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A holographic waveguide based eye tracker

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Abstract

We demonstrated the feasibility of using holographic waveguide for eye tracking. A custom-built holographic waveguide, a 20 mm x 60 mm x 3 mm flat glass substrate with integrated in- and out-couplers, was used for the prototype development. The in- and out-couplers, photopolymer films with holographic fringes, induced total internal reflection in the glass substrate. Diffractive optical elements were integrated into the in-coupler to serve as an optical collimator. The waveguide captured images of the anterior segment of the eye right in front of it and guided the images to a processing unit distant from the eye. The vector connecting the pupil center (PC) and the corneal reflex (CR) of the eye was used to compute eye position in the socket. An eye model, made of a high quality prosthetic eye, was used prototype validation. The benchtop prototype demonstrated a linear relationship between the angular eye position and the PC/CR vector over a range of 60 horizontal degrees and 30 vertical degrees at a resolution of 0.64–0.69 degrees/pixel by simple pixel count. The uncertainties of the measurements at different angular positions were within 1.2 pixels, which indicated that the prototype exhibited a high level of repeatability. These results confirmed that the holographic waveguide technology could be a feasible platform for developing a wearable eye tracker. Further development can lead to a compact, see-through eye tracker, which allows continuous monitoring of eye movement during real life tasks, and thus benefits diagnosis of oculomotor disorders.

Keywords

Eye Tracker; Holographic Waveguide; Oculomotor Disorder

1. Introduction

Binocular vision disorder (BVD) is one of the most common encounter in pediatric optometric clinics, second only to refractive errors, 8.5 times more common than all other ocular diseases combined [1]. BVD are known to relate to school performance, reading

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problems and learning disability in school children [2–4]. Although most clinical BVD management relies on the clinician's subjective observation of abnormal eye movement patterns, direct recording of eye movements is preferable, not only because it is objective and thus depends less on the expertise and experience of the clinician but also because quantitative assessment of the ocular dynamics can lead to better understanding of the underlying oculomotor control dysfunction. Furthermore, there is usually a discrepancy between the testing condition for clinical BVD assessment and the condition for daily activities. For example, most vision tests for reading are performed at a standard viewing distance of 40 cm, but for various reasons, the actual reading/writing distance of many children in school or at home is half of that [5]. How the excessive eye accommodation and convergence associated with such a short working distance may impact ocular development is unknown. A wearable, see-through eye tracker that resembles a pair of normal spectacles in front of the eye would be very useful in understanding and managing real world vision problems.

The most popular eye trackers nowadays are video-based [6]. They use eye cameras to capture the images of the anterior segment of the eye and use image processing techniques to determine the pupil center (PC) and corneal reflection (CR) [7]. However, for effective and reliable eye tracking, the eye cameras have to be able to see the cornea and the pupil unobstructed over a wide range of eye position in all directions. This requirement puts restrictions on the placement of the eye cameras in a wearable eye tracker, in which the eye cameras are typically installed above and below the eye in the frame of a pair of spectacles. How effectively such an eye tracker works would depend on how far removed the spectacle plane is from the eye. For young children and subjects of certain races, the effective spectacle plane can be very close to the eye and the eye cameras' view of the eye may be obstructed. Arranging the eye cameras around the eye also precludes bright pupil tracking, which is preferable to dark pupil tracking in subjects who have very dark irises. One solution to these problems is to use an oblique half-mirror to intercept the image of the anterior segment in front of the eye and to direct the image to cameras either above the eyes or near the temples of the subject. However, this design is bulky in front of the eye and the weight of the mirrors can make the perch of eye tracker on the nose unstable. Such an eye tracker is usually embedded in a headgear similar to a ski goggle so that it can be fastened on the head. Subjects may feel reluctant to wear such a device.

