Visible Light Communication Using Corneal-Reflections for Indoor Localization Area Expansion*

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Abstract

This study explores the feasibility of expanding the measurable range for indoor positioning using visible light communication signals reflected from the cornea. Experiments were conducted using light-emitting diode downlights as landmarks and a smartphone camera to capture corneal reflections. The results demonstrated that landmarks could be reliably detected at 0.5 m, 1.0 m, 1.5m and 2.0 m horizontal distances, indicating their potential for accurate indoor positioning. However, challenges such as extracting landmarks from background noise and optimizing system parameters for different environments persist. Future research should focus on addressing these challenges to enhance the robustness and accuracy of the proposed system.

Keywords

visible light communication, corneal imaging

1. Introduction

Visible light communication (VLC) involves data transmission by modulating the intensity of light from a light source such as a light-emitting diode (LED) [1]. The modulated light is received by a photodetector or camera and converted into digital information for further processing. LED fixtures are ideal for high-frequency digital data transmission in VLC, and VLC communication methods using ON/OFF keying (OOK) have already been standardized [2].

Indoor positioning methods utilizing VLC with lighting fixtures and cameras have been proposed for accurate location (sub 10 cm level) and orientation (sub 10 degrees level) measurement [3]. In this study, we consider a localization scenario in which the landmarks are assumed to be point-light sources, meaning that we use relatively small, circular lighting fixtures whose shape and size information are unavailable. By analyzing camera images, we can estimate the relative relationship between landmarks and devices with higher accuracy than radio-based methods such as Wi-Fi or Bluetooth positioning [4]. Furthermore, using indoor lighting fixtures as landmarks, absolute positioning is theoretically possible, unlike in inertial navigation systems (INS), eliminating the need to consider error accumulation.

One of the challenges in indoor positioning using lighting fixtures and cameras is the occurrence of areas where positioning is impossible owing to the arrangement of lighting

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fixtures in large indoor spaces. In narrow corridors or environments in which sufficient lighting fixture density cannot be ensured, positioning cannot be performed when the minimum number of lighting fixtures required for positioning cannot be observed.

While INS using accelerometers, gyro sensors, and magnetometers can be used for positioning estimation in non-measurable areas [5], it suffers from decreasing positioning accuracy owing to error accumulation. Therefore, it is desirable to maximize the area where absolute positioning is possible using VLC.

As a countermeasure, the positioning area can be expanded using dual-facing cameras on the device to receive reflected light from the floor and observe lighting fixtures that cannot be observed directly [6].

In this study, we investigated an increase in the number of observable lighting fixtures utilizing visible light signals within the corneal reflection image of the device user. Currently, in digital forensics, research is underway to restore the surrounding scenery using corneal reflection images (corneal imaging) [7]. For example, by analyzing corneal reflection images, information about the surroundings where the photo was captured becomes an important clue to the location where the crime was committed. Corneal reflection images are also ideal reflectors for receiving visible light signals over a wide range. Figure 1 illustrates the proposed localization method with a visible light signal received via corneal reflection.

In this study, we investigated the possibility of expanding the indoor positioning area by analyzing the images of VLC light sources reflected by the cornea.

2. Localization Method

Blinking visible light with frequencies of approximately 100 Hz can be perceived by the human eye and may have adverse effects on human health. Therefore, it is desirable for VLC signals from landmark LEDs installed in indoor environments to have frequencies of several hundred

