Indoor positioning using visible light communication and a high-speed camera equipped with fish-eye lens

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Abstract **This study proposes a method for detecting the positions of objects as small as 10 cm in an indoor environment using visible light communication and a high-speed camera equipped with a fisheye lens. The experimental apparatus, which comprises fluorescent or LED lights and a handheld optical sensor, transmits a unique positional signal by means of an additional controller. Reception is accomplished in three steps. In step 1, 9 photo sensors receive a light output. In step 2, a fisheye-lens-equipped camera captures a 180-degree view of the ceiling and the location of the light. Based on the data, the receiver position is triangulated and data on the location of each light are stored in the receiver database. In step 3, a specially-developed high-speed CMOS (Complementary Metal Oxide Semiconductor) device captures both the ceiling image and signature. The maximum sensor resolution is 256 × 240 pixels. The acquisition time for 256 pixels × 30 lines is 250 μs. The maximum sampling rate is 4 kHz/pixel. Using a prototype circuit board with a camera and Field Programmable Gate Array (FPGA), we confirmed the image-acquisition time of 5 ms, for one image (256×240). The maximum signature decoding rate was 1 kHz. Our next task is to add absolute positional information for each light.**

Keywordst; Visible Light Communication; Indoor Positioning; Fish-eye lens; Image sensor; Camera

I. INTRODUCTION

This study proposes a far-less-cumbersome method for detecting the positions of objects in a variety of settings, using visible light communication (VLC) and a high-speed camera equipped with a fisheye lens. The experimental apparatus consists of standard fluorescent or LED lights that transmit unique positional signals using a handheld optical sensor and an additional controller. As LEDs proliferated, in 2003, Masao Nakagawa, a pioneer in the field of VLC, and his colleague Shinichiro Haruyama worked to establish a VLC consortium whose first aim was the standardization and practical application of the technology [1-3]. Because these simple VLC devices rely on existing lighting apparatuses, they require no supplemental power sources. Additionally, they are impervious to standard radio waves and require no government oversight or approval.

II. METHOD

In the first of three steps, an LED light transmits a signal to an optical receiver that comprises nine photo sensors [4-5]. In the second step, which defines a position that is far more precise than the area highlighted in step 1, a camera equipped with a fisheye lens is used to capture a 180-degree view of the ceiling, and the light location. From the location of the lights and signatures (unique IDs), the receiver position is triangulated. Data regarding the location of each light are stored in the receiver database. In step 3, by replacing the old image-sensor in the camera with a specially-developed high-speed CMOS (Complementary Metal Oxide Semiconductor) sensor, we capture both the ceiling image and signature. Fig. 1 shows a photograph of the 9-ch sensor unit used in step 1.

Fig. 2 shows the experimental apparatus used in the second step. It consists of a camera equipped with a fisheye lens, a specially-developed visible light receiver, and a standard personal computer. The fisheye lens and visible light receiver are attached to a movable cart in an orientation such that they point toward the ceiling. The captured image and the signal

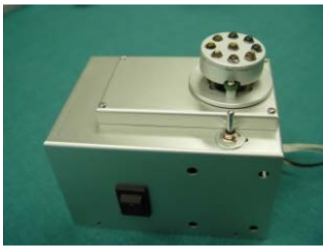


Figure 1. Nine channel sensor head with rotation control unit.

decoded by the receiver are sent to the PC, via an IEEE1394b interface, and a Bluetooth interface, respectively.

Coordinate system

Fig. 3 shows the world coordinates and camera coordinates, while Fig. 4 shows the coordinates of the image captured through the fisheye lens within the camera coordinates. In this part of the experiment, we assume that the floor-surface is flat and smooth. The height of the cart is 1 m. However, we have two unknown parameters, the position of the cart (x,y) in the world coordinate (Xw,Yw) and rotation angle γ around the Zc axis.

