Development of an Eye-Tracking Pen Display for Analyzing Embodied Interaction

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Abstract. In recent times, intuitive user interfaces such as the touch panel and pen display have become widely used in PCs and PDAs. Previously, the authors developed the *bright pupil camera*. They subsequently developed an eye-tracking pen display based on this camera and a new aspherical model of the eye. In this paper, a robust gaze estimation method that uses a integrated-light-source camera is proposed for analyzing embodied interaction. Then, a prototype of the eye-tracking pen display was developed. The accuracy of the system was approximately 12 mm on a 15" pen display, which is sufficient for human interaction support.

Keywords: Embodied interaction, pen display, eye-tracking, aspherical model.

1 Introduction

Today, the intuitive user interfaces of PCs and PDAs, such as touch panel and pen display, have become widely used. These devices are expected to open up a new embodied interaction and communication as well as interaction between humans and computers.

By focusing on the importance of embodied interaction, the authors have developed a Computer Graphics (CG)-embodied communication support system [1]. Especially, the importance of timing control in generating embodied motions and actions is made clear for supporting natural, familiar, and polite interaction via CG and robot agent [2]. However, for making further uses of embodiment, it is required to analyze the relationships between body motion and attention.

If we could integrate pen display and eye-tracker, it becomes possible to analyze various embodied interactions. For example, we could analyze how a presenter indicates or emphasizes a slide in presentation by using intuitive pen display. In addition, such an eye-tracking pen display could become a gadget for realizing a new mode of interaction between humans and computers.

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The authors have already developed a prototype of Eye-Tracking Pen Display, MobiGaze which enables eye-tracking on iPhone, and ETTI (Eye-Tracking Tabletop Interface) [3][4][5]. The accuracy was about 0.7°, which was enough for interaction analysis, however, the robustness of the system was not enough. In this study, we have developed a robust pupil detection method by using aspherical model of the eye and dark pupil method. The evaluation experiment shows the effectiveness of new prototype system.

2 Technical Requirements

There are several eye-trackers which we can be listed as de facto standards such as Tobii T120 [6]. However, they are not suitable for use with pen display. The biggest problem of such eye-trackers is that they have cameras and IR LEDs under their displays (Fig. 1). When a right handed person use a pen on the display, the right arm may hide the camera or LED.

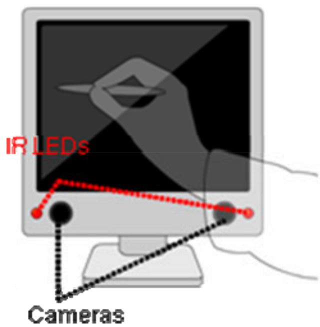

Fig. 1. Typical layout of cameras and LEDs

The tracking distance and gaze angle may also cause a problem when a user draws on a pen display. Because, the tracking distance of existing eye-trackers is approximately 50 cm or more, and the gaze angle is approximately 30° in many cases. If we put an eye-tracker at the left bottom of the display and use a pen on the display, the tracking distance becomes too close and gaze angle becomes too wide.

In addition, easy calibration is required for eye-tracking pen display, so that intuitive interface can be realized. Thus, we can summarize the technical requirements as follows [3]:

- Free arrangement of cameras and LEDs to prevent obstruction by the right hand
- Robust gaze estimation with short distance & wide gaze angle
- Easy calibration

3 Arrangement of Cameras and IR LEDs

We reviewed previous studies and developed a prototype of the system by considering its technical requirements. The 3D gaze-tracking approach was selected for accuracy [7][8][9]. This approach involves the use of two cameras and three or four LEDs. Fig. 2 (a) shows the arrangement of the system proposed by Nagamatsu et al [10]. In this study, we first developed a prototype of the system by positioning the cameras and LEDs: two cameras are placed to the left of the pen display, and one LED each is placed on the top, left, and bottom frames of the pen display (Fig. 2 (b)). However, even with such an arrangement, stable eye-tracking cannot be realized due to the obstructions by the right hand and the eyelid. Therefore, we reviewed the arrangements proposed in previous studies again. Some researchers have proposed camera-LED integrated systems. For example, Ohno developed a system that involved the use of one camera and two LEDs [11]. Chen et al. developed a system that involved the use of two cameras and two LEDs mounted near the camera centers; in this arrangement, the camera and the LED were integrated into one component [12]. We can arrange such a system to the left of the pen display (Fig. 2 (c)); however, such a system would be inadequate if the pen display is to be used at various angles. The two cameras should be separated for the eye tracking pen display system [3].

