Azimuth Estimation for Indoor Localization Using Redundant Planar Circular Photodiode Array

Gergely Zachár[1], Gergely Vakulya[1], and Gyula Simon[1]

[1] Pázmány Péter Catholic University, Budapest, Hungary
simon.gyula@ppke.hu

Abstract. A novel sensor architecture, called Planar Circular Photodiode Array (PCPA) is proposed to provide azimuth measurements for indoor localization systems. The transmitters are blinking LEDs, where the unique blinking frequency identifies the transmitters. The inexpensive sensor device contains a circular photodiode (PD)-array, where each PD measures the intensity of each transmitter. The directions of the transmitters are determined by a Least Squares method, using the reference sensitivities of the sensors. The paper provides simulation analysis to determine the achievable angle measurement accuracy, and as illustrations, the corresponding localization accuracy for some setups. Real physical measurements are also provided, showing potential accuracy below 1 degree.

Keywords: Azimuth Estimation, Angle of Arrival, Position Estimation, Photodiode Array.

1 Introduction

Angle of Arrival (AoA) and Angle Difference of Arrival (ADoA) localization schemes were proven successful in various localization systems. For such solutions bearing measurements of either the target or the deployed beacons are necessary. In the first case the target emits a signal and multiple receivers, deployed in known locations, measure the direction of the signal source (e.g. [1], [2]). In the second case multiple deployed beacons in known locations emit signals and the receiver on the target measures the directions of the beacons (e.g. [3]-[7]). In both cases some kind of triangulation provides the target location.

In AoA/ADoA applications typical signal sources are optical (e.g. blinking LEDs) or acoustic (e.g. weapons as targets or ultrasound emitters as beacons). In this paper we focus on optical sources (LEDs) only. In this case the receivers may be cameras [4], photosensitive devices [2], or simple photodiodes [3]. The target localization can be done in general using 3-D measurements (i.e. both azimuth and elevation [7]) or using only azimuth measurements [4], [5]. In the latter case some restrictions apply to the sensor; either the sensor's direction must be known (e.g. the sensor is looking upwards) [4], or it must be measured with auxiliary sensors (e.g. by a three-axis accelerometer) [5]. However, azimuth only estimation was proven more efficient from the calculation point of view [1]. Moreover, in many applications only the 2-D location is important and the elevation information is not required. In such cases azimuth-only estimation is both computationally efficient and accurate.

In this paper we will propose an azimuth-only measurement method using inexpensive devices. The light sources are LEDs, which transmit their identifier using Visible Light Communication. The proposed receiver is called Planar Circular Photodiode Array (PCPA), which is a redundant sensor device: the source intensity is sensed by many sensors at the same time, and from the detected intensity differences of the sensors the direction of the source can be determined. The direction estimation is based on the sensors' varying radiant sensitivity as the angular displacement of the source changes.

In the literature various sensors were proposed to measure the bearings of light sources. In [8] a pinhole camera was created with a movable hole, from a Thin-Film-Transistor (TFT) unit of a TFT display, and a photodiode. Instead of the pinhole camera, several systems use ordinary cameras, as receivers [4]-[7]. In the system of [3] three orthogonal silicon photodiodes (PDs), forming a cube, were used to measure the azimuth and elevation of light sources. A special camera was created in [13], placing a microlens above an image sensor. A Quadrant Photodiode Angular Diversity Aperture (QADA), combined with an aperture was used in [14]. In this paper an inexpensive PD-array will be used for sensing. Our proposed system will apply ideas from [3], i.e. the sensor's varying radiant sensitivity vs. the angular displacement will be utilized, and the transmitters will be identified using frequency modulation. New contributions are the proposed redundant PCPA sensor architecture, which provides enhanced robustness and noise resilience, with field of view of 360; and the associated Least Squares direction estimation method.