A planar waveguide uses a holographic in-coupler to couple light signal into a flat glass substrate to start total internal reflection. A matching holographic out-coupler at a different location on the glass leads the light signal out of the waveguide to achieve a lateral displacement of the signal [8]. Holographic fringes are typically recorded into the photopolymer films by the interference of two coherent laser beams [8, 9]. This holographic waveguide has found applications in wearable augmented displays, in which digital images on an OLED panel installed on the temple of a pair of spectacles are superimposed on the subject's see-through view through a holographic waveguide display [10]. There have been very fashionable consumer holographic waveguide displays in the market [11]. We decided to use the holographic waveguide in the opposite direction, as an imager of the anterior segment of the eye for eye tracking. In such an eye tracker, the in-coupler of a waveguide is installed in front of the eye on the glass of a pair of spectacles to capture the image of the

anterior segment and to guide the image to the spectacle temple where an out-coupler directs the image to a camera. Such a holographic waveguide eye tracker has the advantage of capturing the frontal view of anterior segment with a very neat design in front of the eye and no obstruction of the subject's field of view. The bright and/or dark pupil tracking can be achieved by using coaxial illumination through the waveguide and/or oblique illumination from a source on the spectacle frame. Such an eye tracker can be integrated into a pair of normal looking glasses so that oculomotor function assessment can be performed while the patient is performing daily activities in her natural environment.

In this study, we built a prototype holographic waveguide eye tracker and used an eye model to proof the concept of using a holographic waveguide imager to track eye movement.

2. Materials and Methods

A green light (505 nm), transmissive holographic waveguide, which was originally built for display, was used for prototype development. It consists of a 20 mm x 60 mm x 3 mm flat glass substrate with integrated 20 mm x 18 mm in- and out-couplers. The in- and out-couplers are photopolymer films with holographic fringes pasted on the glass substrate so that total internal reflection is induced in the glass substrate. An optical diffractive element with a 40-mm focal length was integrated into the in-coupler to serve as an optical collimator. The holographic waveguide was used in this research as an eye imager, the design of which is shown in Figure 1(A). If the holographic waveguide is shown as a feasible platform for eye tracking, we will develop infrared reflective waveguides for future research and development.

An eye model was built to test the capability of the holographic waveguide imager to monitor eye position. It was made of a high-quality porcelain prosthetic eye, which resembled the appearance of a real human eye very well. A piece of black rubber with an eye opening was mounted in front of the eye model to simulate the eyelids. The eye model assembly was mounted onto a rotational stage. Collimated green light from an LED source illuminated the eye model at a 10-degree angle relative to the norm of the corneal apex of the eye model. A relay imaging system consisting of two achromatic lens, Lens 1 (100 mm in focal length) and Lens 2 (30 mm in focal length), was employed to image the anterior segment of the model eye onto an intermediate plane with a demagnification of ~3. Then the intermediate image served as the object of the waveguide imager, as shown in Fig. 1(A). Demagnification is necessary to achieve a large enough field of view (24 mm x 24 mm) for imaging the whole anterior segment of the eye model. The light wave from this intermediate image was collected by the in-coupler of the holographic waveguide, propagated in the glass substrate, was coupled out of the waveguide, and was finally focused by a camera lens (3.67 mm in focal length) onto the camera sensor. Images were taken when the eye model was rotated to different angular positions and were fed to a computer for further processing. The relative distance and orientation between the waveguide and the camera were carefully adjusted to ensure high diffractive efficiency and image quality. A holographic waveguide imager prototype that implemented the design of Fig. 1(A) is shown in Fig. 1(B).

Modern video-based eye tracking usually utilizes two optical landmarks of the eye, the pupil center (PC) and the corneal reflection (CR). Because of a fixed axial separation between the PC and CR, the PC-CR vector is directly related to the rotation of the eyeball around its center of rotation but is less affected by the lateral motion between eye camera and the eyeball. A custom Matlab program was used to compute the locations of PC and CR in each image. The length and direction of the PC-CR was used to infer the angular eye position.

To test the holographic waveguide imager's ability to monitor eye position, the eye model was rotated from -30 degree (right) to +30 degree (left) in 5-degree steps in the horizontal direction and from -15 degree (up) to +15 degree (down) in 5-degree steps in vertical direction. At each eye position, one photo was taken through the holographic imager and a PC-CR vector was computed to determine the relationship between the PC-CR vector and angular eye position.