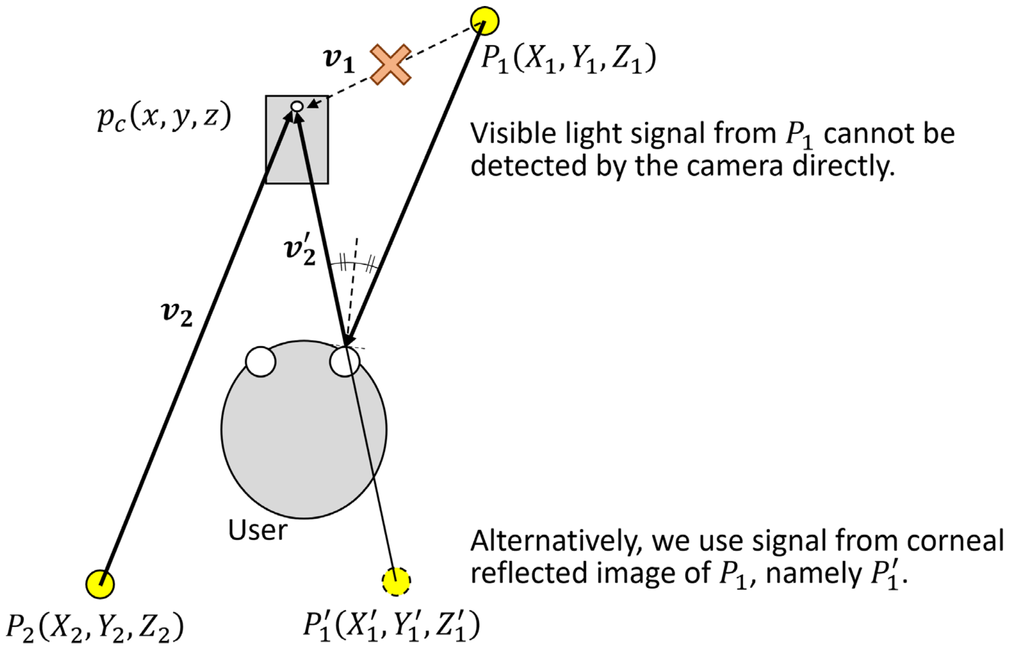


Figure 1: Visible light signal receiving using corneal reflection.

Hertz or higher. There are two main approaches to receiving high-frequency VLC signals in the kilohertz band or higher. These can be categorized according to the type of device used: high-frame-rate cameras (approximately 1,000 fps or higher) and low-frame-rate cameras (up to several hundred fps).

- High-frame-rate cameras (e.g., dedicated positioning devices or future smart devices)
- Low-frame-rate cameras (e.g., cameras in current general-purpose smart devices).

In this study, we utilized a low-frame-rate camera because most smart devices are currently equipped with cameras for up to several hundred fps. Therefore, for VLC positioning, we proposed switching between the two modes by adjusting the camera exposure time.

1. Long-exposure mode: image acquisition for face detection and light source position detection.
2. Short-exposure mode: Light source extraction for landmark identification. (A short exposure time is repeated the necessary number of times.)

In addition, when the same ID information is transmitted repeatedly, the original ID information can be restored, even under undersampling conditions, by appropriately setting the combination of the visible light signal transmission frequency and camera frame rate [8].

The localization process flow of the proposed method is shown in Figure 2. The experimental system is implemented in Python and the Insightface library [9] is used in the "Face detection" and "Eye detection" process. By applying a mask, only the eye regions were extracted, and the corneal reflection image within the extracted region was analyzed. OpenCV component

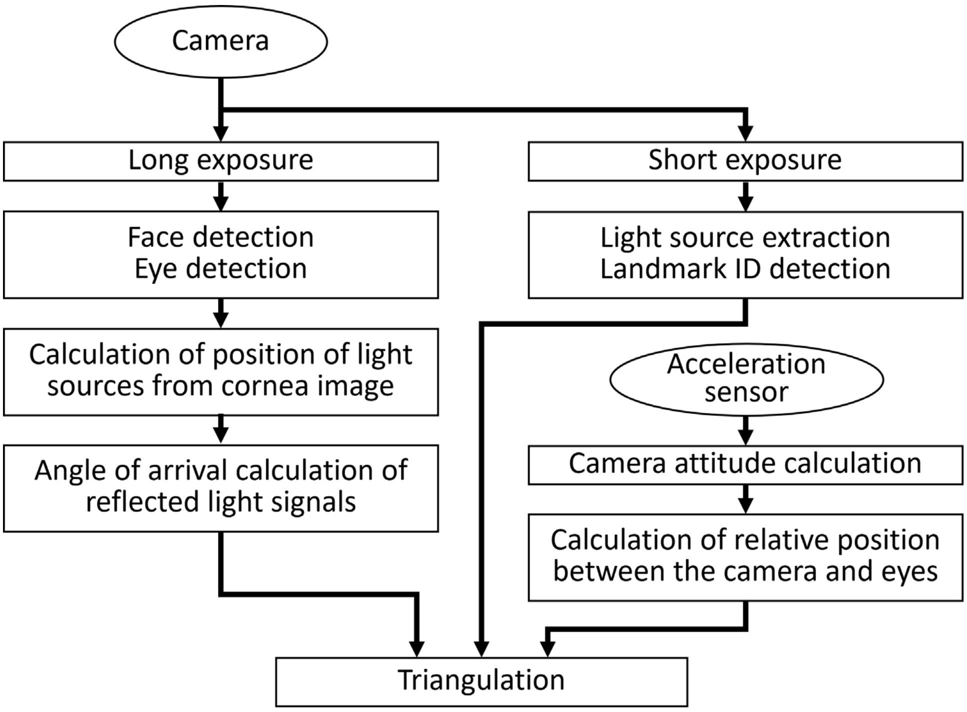


Figure 2: Process flow.