2 Proposed Measurement System

2.1 Measurement Method

Fig. 1 shows the architecture of the measurement method. The transmitters are LEDs, blinking with different frequencies (in the figure three transmitters are shown with frequencies $f_1, f_2, \ldots, f_N$). In the proposed Planar Circular Photodiode Array (PCPA) the PDs are arranged evenly in the outer surface of a cylinder to form a circle, looking outwards in radial directions. We assume that the transmitters are in the same plane as the receivers. Each PD implements a measurement channel. The radiant sensitivity of the channels, as a function of incoming angular direction, is shown in the figure (in this specific example the sensitivity curve is a circle, shown by different colors for each channel). Each channel measures the amplitude of each transmitter's signal, the measured spectra are also illustrated in the figure. Based on the measured signal amplitudes and the calibrated reference sensitivities, the azimuth values α, β, γ for each transmitters are estimated. The figure also illustrates a possible localization scenario: from the estimated azimuth values and the known transmitter (beacon) positions, the location and orientation of the receiver can be determined by any triangulation method.

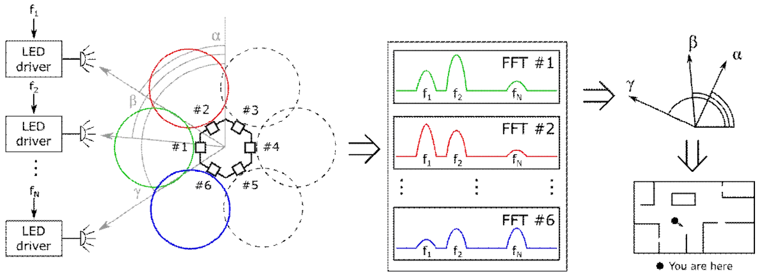


Fig. 1. The architecture of the proposed angle measurement device, and its application in a localization system. From left to right: blinking LED using unique frequencies; PCPA with 6 channels, colored circles represent the PDs' radiant sensitivity characteristics; amplitude measurement using FFT of each channel; azimuth estimation and localization.

2.2 Azimuth estimation

Let N and K denote the number of channels in the PCPA, and the number of transmitters, respectively. The $N \times M$ reference matrix R contains the calibration data as follows: row n $(1 \leq n \leq N)$ represents sensor S_n, while column m represents direction $\varphi_m = m \cdot 360°/M$, where φ_m is measured in the coordinate system of the sensor unit, and $1 \leq m \leq M$. The mth column R_m of R contains the normalized reference light intensities of all sensors in the sensor unit, for light source in direction φ_m, such that the maximum value in each column is one. Thus

$$R = [R_1 \quad R_2 \quad \dots \quad R_M], R_m = [r_{1,m} \quad r_{2,m} \quad \cdots \quad r_{N,m}]^T \tag{1}$$

where $(.)^T$ is the transpose operator and $\max\limits_n r_{n,m} = 1$. Let Ψ_n^k denote the measured intensity value of transmitter $T_k, 1 \leq k \leq K$, by sensor S_n. Vector Ψ_k contains the measurements of all sensors as follows:

$$\Psi_k = [\Psi_1^k \quad \Psi_2^k \quad \dots \quad \Psi_N^k]^T. \tag{2}$$

The applied cost function is the following:

$$e_m^k = \min_\lambda E_m^k(\lambda) = \min_\lambda \|R_m - \lambda\Psi_k\|_2. \tag{3}$$

where λ is a scaling factor to compensate for the unknown source light intensity. The minimum of $E_m^k(\lambda)$ is at value λ_m, where $\frac{d}{d\lambda}E_m^k(\lambda_m) = 0$, thus $\lambda_m = \frac{{R_m}^T\Psi_k}{{\Psi_k}^T\Psi_k}$. If m_0^k is the direction index for which e_m^k is minimal then the azimuth estimation $\hat{\varphi}_k$ for transmitter T_k is

$$\hat{\varphi}_k = \varphi_{m_0^k}. \tag{4}$$

Note: The M reference points are stored in matrix R. The resolution can be increased by applying interpolation between consecutive points $r_{n,m}$ and $r_{1,m+1}$.