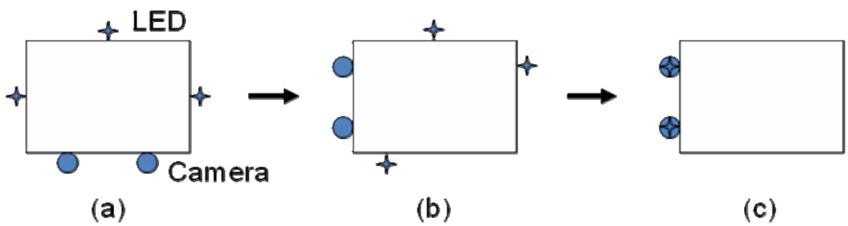

Fig. 2. Arrangement of cameras and LEDs

4 Estimation Method of the Optical Axis of the Eye

Here, we estimated the optical axis by using two cameras and two IR LEDs by using the arrangement as shown in chapter 3. First, we calibrated the external parameters of the cameras to acquire the relative 3D position of the cameras and the displays. Next, on the basis of the results of image processing, we detected the position of the pupil and two bright points as a Purkinje image as shown in Fig. 4 (a). We assumed that the light source and the camera center were at the same position. Then, we obtained a plane that contained vectors $\mathbf{A}$ and $\mathbf{B}$, as shown in Fig. 3 by using the expression $(\mathbf{C}_j-\mathbf{B}'_j)\times(\mathbf{P}'_j-\mathbf{C}_j)\cdot(\mathbf{X}-\mathbf{C}_j)=0$, where $\mathbf{X}$ is a point on the plane. One camera and one LED were used for determining a plane that contained the optical axis. Therefore, the optical axis could be obtained as the intersection of two planes by using the two cameras and two LEDs. Then, the user gazed at a point on the tabletop interface for the calibration. The difference between the optical axis and the visual axis of the eye was revised by carrying out this calibration. The cross point of the visual axis and the pen tabletop was estimated as the gaze point [3].

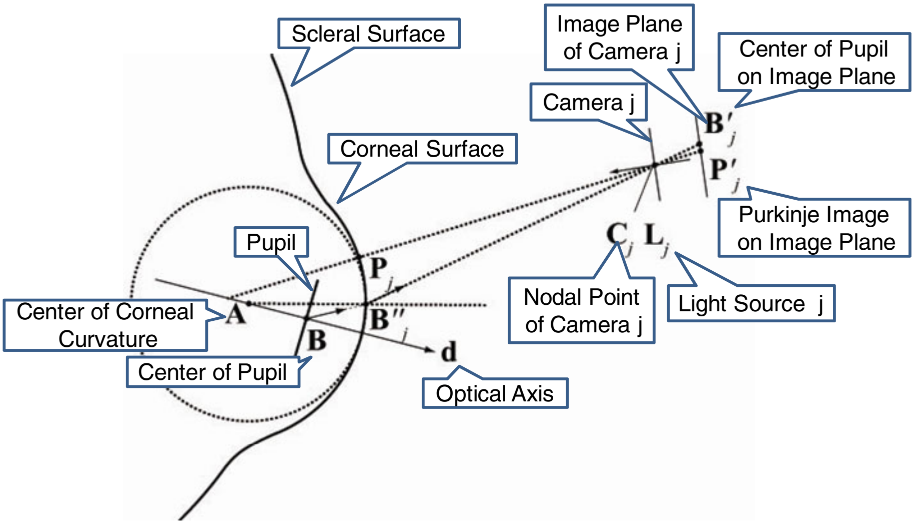

Fig. 3. Estimation of the optical axes

5 Image Processing

We have developed an eye-tracking pen display and achieved eye tracking of up to approximately 60° on the basis of our estimation method of the optical axis of the eye, which is introduced in chapter 4, using a robust layout of cameras and LEDs [3]. However, because of the unstable estimation of the optical axis, which is caused by image processing error in bright pupil method, as shown in Fig. 4 (b), the analysis of embodied interaction was difficult. Although the dark pupil technique with one IR LED around lens proved reliable (Fig. 4 (c)), it is necessary to develop a new pupil detection method because the distance between the LED and camera center causes error.