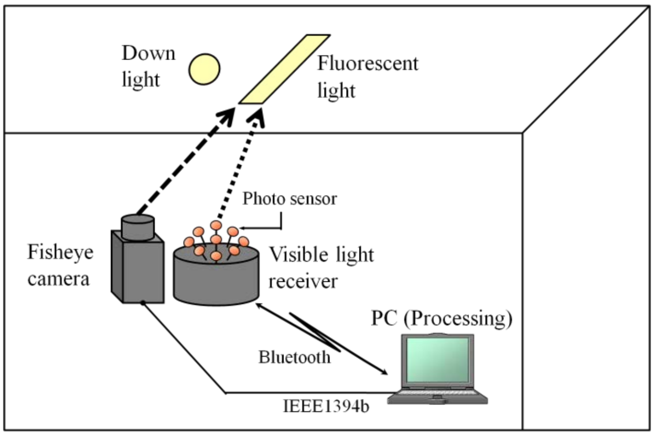


Figure 2. System configuration for Step 2.

Camera: Grasshopper, Point Grey Research, 600 × 1200 resolution, RAW8, and 30 fps

Fisheye lens: Fujinon, FE185C057HA-1, Viewing angle: 185 degrees, Equidistance projection

Personal computer: Lenovo, ThinkPad T400

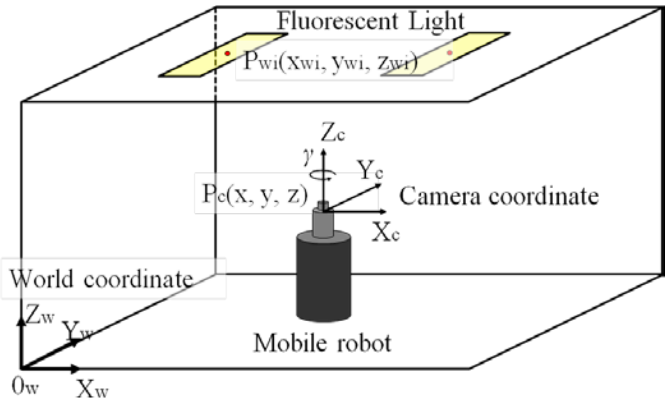


Figure 3. Coordinate system 1

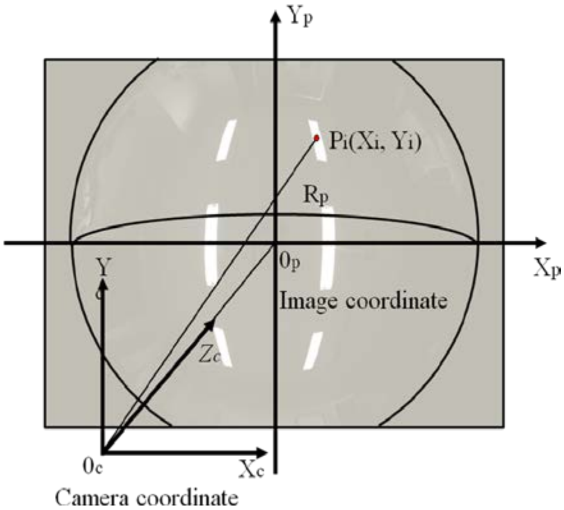


Figure 4. Coordinate system 2

(a) Photographic image (b) Extracted binary image

Figure 5. Fisheye image.

Fisheye camera

Fig. 5(a) shows an original image of the ceiling. Fig. 5(b) is a binary image of the fluorescent lights taken from Fig. 5(a). Using Fig. 5(b), the central coordinates for each of the lights, Pi(Xi,Yi), is calculated.

VLC

The light used for VLC can transmit unique positional signals (IDs) by means of an additional controller. Frequency-shift keying (FSK) is used for fluorescent lights, and subcarrier modulation (28.8 kHz) or amplitude modulation (AM) is used for the LEDs in the down lights. A 9-channel VLC receiver decodes the data, Pi(Xi,Yi), which are used as reference keys, to search for the corresponding coordinate, $P_{wi}(x_{wi},y_{wi},z_{wi})$, in the world coordinate. This process is called "labeling."

Positioning

Since the height of the cart that contains the camera and the VLC receiver is set to 1 m, for the purposes of the experiment, it is necessary to calculate three unknown parameters, x, y and γ. For this calculation, the least squares (Levenberg-Marquardt) method is used [6]. If we have only one data-point during the experiment, unknown parameters (x,y) are calculated after is set to 0 degrees.