3 Simulation results

3.1 Azimuth Estimation

In this section simulation test results on the accuracy of the proposed azimuth measurement method, as a function of the N number of sensors and the α angle of half sensitivity of the sensors, will be presented. In the simulations values of $N = 6, 12, 24, 48$ and $\alpha = 15°, 30°, 60°$ (typical values for PDs) were used. The radiant sensitivity S_k for channel k ($k = 1,2, \dots N$), as a function of angular displacement x, was simulated as

$$S_k = \begin{cases} \cos\left(x\frac{\pi}{3\alpha} - k\frac{2\pi}{N}\right) & \text{if } -\frac{3}{2}\alpha + \frac{6k}{N}\alpha \le x \le \frac{3}{2}\alpha + \frac{6k}{N}\alpha \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

The resolution was set to $M = 3600$. Various amount of noise was added to the ideal measurements of each channel, to simulate measurement errors. To each measured signal amplitude (the highest of which was normalized to 1) a zero mean Gaussian noise was added, with variance of $\sigma_{noise} = 0.010$, 0.025 and 0.050. The simulation results are presented in Fig. 2, showing the absolute mean of the estimated azimuth error with symbols and its standard deviation (std) with whiskers.

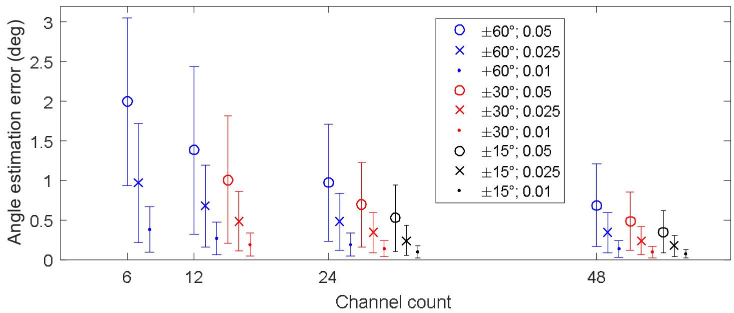


Fig. 2. Azimuth estimation error of the PCPA azimuth measurement method, as a function of the number of channels (vertical axis), the angle of half sensitivity (blue: ±60°, red: ±30°, black: ±15°), and the std of the measurement noise (o: 0.05, x: 0.025, dot: 0.01).

It is apparent that higher number of channels gives lower estimation error. Smaller angle of half sensitivity also provides better results. With the smallest noise level of $\sigma_{noise} = 0.01$ the mean azimuth estimation error is $0.07°$ with std of $0.05°$, for $N = 48$ and $\alpha = 15°$. For $N = 6$ and $\alpha = 60°$ the same noise level produced mean error of $0.38°$ with std of $0.29°$. For higher noise levels the estimation error increases approximately linearly with the noise level.

3.2 Localization Accuracy

Using Gaussian azimuth error $N(0{,}0.75°)$, simulations were conducted to determine the potential localization accuracy. The K number of transmitters in two setups were 3 and 8. The layout of the 5m × 4m test area is shown in Fig. 3, the transmitters are denoted by red dots. The 15 test points were on the 0.5m grid, between (1.5m, 1.5m) and (3.5m, 2.5m). In each setup 50 independent test were conducted for each test locations, the estimated positions are shown by colored points around the ideal location. For $K = 3$, shown Fig. 3(a), the geometric dilution of precision (GDOP) is apparent towards the upper right corner, where there is no transmitter. The mean localization error in this scenario was 5.3cm with std of 3.3cm. The other setup contained 8 transmitters, as shown in Fig. 3(b). Here the effect of GDOP is not visible, and the mean localization error was 1.9cm with std of 1.1cm.

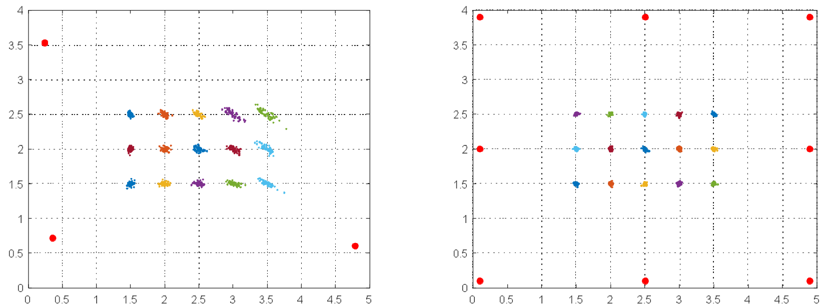


Fig. 3. Simulated position estimation errors in 3-beacon and 8-beacon scenarios.

