A VLP Approach Based on a Single LED Lamp

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Abstract. Visible light positioning (VLP) has become a promising indoor localization approach as it can provide sub-meter localization. VLP usually requires no less than three LED lamps for angle-of-arrival (AoA) or received-signal-strength (RSS) based localization. However, it is hard to identify multiple LED lamps in some indoor environments, such as a long corridor or tunnel, which makes existing VLP useless. To address this problem, we propose a VLP approach using only a single LED lamp. In this approach, we utilize the inertial measurements to infer rotation angles and exploit visual projection geometry to calibrate rotation angles. The experiment results demonstrate the proposed VLP approach can achieve sub-meter positioning accuracy by using only one LED lamp.

Keywords: Indoor localization · Visible light communication · Visible light positioning · Smartphone camera

1 Introduction

Indoor localization has been a hot topic for decades for its massive applications. Although GPS technology can provide accurate positions outdoors, it's not a good choice for indoor localization because of the signal shielding of indoor buildings. Hence WiFi, RFID, UWB, iBeacon, infrared technique, ultrasound technique and so on have been applied for indoor localization. However, they all have inevitable drawbacks. For the WiFi positioning technology, it requires the deployment of WiFi modules in the surrounding environment and the accuracy will be degraded by the surrounding interference. As inertial navigation technology uses accelerometer and gyroscope to measure angle, direction, acceleration and etc., the accumulative error will increase with time. Thus, inertial navigation cannot be used independently due to the lack of self-correction. RFID performs poorly in anti-jamming ability, short operating distance and integration with the other technologies. Also the user security privacy protection and standardization of RFID is an issue to be solved too. Straight line of sight and short transmission

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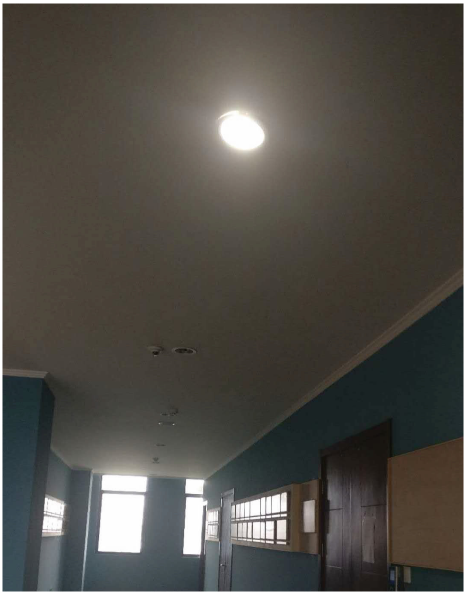

Fig. 1. Only a single lamp can be captured by the light receiver (camera).

distance are two major drawbacks of infrared. Infrared positioning also needs to install receiving antennas in each region of interest, which is deployment expensive and it is easy to be disturbed by ambient light. At a relatively high cost, UWB can only achieve limited indoor coverage.

Recently, visible light positioning (VLP) has become a promising method for indoor localization. Along with LEDs are widespread available, people begin to use visible light emitted by the LED lamps as a means of green communication, indoor localization, etc. Generally, VLP mainly uses RSS based triangulation or AoA, which means no less than three LED lamps are required. However, as shown in Fig. 1 in some indoor environments including narrow corridors or tunnels, only one LED lamp can be captured by the light receiver. In such scenarios, RSS based triangulation and AoA are infeasible and VLP approach using only one (or two) LED lamp is required. In this paper, we propose a VLP approach using only a single LED lamp. The basic idea is utilizing the inertial measurements to infer rotation angles. Considering the high angle measurement error, we exploit visual projection geometry to calibrate rotation angles. The experimental results demonstrate the proposed VLP approach can achieve submeter positioning accuracy by using only one LED lamp.

2 Related Work

In this section, we review the literature on VLP using one LED lamp. We divide the literature into two classes, i.e., RSS based and AoA based VLP.

2.1 RSS Based VLP

Li et al. [4] explore how to achieve single LED based VLP with the user involvement. With the help of the guided hand motion and recorded inertial measurements, the light sensor can collect different RSS measurements for triangulation so that localization with one LED lamp is feasible. Xie et al. [7] use a similar method in which the light receiver needs to rotate to collect different RSS measurements. In addition, the authors design a receiver on which multi-face sensors are dedicated deployed [8]. In [1], a photodetector (PD) attached to a smartphone and a camera are used to measure RSS along with a magnetic field sensor is used to obtain incident light azimuth angle. However, the measurement error of the azimuth angle and the method using camera to measure RSS is not addressed.