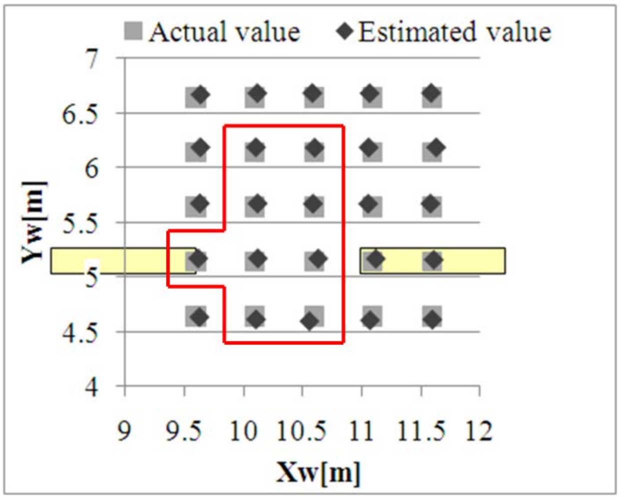
III. EXPERIMENT

An experimental apparatus that consists of a 2 m × 2 m lattice with measuring points (25 in total) was positioned at 0.5 m intervals and used to evaluate the degree of error between actual and estimated positions. Two 1.2-m long fluorescent lights, positioned 2.5 m apart, and 4 downward-facing LED lights were used. The height of the ceiling, $P_{wi}(Z_{wi})$, was measured to be 2.4 m.

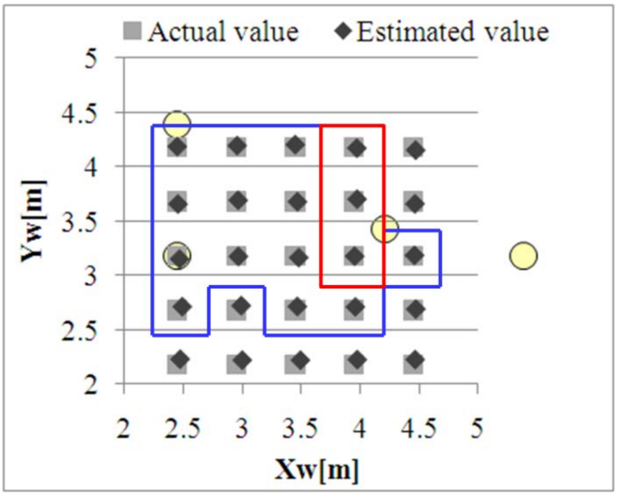
Fig. 6(a) shows the two tube-type fluorescent lights (yellow rectangular symbols) used as VLC transmitters. Actual (squares) and estimated (diamonds) values were plotted at appropriate lattice positions. Due to the limited sensitivity of the receiver, we could observe only two lights simultaneously within the area bounded by the red line. In the other areas, only one light was observed but, the rotation angle was assumed to be 0 degrees. In the experiment, the average margin of error was 2.41 cm in Xw, 3.62 cm in Yw, and 0.01 degrees in γ.

Figure 6(b) shows the results of an experiment that involved four downward-facing lights (yellow circular symbols). In the area enclosed by the red lined, it was possible to detect four lights, while in the area surrounded by the blue line, three lights were used for calculation. In other areas, two lights were employed. The results show discrepancies of 1.80 cm in Xw, 2.36 cm in Yw, and 0.06 degrees in γ. At the same time, in the red area, we compared calculation errors based on two and four lights. In the latter, the estimated position error was reduced by approximately 50%.

The total processing time was approximately 285 ms. Light-position extraction took 11 ms; determining the central position of the light, Pi(Xi,Yi) calculation, took 210 ms; labeling took 15 ms; and the camera position calculation took 49 ms.