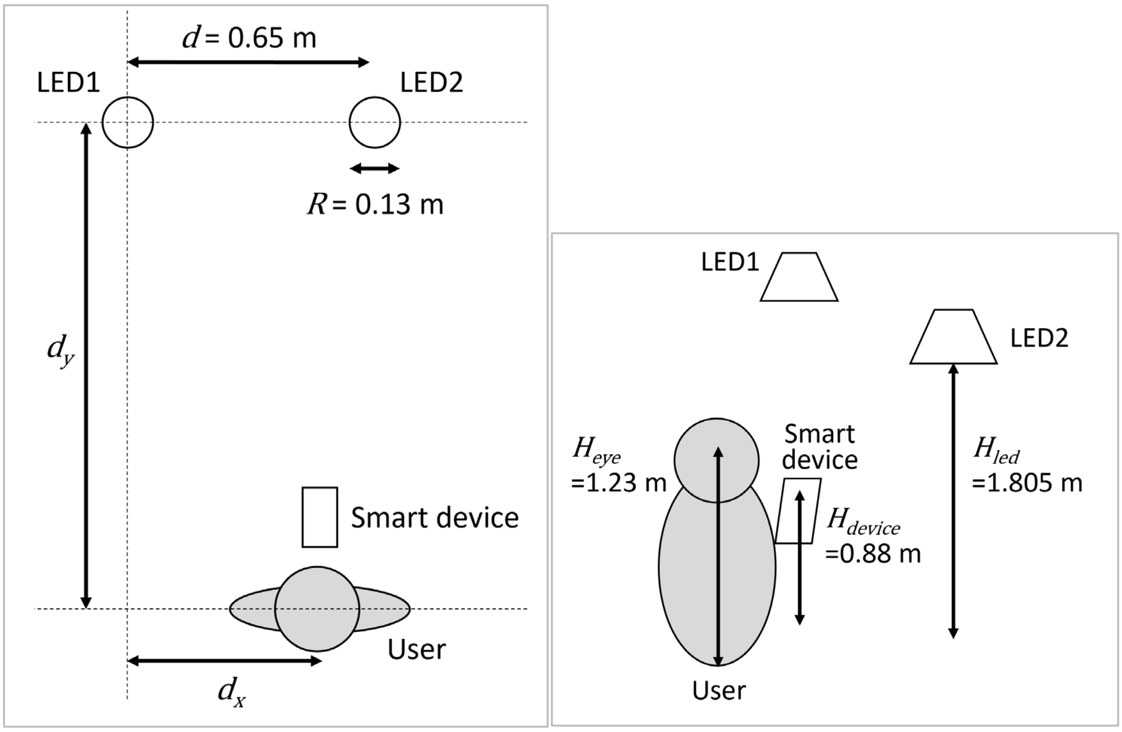
detection was used for landmark position extraction [10]. In this study, we focused on extracting light sources that were 1% or less the size of the eye region. Experiments were conducted to verify whether the landmark position can be identified from the corneal reflection image.

3. Experiments

Experiments were conducted using two LED downlights as positioning landmarks and a front-facing (user's side) camera embedded in a smart device (Google Pixel 6 Pro, the front-facing camera: 2880*3840 pixels) as a landmark detection camera.

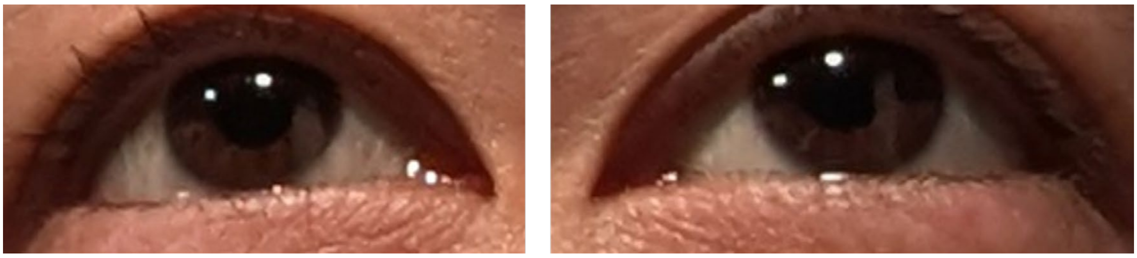
3.1. Setup

Experimental setup is illustrated in Figure 3. Two LED downlights, whose diameter is 0.13 m, were installed at a height of 1.805 m as VLC landmarks, and the user held a smartphone for landmark detection. The user is sitting on a chair, and the height of the user's eye level is 1.230 m. Thus, the vertical distance between the LEDs and user d_z is 0.575 m. Assuming that the user holds his/her smartphone in his/her hand, the smartphone is fixed at a height of 0.880 m, whose inner camera is directed to the user's face.
In this experiment, the x-axis horizontal distance between LED1 and user d_x was fixed at 0 m. The y-axis horizontal distance between LEDs and the user d_y is varying at 0.5 m, 1.0 m, 1.5 m, and 2.0 m. To thoroughly evaluate the proposed method, future experiments should be conducted under different (d_x, d_y, d_z) conditions.

