation $\mathbf{X} = (x, y)^T$ and an arbitrary rotation $\mathbf{R}(\theta)$ is given by:

$$\mathbf{X}_k = \mathbf{X} + \mathbf{R}(\theta)\mathbf{X}_k^o \quad (1)$$

The translation vector $\mathbf{X}$ is the center position of the sensor and the objective of the estimation procedure. r_k defines a circle with the center $\mathbf{X}$ and passing through $\mathbf{X}_T$, which form a set of three quadratic equations in standard form as given by:

$$(\mathbf{X}_T - \mathbf{X}_k)^T(\mathbf{X}_T - \mathbf{X}_k) = r_k^2 \quad (2)$$

Note r_k is estimated using RSS. Developing equation (2) gives:

$$\mathbf{X}_T^T \mathbf{X}_T + R_s^2 + \mathbf{X}^T \mathbf{X} - 2(\mathbf{X}_k^o)^T \mathbf{R}(\theta)^T (\mathbf{X}_T - \mathbf{X}) = r_k^2 \quad (3)$$

From (1) and (2) we know that $(\mathbf{X}_k^o)^T \mathbf{X}_k^o = R_s^2$ and $\mathbf{R}^{-1}(\theta) = \mathbf{R}^T(\theta)$. The quadratic terms on the left hand-side of (3) can be removed by subtraction, thus yielding a system of two linear equations, which in the matrix form is given by:

$$-2R_s \mathbf{A}_s \mathbf{R}(\theta)^T (\mathbf{X}_T - \mathbf{X}) = \Delta \mathbf{r} \quad (4)$$

with

Fig. 2. System model of a single LED-based Tx and the Rx sensor with three PDs

$$\mathbf{A}_s = \frac{1}{R_s} \begin{bmatrix} (\mathbf{X}_2^o)^T - (\mathbf{X}_1^o)^T \\ (\mathbf{X}_3^o)^T - (\mathbf{X}_2^o)^T \end{bmatrix} = \frac{1}{R_s} \begin{bmatrix} 3/2 & \sqrt{3}/2 \\ 0 & -\sqrt{3} \end{bmatrix} \quad (5)$$

$$\Delta \mathbf{r} = \begin{bmatrix} r_2^2 - r_1^2 \\ r_3^2 - r_2^2 \end{bmatrix} \quad (6)$$

The estimated position is directly given by:

$$\mathbf{X} = \mathbf{X}_T + \frac{1}{2R_s} \mathbf{R}(\theta) \mathbf{A}_s^{-1} \Delta \mathbf{r} \quad (7)$$

Equation (7) exhibits some interesting features. (i) most terms in (7) are fixed vectors and matrix except from $\Delta \mathbf{r}$ and $\mathbf{R}(\theta)$. The sensor matrix $\mathbf{A}_s$, is fixed by the standard PD's positions, see Fig. 1. The arbitrary rotation of the sensor can be dealt with using a compass or a gyroscope. Here, we assume that $\theta = 0^\circ$ (i.e., no rotation). Furthermore, as it will be demonstrated, the error performance is not affected by the sensor's rotation.

A The Rx Signal Strength

Figure 2 depicts the set up conditions for signal transmission, between the Tx and the k^{th} Rx. The objective of RSS is to measure r_k , i.e., the projection of the distance vector $\mathbf{d}_k$ on the x - y plane. These estimations are based on the DC channel gain of the communications link. The received signal for Lambertian emitter for a line of sight (LoS) path is given by:

$$S_k = H_o T_s(\varphi_k) g(\varphi_k) \frac{\cos^m(\psi_k) \cos(\varphi_k)}{\|\mathbf{d}_k\|^2} \quad (8)$$

where

$$H_o = \frac{m+1}{2\pi} G_o \mathcal{R} A_r P_t \quad (9)$$

$$m = -\frac{\ln(2)}{\ln(\cos(\text{HPA}))} \quad (10)$$

where HPA is the half power angle for the light source, ψ_k is the angle between $\mathbf{d}_k$ and the LED normal, φ_k is the angle between $\mathbf{d}_k$ and the PD normal, A_r is the PD active area, G_o is the transimpedance gain of the Rx, $\mathcal{R}$ is the PD responsivity and P_t is the transmit power. $T_s(\varphi_k)$ is the Rx filter and $g(\varphi_k)$ is the optical concentrator [23]. For the forgoing analysis, we will assume that, $T_s(\varphi_k)$ and $g(\varphi_k)$ are both unity. Knowing that $\|\mathbf{d}_k\|^2 = r_k^2 + h^2$ we can solve (8) to find r_k^2 as given by:

Fig. 3. The distance error geometrical factor G_s for two different HPA values.