Fig. 4. Image processing

6 Pupil Detection Method

In this study, the authors developed integrated-light-source cameras that had IR LEDs around their lenses. By calculating the barycentric position of two or three of the LEDs around the lens, we simulated a virtual light source (Fig. 5). These IR LEDs were controlled by Arduino microcontroller [13]. To evaluate the effectiveness of our technique, we performed an experiment wherein we compared the results of pupil detection technique using light integrated cameras with one, two, and three light sources and those of the bright pupil technique. Fig. 6 shows the system configuration.

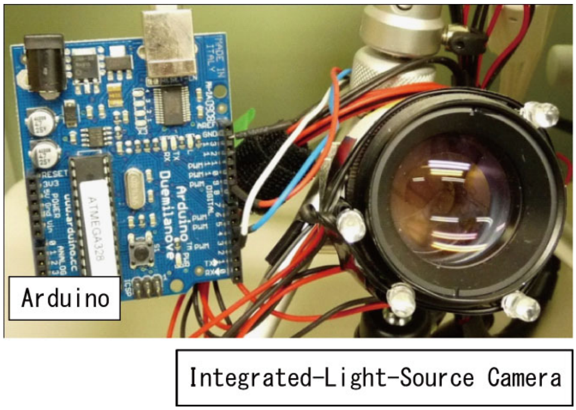

Fig. 5. Integrated-light-source camera

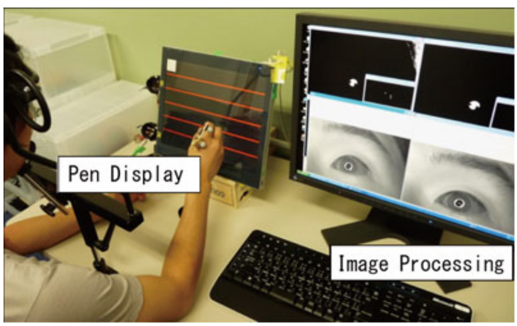

Fig. 6. Prototype of eye-tacking pen display with integrated-light-source cameras

In the experiment, we lit the IR LEDs, positioned the subject's head on a chin rest, and asked the subject to look at the marker on the left side of the pen display for calibration. Next, we displayed a white cross on the pen display and asked the subject to gaze at the center of the white cross for 10 frames. The cross was displayed on each of the 128 pixels in the right side and each of the 192 pixels in the left side. The center of the cross was displayed more to the right because a large margin of error was expected for the light integrated cameras set up on the left side of the pen display. In this manner, we evaluated four patterns (one, two, three LEDs, and bright pupil). The same light volume was ensured for the LED patterns by adjusting the light volume using a phototransistor. Five unaided-eye students participated in the experiment.

Fig. 7 shows the results. There was no significant difference between the results of two LEDs, three LEDs, and bright pupil method, as suggested by one-way analysis of the variance to average error (Fig. 8). Therefore, we decided to use two LEDs. The processing speed of our system was 9.1 fps with a computer having a Intel Core 2 Duo 3.0 GHz processor, and the delay between human action and gaze measurement was 7/30 frame.