2.2 AoA Based VLP

In [6], the authors design a receiver combining photodiodes (PDs) and apertures. With the apertures detecting the light emission direction, the receiver extracts AoA from the received signal by comparing the relative differences between the received signal strengths without awareness of the transmitted optical power. SmartLight [5] shifts all the design complexity to the LED lamp. It designs a LED lamp consisting of a LED array and a convex lens and exploits the light splitting properties of convex lens to localize the light receiver. The work of Zhang et al. [9] is the most similar to ours. It assumes the LED transmitter is circular and the geometric features of the LED image are computed to obtain the receiver‘s orientation and location relative to the reference LED. To address the symmetric feature of the circular LED lamp, a red point marker is added on the LED lamp for global rotation matrix calculation.

From the literature review, we can see that there is few work on VLP based on a single LED lamp. Most work requires dedicated transmitter/receiver design, i.e., non-commercial-off-the-shelf (non-COTS) light transmitters or receivers. In this paper, we present a single LED lamp based VLP using a COTS LED lamp as the transmitter and COTS smartphone as the receiver.

3 Localization

In an indoor environment, sparse LED lamps are mounted on the ceiling. For example, in a long lane, the LED lamps are deployed in a line with a long distance between neighboring LED lamps. In such cases, only one LED lamp can be captured by the camera held by the user or only the data transmitted from one LED lamp can be successfully decoded by the camera.

To achieve the single LED lamp based localization, the basic idea is combining the projection geometry and internal sensor measurements. While the inertial sensor measurements can be used to provide rotation angles for localization, they are not accurate enough and need to be calibrated. As well known, the projection geometry implies rich rotation information. For example, when shooting a circular LED lamp, the higher rotation angle along the horizontal axis, the flatter the ellipse on the image plane. Although we cannot derive the rotation angles directly

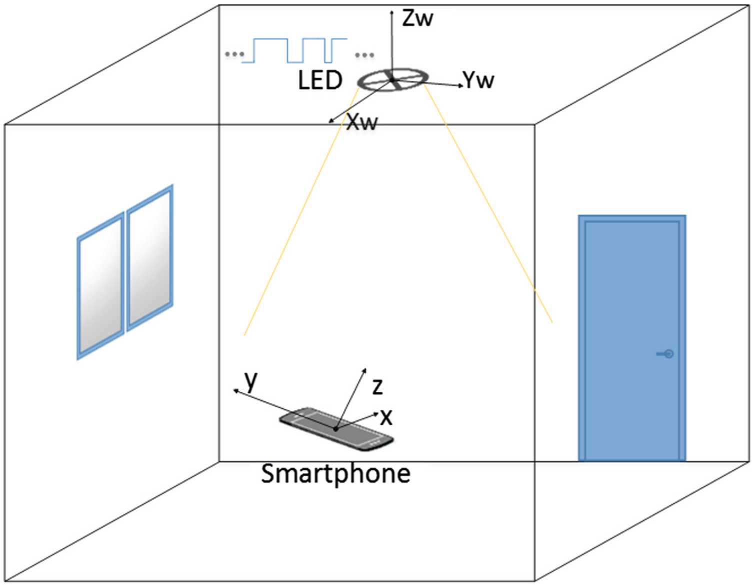

Fig. 2. System overview.

from the projection geometry, we can exploit the projection geometry to calibrate the inertial readings.

Figure 2 shows an application scenario of the proposed indoor VLP system using a single LED lamp. The circular LED lamps are mounted on the ceiling of the target indoor environment. Each LED lamp is assigned with a unique ID number which is stored in an ID-location database and broadcasts its ID number repeatedly by modulated light intensity (the readers may refer to [2] for a reliable LED-camera communication). The dimensions of the LED lamp (i.e. the radius) is also stored in the database. When a user holding a smartphone want to know his/her location, the smartphone will capture the LED lamp and record the inertial readings at the same time. The smartphone will firstly decode the ID information, process the projection geometry of the projected LED lamp, and then exploit this projection geometry to refine the inertial readings and finally derive the localization result.

