Visible Light Indoor Positioning Based on Camera with Specular Reflection Cancellation

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Abstract: **We experimentally demonstrate a visible light indoor positioning based on camera with specular reflection cancellation. Results show that specular reflection is cancelled effectively and the robustness of the positioning system is improved significantly.**

Keywords: Indoor positioning; Visible light communication; LED; Image sensor

I. INTRODUCTION

Positioning system has been widely used in our daily life for providing various location-based services. In terms of indoor environment, compared with global positioning system (GPS) or radio frequency (RF)-based positioning system [1, 2], visible light communication (VLC)-based positioning (VLP) has unique advantages of high accuracy, no electromagnetic radiation [3], etc. A camera-based VLP has been proposed in [4-6], in which three-dimension (3-D) positioning is achieved by using angle-of-arrival (AOA) algorithm. Since camera is widely integrated into smartphones, this VLP can be accomplished with a commercially available smartphone and is regarded as one of the most promising solutions. However, the specular reflections from windows or some glossy furniture in an actual indoor environment would dramatically influence the LED beacons recognition for the receiver, and then a high positioning error would be induced. To solve this issue, we propose a camera-based visible light indoor positioning scheme with specular reflection cancellation in this paper. The experimental results show that specular reflection is recognized and cancelled effectively and the positioning accuracy is improved significantly.

II. POSITIONING ALGORITHM AND SPECULAR REFLECTION CANCELLATION

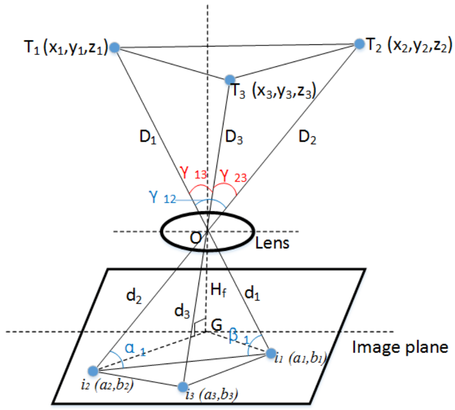

Fig. 1 Schematic of the positioning algorithm

The positioning algorithm based on camera is illustrated in Fig. 1. We assume transmitters T_1 (x_1, y_1, z_1), T_2 (x_2, y_2, z_2) in the global frame of reference and their images i_1 (a_1, b_1), i_2 (a_2, b_2) in the camera's image plane, respectively. According to the Pythagorean Theorem, the following equations are obtained:

$$\begin{cases} d_1^2 = H_f^2 + \overline{Gi_1}^2 \\ d_2^2 = H_f^2 + \overline{Gi_2}^2 \end{cases} \tag{1}$$

where H_f is the focal length of the lens, G is the center of the image plane, O is the center of the lens, and d_1, d_2 are the distance from i_1, i_2 to O, respectively. Since d_1, d_2 and $\overline{i_1 i_2}$ have been determined, based on the law of cosine, α_1 and β_1 can be obtained. As a light beam will not refract when it passes through the center of a biconvex, T_1, i_1 and O are in a straight line, so are T_2, i_2 and O. Thus the angle $\gamma_{12} = \pi - (\alpha_1 + \beta_1)$. If another transmitter T_3 and its image i_3 are assumed, then γ_{13} and γ_{23} can be deduced in the same way. According to the law of cosine, we get

$$\overline{T_iT_j}^2 = D_i^2 + D_j^2 - 2D_iD_j\cos\gamma_{ij} \qquad (1 \le i < j \le 3) \qquad (2)$$

where D_i is the distance between lens and the *i*-th LED beacon. If we assume O (x_0, y_0, z_0), then D_i meets the following equation:

$$(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 = D_i^2 \qquad (3)$$

Therefore, if three or more transmitters are assumed, the receiver's 3-D coordinates of O (x_0, y_0, z_0) can be achieved by solving an optimization problem which seeks the minimum mean square error of:

$$\sum_{i=1}^{N}\left\{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 - D_i^2\right\} \qquad (4)$$

where N is the number of LED transmitters.

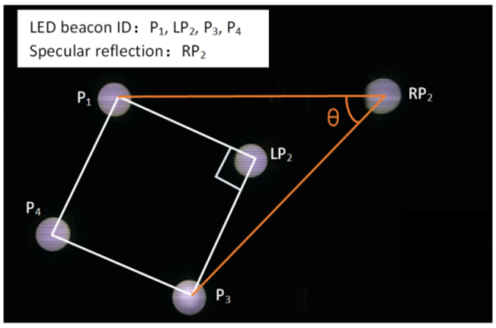

Fig. 2 A case of specular reflection and LED beacons projected on the image

LED beacon is used as the transmitter since it offers illumination and wireless communication simultaneously. In the transmitter end, a field programming gate array (FPGA) is used to generate the unique IDs with different frequencies. And then, the IDs are directly modulated to drive current of the LED beacons. In the receiver end, a complementary metal-oxide-semiconductor (CMOS) image sensor integrated into a smartphone is used. According to the rolling shutter effect, as the CMOS image sensor scans an image from the top down, the whole picture is exposed column by column. When the scanning frequency exceeds the transmitted signal frequency, the image of LED beacon will be composed of dark and white bands. Thus the width of a single band is determined by the frequency of the transmitted signal and the scan time. After the fringe width is determined by image processing using fast Fourier transform (FFT), the transmitted signal frequency can be calculated as $f = k/(2N_pT)$, where T is the scan time, k is the scanned column number in an image, and N_p is the number of pixels in a stripe. Therefore, the LED beacons' IDs can be extracted.