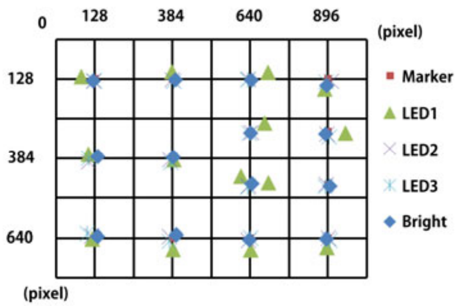

Fig. 7. Result of evaluation experiment

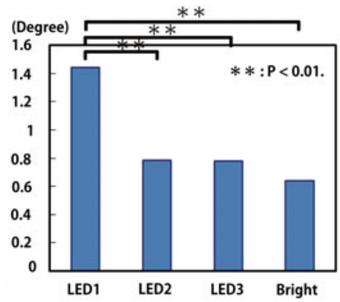

Fig. 8. Result of one-way analysis of variance

7 Assessment of Accuracy for Dynamic Gaze Tracking Accuracy

We also performed an experiment to analyze gaze interaction. Here, we asked the user to gaze at a moving marker. The speed of the moving marker was 284 pixel/s that human being drew a line. This speed was lower than that of the saccades. In addition, there were two kinds of marker move: one was the drawing of a pattern of five lines (of length from 128 pixel to 896 pixel) and the other was the drawing of the figure "Z." The average error for the five-line pattern was 42.9 pixel (12.4 mm) and that for the "Z" pattern was 48.1 pixel (14.3 mm). Fig. 9 shows an example of the results. Fig. 10 shows the interaction timing of the five-line patterns and the gaze points of the subjects. The x-axis shows the frame on following the marker, and the y-axis shows the pixel on the screen. There was a gaze position lag of approximately 0.66 s (average value for three subjects) against the movement of the marker. Fig. 11 shows the interaction timing of figure "Z." The average lag was approximately 0.61 s.

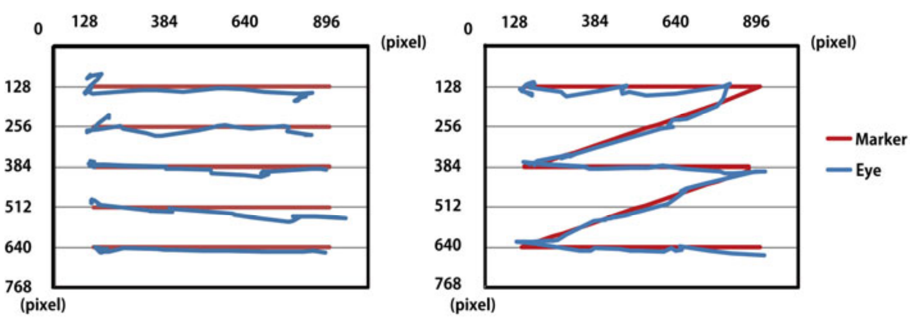

Fig. 9. Example of results

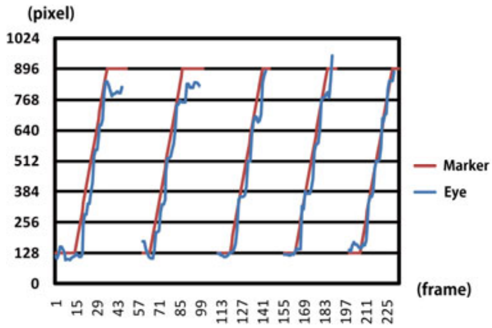

Fig. 10. Example of results of x-axis of 5-line pattern

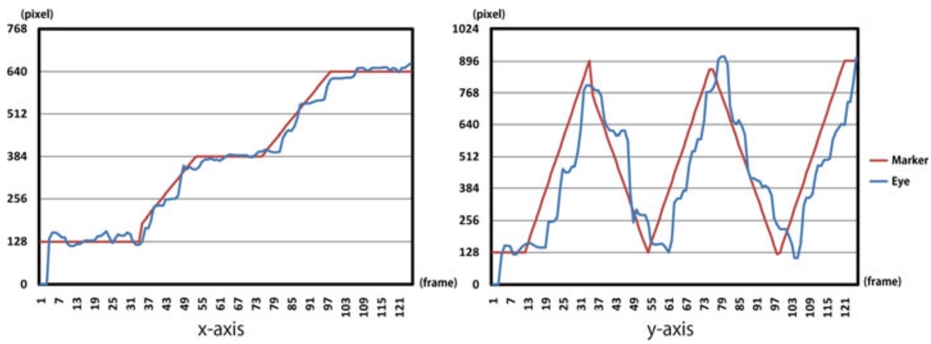

Fig. 11. Results of figure "Z" pattern

8 Conclusion

In this paper, a robust gaze estimation method was proposed for analyzing embodied interaction, and a prototype of an eye-tracking pen display based on integrated-light-source cameras was developed. The experimental results show that the accuracy of the system was approximately 12.4 mm for the 5-line pattern and 14.3 mm for the figure "Z" pattern on a 15" pen display. Because these were measured in an embodied interaction experiment, it is clear that the accuracy was sufficient for human interaction analysis.

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