3. Results and Discussions

Figures 2(A) to 2(F) show images of the anterior segment of the eye model taken through the holographic waveguide imager, when the eye model was at different horizontal angular positions. The minus sign means rotation to the right. Each image contains 400×400 pixels with a pixel size of 100 μm at the pupil plane. The custom program identified the pixels of the pupil edge and fitted them with an ellipse (blue circle). The center of the best-fitting ellipse was the pupil center (green dot). The program also identified the corneal reflection, which was the high-light spot and determined its center (red circle and plus sign). The horizontal and vertical offsets between the PC and CR in pixels were then computed. It is found that between -30 and +30 degrees horizontal eye rotation, there was only a small fluctuation of vertical offsets (SD=2.30 pixels). In comparison, there was a large, monotonic increase of the horizontal PC-CR offset from -30 and +30 degrees horizontal eye rotation. The relationship between the angular position of the eye model and the horizontal PC-CR offset was highly linear ($r=0.9982$), as shown in Fig. 2(G). The linear regression model suggested that a one-degree horizontal eye rotation corresponds to a 1.442-pixel horizontal PC-CR offset, as follows

$$y = 1.442x - 6.601 \quad (1)$$

where x represents the angular eye position in degree, and y represents the horizontal PC-CR offset in pixels. At very large angular eye positions, the bright spot in the images was positioned on or beyond the limbus, the junction between the cornea and the sclera. It was no long corneal reflection but limbus or sclera reflection. Because the curvatures of the cornea and the sclera differ greatly, the relationship between PC and CR would not hold beyond the limbus. This is the physical limitations of the ranges of eye tracking using the PC-CR vector method.

Figures 3(A) to 3(F) show images of the anterior segment of the eye model taken through the holographic waveguide imager, when the eye model was at different vertical angular positions. The minus sign means upward rotation. It is found that between -15 to +15

degrees vertical eye rotation, there was only a small fluctuation of horizontal offsets (SD=0.959 pixels). In comparison, there was a large, monotonic increase of the vertical PC-CR offset when the eye was rotated from -15 to $+15$ degrees. The relationship between the eye model angular position and the vertical PC-CR offset was highly linear ($r=0.9956$) as shown in Fig. 3(G). The linear regression model suggested that a one-degree horizontal eye rotation corresponds to a 1.565-pixel horizontal offset between the pupil center and the corneal reflex, as follows

$$y = 1.565 x - 11.479 \quad (2)$$

When vertical rotation became larger than 15 degree or smaller than -15 degree, the eyelids began to block the eye pupil, which interfered with accurate computation of PC.

To evaluate the system noise of the imager and the PC-CR extract algorithm, 10 repeated measurements were made at -10 , -5 , 0 , 5 and 10 degrees horizontal eye positions. To quantify the noise, we made a scatter plot of the horizontal and vertical offset of the 10 repeated measures in a 2D plane and then found a circle that covers at least 8 of the 10 data points. The diameter of the circle was used to quantify measurement uncertainty. Figure 4 shows the scatter plot at 0 degree where the red circles represent data points and the black circle encloses at least eight data points. The uncertainty, i.e. the diameter of this black circle, is 0.61 pixels. Using the same method, we found that the uncertainties at -10 , -5 , 5 , and 10 degrees were 1.20, 0.38, 0.75, and 0.70 pixels respectively.

4. Conclusions

The benchtop prototype holographic waveguide eye tracker appears to be able to monitor eye position over a range of 60 deg horizontal and 30 deg vertical, which is comparable to the eye tracking ranges of currently available commercial eye trackers. The smaller range in the vertical direction is expected because of the interference of the eyelids. The prototype exhibits a resolution of 0.64–0.69 degrees/pixel by simple pixel count. Increasing camera pixel count and employing image processing algorithms that allow sub-pixel resolution can expect to improve resolution. The small uncertainties suggested a low level of system noise, which is important for precise eye tracking. In summary, holographic waveguide appears to be a viable platform for developing wearable see-through eye trackers. Future research and development will be focused on fabricating efficient infrared reflective waveguide components, developing more precise image processing algorithm, integrating the imaging and processing units into a wearable device and human subject validation.

Acknowledgments

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Fig. 1. Optical apparatus of the holographic waveguide based eye tracker. (A) Schematic diagram of the optical design. (B) Photo of the setup.

Fig. 2.

Experimental results from the holographic waveguide based eye tracker when the eye model was rotated horizontally. (A)–(F) Images of the eye model at different angular positions. (G) Linear regression of the horizontal PC-CR offset in pixels and the angular positions of the eye model.

Fig. 3. Experimental results from the holographic waveguide based eye tracker when the eye model was rotated vertically. (A–F) Images of the model eye at different angular positions. (G) Linear regression of the vertical distance between the pupil center and the corneal reflex center and the angular positions.

Fig. 4.
Ten repeated measurements of the horizontal offset at 0-degree horizontal position.