4 Measurement results

4.1 System Architecture

The block diagram of the measurement system is shown in Fig. 4. The high-power infrared LED was switched with an IRF540 MOSFET, which was driven by a PIC16F18313 microcontroller, using the NCO peripheral, allowing the setting of the switching frequency with sub-Hz precision. In the experiments the following frequencies were utilized: $f_1 = 4219\text{Hz}$, $f_2 = 4570\text{Hz}$, $f_3 = 4883\text{Hz}$.

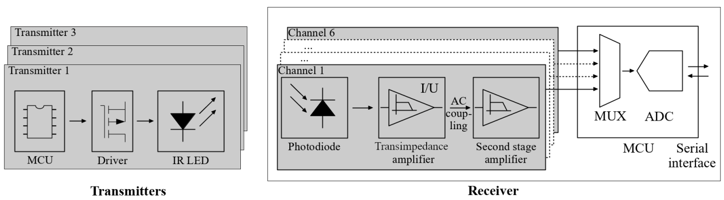
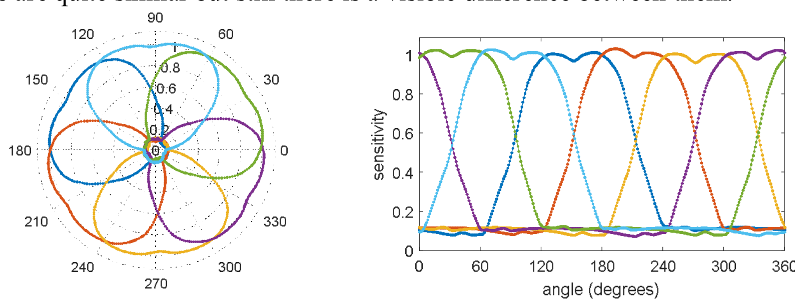


Fig. 4. The hardware architecture of the PCPA

In the receiver six Vishay BPW41N infrared photodiodes (with $\alpha = \pm 65°$) were utilized. The signal of each channel was preamplified by a transimpedance amplifier. The gain of this stage was chosen to provide enough sensitivity, but to avoid saturation by the DC component caused by normal daylight infrared radiation. The second stage amplifier is AC-coupled. The corner frequency of both stages was set to 10 kHz to suppress the higher harmonics of the received square wave. The conditioned signals were connected to six ADC pins of a dsPIC33 microcontroller and each channel was sampled with 40 kHz. The received signal amplitudes were calculated using a 1024-point FFT with flat-top window.

4.2 Reference channel sensitivities

The rows of the reference matrix R represent the relative radiant sensitivity of the channels of the PCPA. The reference matrix was measured in ideal circumstances: we used one beacon in fixed position, no other light sources were present (dark room). Using an automatic turntable, $M = 360$ was provided. The values are the average of 20 independent measurements. The channel sensitivities are shown in Fig. 5. Notice that the curves are quite similar but still there is a visible difference between them.



(a) (b)

Fig. 5. Radiant sensitivity of the six channels of the PCPA. (a) Polar coordinates, (b) Cartesian coordinates.

4.3 Azimuth estimation

Test were conducted to determine the azimuth measurement error of the proposed PCPA. In the tests three transmitter units were utilized simultaneously. The positions (direction and distance) of the transmitters were varied around the PCPA. Test results obtained using artificial lighting, daylight condition, and a special scenario with a reflective surface 1m from the sensor are summarized in Fig. 6.