3.1 Localization

A common circular LED lamp is used as the reference LED in our system, which is projected into an ellipse in the image plane. The LED lamp lies on the plane $z = 0$ and its world coordinate (the coordinate of the centre) is $O = (0, 0, 0)$. We need to derive the localization of the camera $P_c = [P_x, P_y, P_z]^T$. Each point on the LED lamp P projects to p by

$$p = KR(P - P_c), \tag{1}$$

where $K = diag\{f, f, 1\}$ is the camera calibration matrix which is calibrated in advance and f is the focal length, $p = [u, v, 1]^T$ is the image coordinate, P is a point in the world coordinate, and R is the rotation matrix as shown in (2),

$$\begin{aligned} R &= R(\alpha, \beta, \gamma) \\ &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma \\ 0 & \sin\gamma & \cos\gamma \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} \cos\gamma\cos\beta & \cos\gamma\sin\beta\sin\alpha - \sin\gamma\cos\alpha & \cos\gamma\sin\beta\cos\alpha + \sin\gamma\sin\alpha \\ \sin\gamma\cos\beta & \sin\gamma\sin\beta\sin\alpha + \cos\gamma\cos\alpha & \sin\gamma\sin\beta\cos\alpha - \cos\gamma\sin\alpha \\ -\sin\beta & \cos\beta\sin\alpha & \cos\beta\cos\alpha \end{bmatrix} \end{aligned} \tag{2}$$

Let $[X, Y, Z]^T = R(P - P_c)$, the projection can be re-written as

$$u = fX/Z \tag{3}$$

$$v = fY/Z. \tag{4}$$

If the dimension of LED lamp is significantly small compared with the distance of the camera and LED lamp and the LED lamp lies close to the optical axis, we can approximate perspective by weak perspective projection [10]. That is we can assume Z for every point P on the LED lamp is the same. Also under weak perspective projection, the major axis of the ellipse is always perpendicular to OE where E is the projected ellipse center [3] and there always exists a diameter which is perpendicular to OE in the circle. Thus the scale factor is a/r, where a is the major axis of the ellipse, r is the diameter of the circular LED lamp. Specifically, we have approximately

$$u = \frac{a}{r}X = fX/\bar{Z} \tag{5}$$

$$v = \frac{a}{r}Y = fY/\bar{Z}, \tag{6}$$

where $\bar{Z}$ is the average Z for all points on the LED lamp.

When we substitute O into (5)(6), we denote $[X_0, Y_0, Z_0]^T = R(O - P_c) = -RP_c$ and the projected $p_0 = [u_0, v_0]$ (i.e., the ellipse center). We can easily obtain $\bar{Z}$ as Z_0 and X_0, Y_0. Sequently, with the obtained $[X_0, Y_0, Z_0]^T$, we can derive P_c easily by $P_c = -R^{-1}[X_0, Y_0, Z_0]^T$. Now the problem unsolved is how to obtain the three rotation angles α, β, γ and further the rotation matrix R.

3.2 Angle Calculation

In this subsection, we describe how to obtain the three rotation angles. It is easy to obtain the pitch, roll, and azimuth angle which are denoted as α, β, γ, respectively from the IMU of the smartphone. However, we cannot directly use them for rotation matrix. As shown in [8], the pitch, roll angle has the measurement error of about 1°–2° while the error of azimuth angle is up to 26°. The reason of the high error in the azimuth angle is the high noise in compass sensor. Therefore, we use the pitch and roll angle directly for rotation matrix but calibrate the azimuth angle by using projection geometry.

Firstly, we have

$$u' = u - u_0 = \frac{a}{r}(X - X_0), \tag{7}$$

$$v' = v - v_0 = \frac{a}{r}(Y - Y_0). \tag{8}$$

where $[X - X_0, Y - Y_0, Z - Z_0]^T = R(P - O) = RP$. As $p = [u, v, 1]^T$ is on the ellipse C_e, the point $p' = [u', v', 1]^T$ is on the conic of the same shape but with a translate. We denote the conic associated with p' as C'_e, and we have

$$p'^T C'_e p' = 0. \tag{9}$$

Under the perspective projection, we have

$$p' = KR(P - P_c) - KR(O - P_c) = KRP \tag{10}$$

Substituting (10) into (9), we can obtain

$$(KRP)^T C'_e (KRP) = P^T R^T K^T C'_e KRP = 0 \tag{11}$$

Let $R^T K^T C'_e KR = [c_1, c_2, c_3; c_4, c_5, c_6; c_7, c_8, c_9]$ and $P = [x, y, 0]^T$ on the circular courteous of the LED lamp, for each $x^2 + y^2 = r^2$ we have

$$c_1 x^2 + c_5 y^2 + (c_2 + c_4)xy = 0. \tag{12}$$

Only $c_1 = 0$, $c_5 = 0$, $c_2 + c_4 = 0$ can meet (12) regardless the values of x, y.