(a) Tube type light

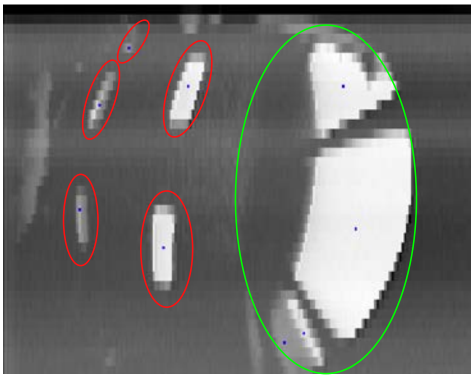


(b) Down light

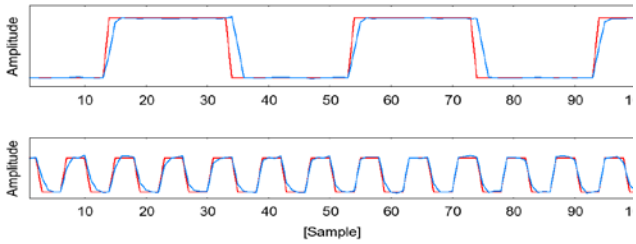
Figure 6. Results of measurements (Step 2).

Results for Step 3

By replacing the old image-sensor in the camera with a specially-developed high speed CMOS sensor, we were able to capture both the ceiling image and signal. The maximum resolution of the image sensor is 256 × 240 pixels and the acquisition time for 256 pixels × 30 lines is 250 µs. Therefore, the maximum sampling rate at which the brightness is measured for each pixel is 4 kHz. In the experiment using a prototype circuit board with a camera and Field Programmable Gate Array (FPGA), we confirmed that the image acquisition time is 5 ms for one image (256 × 240). The maximum signature decoding rate was 1 kHz. Figure 7 shows the image of the ceiling captured by the CMOS image sensor (Fig. 7(a)). For signal detection, because of the limited acquisition time, we used a small CMOS sensor (192 × 41 pixels), and detected the signal (Fig. 7(b)) using a similarly small LED at the light spacing of 10 cm. Figure 7(b) shows the detected 50 Hz and 250 Hz signals, at a sampling frequency 2 kHz. Figure 7(c) shows the results of signal decoding using LED down light (Panasonic: NNNH73013, 22.7W) at a distance of 1m. Figure 7(d) shows the CMOS image sensor evaluation board used for signal decoding in Fig. 7(c).

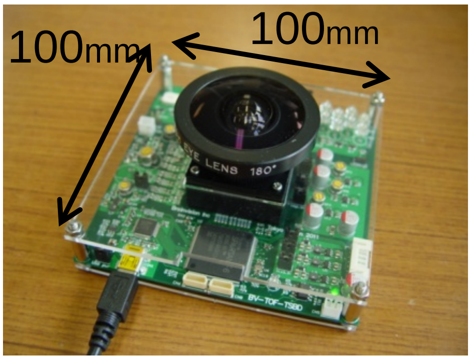


(a) Captured image (192 × 41 pixels)



(b) Detected signal from LED light

(c) Results of signal decoding
The results of signal decoding using LED (Panasonic: NNNH73013, 22.7W) at a distance of 1 m.



(d) CMOS image sensor evaluation board

Figure 7. Results of measurements (Step3).

IV. DISCUSSION

For an indoor positioning and communication system using VLC, this paper presented a location estimation method based on a high-speed camera equipped with a fisheye lens. Measurement is a straightforward three-step process. The first step uses a photo-sensor/receiver. Basically, position is determined from the limited area immediately below and illuminated by a given light, which corresponds to a single coordinate (ID). By combining 9 photo sensors [5], positional data are obtained for an area measuring 0.25 $\times$ 0.25 m (step 1). In step 2, a precision camera equipped with a fisheye lens was used, with a photo sensor estimating the camera position. As a result, the average horizontal error was 0.1 m for Xw and Yw , and 1 degree for rotation angle γ around Zc. Moreover, in step 3, we used a high-speed CMOS image sensor for VLC signal decoding. As a result, it was possible to capture a 256$\times$240 pixel image, within 5 ms. By measuring 2 pixels simultaneously within 30 s, we confirmed the brightness sampling function of a rectangular waveform, up to 2.5 kHz. In the future, we aim to develop a small receiver capable of decoding a 9600 bps signal based on the JEITA CP-1222 standard [6].

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