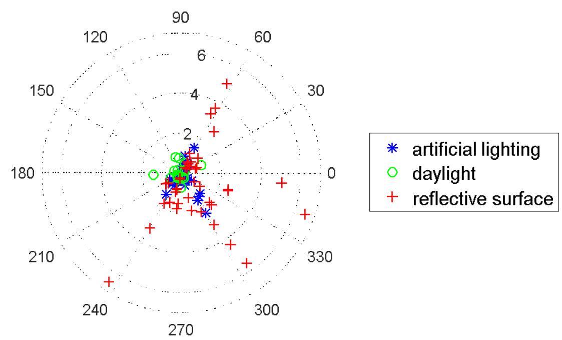


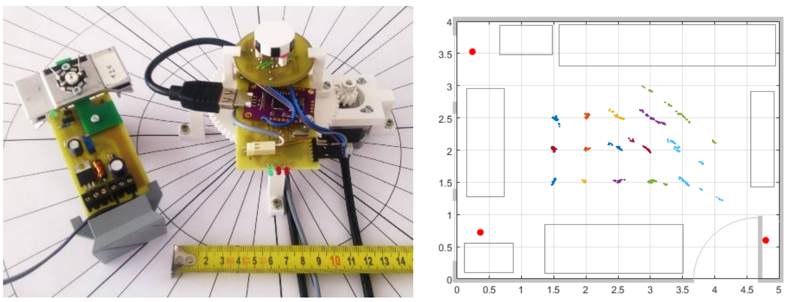
Fig. 6. Azimuth estimation error of the PCPA.

4.4 Localization example

An illustrative localization test was performed using $K = 3$ transmitters in a room of size $5\text{m} \times 4\text{m}$. One of the transmitters and the 6-channel PCPA, mounted on the turntable, are shown in Fig. 7(a). The localization results are shown in Fig. 7(b). The test setup is the same as in the 3-beacon simulation, presented in Section 3.2 in Fig. 3(a). The positions of the transmitters are denoted by red dots, the positions of the 15 reference points were also the same (on grid points). From each reference points 36 independent measurements were made by rotating the sensor unit by 10 degrees between the measurements. From each measurement the location estimate was calculated using a least squares method, the results are shown by colored points in Fig. 7(b). The measurement results correspond well with the simulations. However, on the left hand side the precision is higher, which severely degrades towards the upper left corner, and becomes significantly higher than in the simulations. The reason is due to two effects: the GDOP is higher towards the upper right corner, as can be seen in Fig. 3(a). Also, the angle measurements in these locations produced high errors (occasionally as high as 8 degrees), probably due to reflections. The two reinforcing effects resulted in a high position error. For all the 15 test points the mean localization error and std were 8.7cm and 7.2cm, respectively. Excluding the three points on the right hand side, the remaining 12 test points produced mean error and std of 5.3 cm and 4.1 cm, respectively.

5 Summary

A novel sensor to measure the azimuth of modulated light sources was proposed, using a Planar Circular Photodiode Array (PCPA). According to simulation analysis, the proposed measurement method with the redundant PCPA allows the measurement of the azimuth of the light source with accuracy in the range of $0.5° - 2°$, depending on the size of the array. The proposed low-cost solution can be a good alternative of more costly (e.g. camera-based) sensors in AoA/ADoA localization systems. In an illustrative localization example using a 6-channel PCPA and only 3 beacons, the mean localization error was below 0.1m in a $5\text{m} \times 4\text{m}$ room.



(a) (b)

Fig. 7. (a) The measurement setup with a beacon (left) and the 6-channel PCPA (right), deployed on an automatic turntable. (b) Localization results using 3 beacons.

Simulation studies suggest that sensors with more channels provide higher measurement accuracy (e.g. the accuracy of a 24-channel PCPA is twice of that of a 6-channel one). Utilization of higher number of beacons also increases the localization accuracy.

The accuracy of the proposed system is comparable with that of radio time of flight systems, with the additional advantage of the possible orientation estimate. The application of the proposed system requires that the transmitters and the PCPA be at the same plane. Uncontrolled elevation of the transmitters may cause additional error. The effect of reflections may also cause performance degradations in environments with highly reflective surfaces. These effects are subject of further studies.

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