$$r_k^2 = \left(\frac{H_o h^{m+1}}{S_k} \right)^{\frac{2}{m+3}} - h^2 \quad (11)$$

where h is the vertical distance between the Tx and the Rx. Using (11), the $\Delta \mathbf{r}$ vector can be expressed as a function of the received signals on the 3 PDs by:

$$\Delta \mathbf{r} = (H_o h^{m+1})^{\frac{2}{m+3}} \Delta \mathbf{S} \quad (12)$$

$$\Delta \mathbf{S} = \begin{bmatrix} S_2^{-\frac{2}{m+3}} - S_1^{-\frac{2}{m+3}} \\ S_3^{-\frac{2}{m+3}} - S_2^{-\frac{2}{m+3}} \end{bmatrix} \quad (13)$$

III ERROR PERFORMANCE ANALYSIS

The error performance analysis can be assessed using (7). The reasoning is very simple. If the detected signal is affected by noise, the measured signal power will contain errors, which are defined by small changes in $\Delta \mathbf{r}$, i.e., $\Delta \mathbf{r} \rightarrow \Delta \mathbf{r} + \delta \mathbf{r}$. Using (7) we have $\Delta \mathbf{X} \rightarrow \Delta \mathbf{X} + \delta \mathbf{X}$, where $\delta \mathbf{X}$ is the coordinate displacement due to $\delta \mathbf{r}$, which is given by:

$$\delta \mathbf{X} = \frac{1}{2R_s} \mathbf{R}(\theta) \mathbf{A}_s^{-1} \delta \mathbf{r} \quad (14)$$

We may transform this into a distance error, as given by:

$$\delta X = \sqrt{\delta \mathbf{X}^T \delta \mathbf{X}} = \frac{1}{2R_s} \sqrt{\delta \mathbf{r}^T \mathbf{A}_s \delta \mathbf{r}} \quad (15)$$

where $\mathbf{A}_s = (\mathbf{A}_s^{-1})^T \mathbf{A}_s^{-1}$. Equation (15) shows that, the distance error does not depend explicitly on the sensor's rotation.

A The Effect of Noise on $\delta \mathbf{X}$

Noise can be incorporated into the error model in a very simple way. The effect of noise on the detected signal, by the k^{th} PD is expressed by $S_k \rightarrow S_k + n_k$, where n_k is the additive white Gaussian noise. Using the signal to noise ratio (SNR), γ , we find a simple transformation rule, which states $S_k \rightarrow S_k(1 + 1/\sqrt{\gamma})$. Now, using (12) and (13), and re-working (15) we have:

Table.1 Default value of the system's parameters.

Tx-Rx parameter		
A_r	100 mm ²	Area of the PD
$\mathcal{R}$	1 A/W	Responsivity
P_t	1 W	Transmit power
G_o	1 M Ω	Rx's gain
HPA	60°	Half power angle
Geometrical Parameter		
dx	0.5 m	x grid resolution
dy	0.5 m	y grid resolution
$\mathbf{n}_t$	(0, 0, -1) ^T	TX heading vector
$\mathbf{n}_r$	(0, 0, 1) ^T	RX heading vector
$\mathbf{X}_T$	(0, 0, $h + h_r$) ^T	TX position
R_s	0.1 m	Sensor radius
h	2.2 m	Ceiling height
h_r	0.2 m	Sensor height
θ	0°	Sensor rotation angle

$$\delta X = G_s \frac{(H_o h^{m+1})^{\frac{2}{m+3}}}{2R_s} \left(\left(1 + \frac{1}{\sqrt{\gamma}} \right)^{-\frac{2}{m+3}} - 1 \right) \quad (16)$$

where $G_s = (\Delta \mathbf{S}^T \Delta \mathbf{S})^{1/2}$. Equation (16) exhibits the distance error dependency on all the system's parameters. It is noticeable that, the geometrical factor G_s depends on the sensor geometry (i.e., via $\mathbf{A}_s$) and the detected signal power. Figure 3 depicts G_s for two different values of HPA (i.e., 60° and 30°), in a room of size 10×10×2.4 m³, with one Tx positioned in the center. As it can be seen, G_s has a circular symmetry, showing that the distance error is indeed independent of sensor's rotation.

IV SIMULATION RESULTS

This section outlines the system set-up conditions and present the simulation results. The simulation set-up default parameter' values are given in Table 1.

A General Error Performance Assessment

The effect of noise on the estimated position can be assessed through simulation, using Matlab. This is accomplished by adopting the following steps: (i) simulating the signal reception for a grid of possible Rx's positions; (ii) using (11) to calculate r_k for each PD; (iii) estimate the position using (7); and (iv) finally, calculate the PE as the difference between the estimated and real positions. This procedure is repeated for different SNR values.