As α, β have been obtained from IMU readings accurately, only γ is unknown. We can calculate γ from (12) by brute-force searching with initial value as the measured γ and searching radius 26°. During searching, we choose the solution that minimizes $c_1^2 + c_5^2 + (c_2 + c_4)^2$.

4 Evaluation

To evaluate the proposed VLP method, we build a testbed in which a circular LED lamp with a diameter of 21 cm is mounted on the ceiling. The LED lamp transmits its ID information at a frequency of 3 KHz repeatedly. As for the receiving end, the back faced camera of HUAWEI TRT-AL00A smartphone is used to decode the LED's ID information.

We divide the target area into grids of size 20 cm × 20 cm and let a volunteer holding a smartphone shoot the target LED lamp in each grid ten times with different rotation angles. The positioning results in Fig. 3 is the average errors of all localizations.

In Fig. 3, it is shown that the proposed positioning method in this paper achieves sub-meter positioning accuracy. All the positioning errors are below 16 cm and can be down to about 1.2 cm. Meanwhile, we also find that generally the higher the horizontal distance (thus the higher Euclidean distance) between the smartphone and the LED lamp, the higher the positioning error. When the smartphone is just below the LED lamp, we obtain the highest positioning accuracy, and the positioning error is as low as 1–2 cm. This result conforms with our intuitive understanding.

Figure 4 shows us more clearly how the VLP method performs in terms of Cumulative Distribution Function (CDF) of the localization errors. The errors achieved by ours are below 10 cm by the percentage of 90% and the average error is down to roughly 5 cm. In one word, our localization method that exploits the projection geometry to calibrate the rotation angels can achieve high localization accuracy.

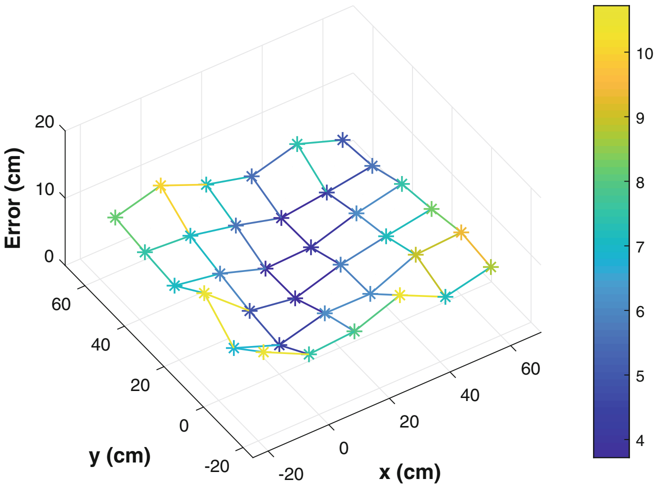

Fig. 3. Localization errors in each grid.

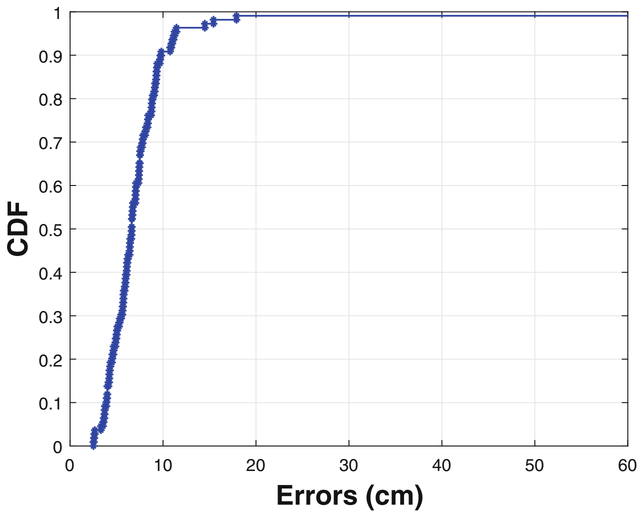

Fig. 4. CDF of the localization errors.

5 Conclusion

In this paper, we present an indoor positioning method with visible light communication based on a single LED lamp. We combine the multi-modal information collected by the camera and the IMU of the smartphone to compensate for the lack of information caused by a single LED lamp. Specifically, during the positioning process, we exploit the projection geometry to constrain the rotation angels of the smartphone. We build an experimental platform and evaluate the proposed VLP method. The results show that the errors achieved by ours are below 10 cm by the percentage of 90%.

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