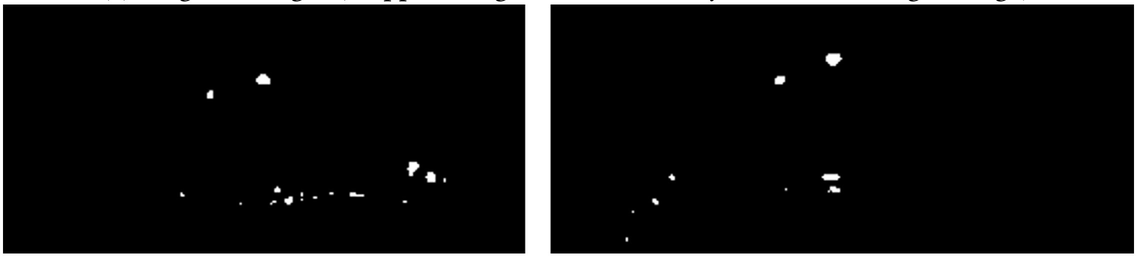


(a) Top view. (b) Side view.

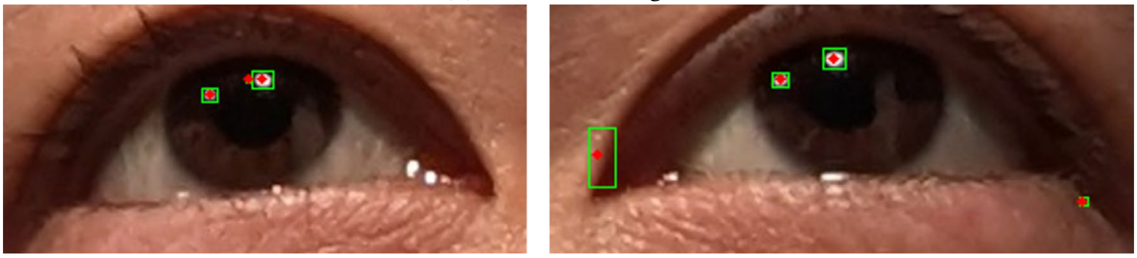
Figure 3: Experimental setup.



(a) Original images (cropped images around both eyes from one single image).



(b) Binarized images.



(c) Detected landmarks (green) and center of mass (red) on corneal reflected images.

Figure 4: Eye image processing results.

(the user's right eye is on the left side, left eye is on the right side, about 280*130 pixels each)

3.2. Results

Experiments were conducted at vertical distances d_z = 0.575 m and horizontal distances (d_y = 0.5, 1.0, 1.5, and 2.0 m, and d_x = 0 m. In all cases, the landmarks were successfully detected on the corneal images.

3.3. Discussions

Our experiments indicate that optical signals can be successfully received at horizontal distances of up to approximately 2 m between the landmark and user. To assess the practical applicability of this technology, future studies should involve conducting experiments in realistic environments at extended distances.

The typical ceiling height of a building is approximately 3 m. Considering that the height of a user is approximately 1.5 to 2.0 m, the vertical distance between a ceiling-mounted landmark and a user's device can be estimated to be 1.2 to 1.8 m. In our experiment, the vertical distance between the landmark and the device was less than 1 m. Experiments under conditions that simulate actual ceiling heights are necessary to evaluate the reception accuracy of VLC signals.

Figure 4(c) of the experimental results shows that unnecessary light sources other than landmarks were also extracted. Therefore, further investigation is required to determine appropriate methods for landmark extraction. In this study, only images obtained with long exposure were used; however, combining short-exposure images may help extract only the necessary landmarks. For example, by repeatedly capturing short-exposure images of landmark-emitting VLC signals, taking the difference, and accumulating the images, it may be possible to extract only the signal source.

4. Conclusion

In this study, we investigated the expansion of the measurable range of indoor location using visible light signals within the corneal reflection images of a device user. Experiments were conducted using two LED downlights as positioning landmarks and a camera embedded in a smart device as the landmark detection camera.

Landmark detection experiments were conducted at a vertical distance of d_z = 0.575 m with varying horizontal distances (d_y = 0.5 m, 1.0 m, 1.5 m, and 2.0 m, d_x = 0 m). Landmarks were successfully detected in all the corneal images obtained under these conditions.

These experimental results suggest that positioning using visible light signals within corneal reflection images can expand the measurable range indoors. In the future, we plan to conduct further experiments to measure the communication quality (speed and accuracy) of VLC through corneal reflection images and to evaluate the positioning accuracy and measurable range.

Acknowledgements

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