In addition, the layout of LED beacons obeys a regular pattern to ensure an even intensity of illumination. In this paper, we assume a square layout (our method still works in other layouts). Besides, due to the known LED beacons locations, a database is constructed based on the layout properties of the distance of every pair of adjacent LED beacons, the angle formed by a beacon and its neighbor, and the beacons sequence arrangement. After the IDs are decoded by image processing, each light spot with the same ID in the image is tested if it matches the database. For example, as Fig. 2 illustrates, two light spots are detected with the same ID of P_2, which are denoted as LP_2 and RP_2, respectively. Since the distances between RP_2 and P_1, P_3 are not equal to the side length of the pattern and the vertex angle θ is not congruent with the database, RP_2 is regard as specular reflection.

III. Experiment and Results

TABLE I. Experiment Parameters

Parameters	Value
Image sensor pixels	5312×2988
Image sensor	SONY IMAX 234
Frequency of LED transmitters	3kHz, 3.5kHz, 4kHz, 5kHz
Focal length of the lens H_f	4.3mm
Distance between 2 adjacent point in x axis	4cm
Distance between 2 adjacent point in y axis	4cm
Number of testing point	16
Pointing area	30cm×30cm
Distance between 2 adjacent LED beacons	20cm
Height of LED beacons	72cm

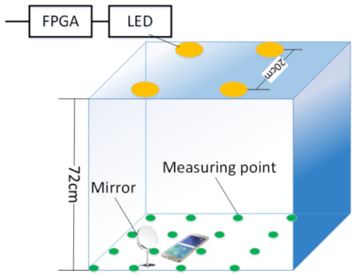

Fig. 3 System layout

Following the system setup depicted in Fig. 3, an experiment is conducted to verify the proposed scheme. The experimental parameters are listed in Table I. The system consists of 4 LED beacons, an FPGA (Altera Cyclone II De2), a smartphone (Nubia Z9 Max) with a front camera, and a mirror with a size of 15cm×20cm. The FPGA is used to generate the ID information and the mirror deployed near the smartphone at a right angle is used to create the specular reflection.

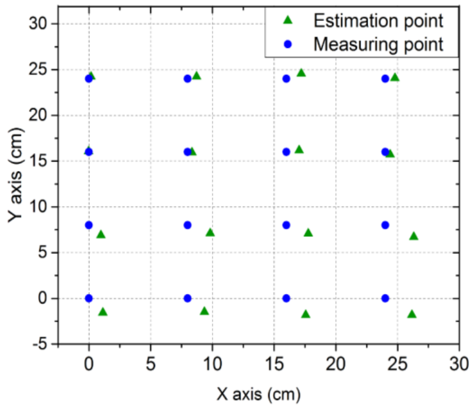

Fig. 4 2-D Positioning results with no specular reflection

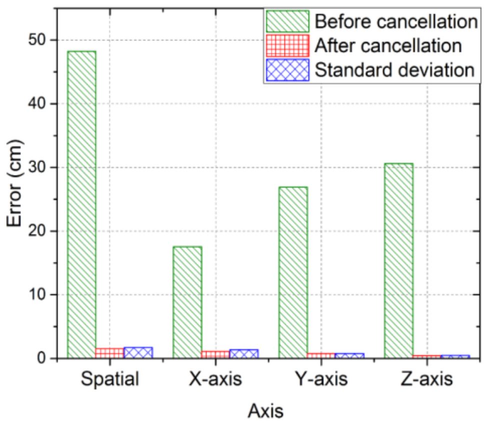

Fig. 5 3-D Positioning results before cancellation

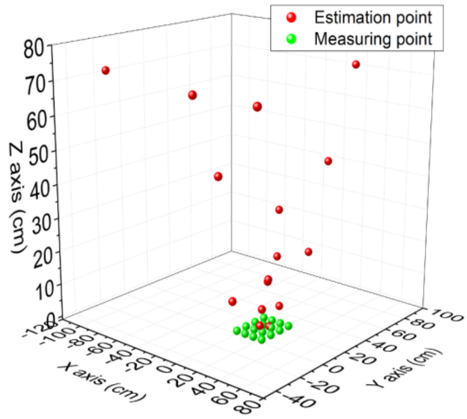

Fig. 6 Positioning errors in spatial field and X, Y, Z axis

Fig.4 shows the positions of all measuring points and estimation points in XoY plane with no specular reflection. The mean biased error is 1.78cm, which is the standard deviation of our system. Fig.5 shows the 3-D positioning results of the estimation points and measuring points before cancellation. Here, specular reflection is taken into calculation instead of the real LED beacons as a comparison. Since the specular reflection occurs randomly, the estimation points in Fig. 5 far exceeds the boundary of our positioning area. Fig.6 shows the positioning errors in the spatial field, X-axis, Y-axis and Z-axis, respectively. The average spatial positioning error is 48.25cm before cancellation while the value is 1.53cm after cancellation. The results show that the scheme we proposed recognizes the specular reflection effectively and saves 96.3% of the positioning error.

IV. Conclusions

In this paper, we propose and experimentally demonstrate a camera-based visible light indoor positioning scheme with specular reflection cancellation. The positioning algorithm is addressed and the geometrical relationship of LED beacons is used to identify and cancel the specular reflection. Using this method, we save more than 90% of the positioning error and improve the robustness of the positioning system significantly.

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