Figures 4 and 5, depicted the PE spatial distributions in a room of 10×10×2.4 m³, for SNRs of 50 and 60 dB, respectively. The unusually high SNR values are a clear indication of the susceptibility of the sensor to noise. RSS relies on detected signal power, as sensor PDs are closer together, where the received signal power by the three PDs do not change much. Noise effects become of paramount importance under these circumstances. As it can be seen from Figs. 4 and 5, the error increases as we move to the periphery of the room, which is in agreement with the geometrical error dependence embedded in G_s , see Fig. 3.

Statistically speaking, it is not very relevant to compare performance in terms of extreme error achievements, since the error changes randomly for different simulations. In addition,

 Fig. 4. The positioning error spatial distribution with $SNR=50$ dB.

 Fig. 5. The positioning error spatial distribution with $SNR=60$ dB.

the average errors are not good performance indicators, as both high and low measured errors are taken into consideration with the equal weight. Instead, we propose a different error measure, which is more aligned with the probability theory. This measure, computes the percentage of estimates that fall below a certain distance criterion. In a total of N estimates, let $\#(e_{rr} < \varepsilon)$ represent the number of estimates with the positioning error below ε , the PE is defined by:

$$e_{rr}(\varepsilon) = \frac{\#(e_{rr} < \varepsilon)}{N} \quad (17)$$

It is readily apparent that, as N tends towards infinity, $e_{rr}(\varepsilon)$ tends to the probability of having error estimates below ε . In Figs. 4 and 5, the achieved indicators for $\varepsilon=10$ cm, were, 31.5% and 79.1% for 50 and 60 dB, respectively.

B Error Performance R_s Dependency

Figures 6 and 7 depict the PE dependency on SNR and R_s . As before $\varepsilon=10$ cm. Fig. 6, depicts the percentage of estimates with the error below 10 cm, for different values of R_s (5, 7.5 and 10 cm) for variable SNR values (20 to 70 dB). The simulation considered a room size of $10 \times 10 \times 2.4$ m³ with a grid resolution of 5 cm (corresponding to $N = 40401$ position estimates). As it can be seen, the number of estimates with the error below 10 cm tends to increase with SNR, which is in agreement with (16). Lower values of R_s require higher SNRs

 Fig. 6. The positioning error performance as function of SNR, for fixed values of R_s .

 Fig. 7. The positioning error performance as function of R_s , for fixed values of SNR.

to achieve the same performance. Equation (16) seems to suggest that, the error is monotonic with R_s - higher R_s values mean less error. In order to further explore the error dependency on R_s , we repeated the simulation for fixed values of SNR (50, 60 and 70 dB) and for range of R_s (i.e., 1 to 20 cm, as shown in Fig. 7. For each SNR value error performance increases monotonically with R_s . This behavior can be understood by recalling that Δ_s depends on the norm of the distance vectors $\mathbf{d}_k$. Since the PDs positions are function of R_s , $\mathbf{d}_k$ depends on R_s as well.

C Error Performance HPA Dependency

Figures 8 and 9 depicts the PE dependency on both SNR and HPA. For this study, we followed a similar approach as described in section IV-B. Figure 8 depicts the percentage of errors below 10 cm, for fixed values of HPA (45° , 30° and 15°) and a range of SNR. Here too, the PE increases with the SNR and decreasing values of HPA. Note, lower HPA, means transmitting sources with higher directivity and thus higher values for m , which translate to less geometrical dependence - G_s becomes flatter. Figure 9 shows the PE as a function of HPA for range of SNRs. Here we see that, the PE reduces with increasing values of HPA as predicted from G_s .

Fig. 8. The positioning error performance as function of SNR, for fixed values of HPA.

Fig. 9. The positioning error performance as function of HPA, for fixed values of SNR.

D Error Performance using Averaging Techniques

Figure 10 depicts the averaging effect on the PE, which shows the error below 10 cm for fixed values of SNR of 30, 40 and 50 dB as function of the number of averaging steps. It can be seen from Fig. 10 that, the error performance increases with the number of averaging steps and SNR. Therefore, it is possible to use averaging to improve PE.

V CONCLUSIONS

This paper presented a feasibility study on the usage of reverse trilateration for position estimation, based on RSS. The system under study, comprised a single Tx and three PDs based Rx. Simulation results disclosed that, the system is very susceptible to the noise, demanding very high SNR in order to achieve low positioning error performance. As a standalone system, the proposed scheme is not feasible. However, considering that RSS can be supported with averaging techniques (such as spread spectrum) able to improve SNR, the proposed system can represent a possible choice for low power and low complexity VLP positioning sensors. System performance analysis disclosed some important results, which could be of interest for other applications, namely: (i) the simple estimation equations can be of use to study and optimize transmitter placement in conventional trilateration schemes; and (ii) performance based on the probability of

Fig. 10 – Averaging effect on the error performance for a range of SNRs.

error being lower than some predefined value can be taken as a standard approach for performance analysis in VLP systems.

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