Title

Wearable line-of-sight detection system using micro-fabricated transparent optical sensors on eyeglasses

Author

Masataka Ozawa¹, Kota Sampei¹, Cortes Carlos¹, Miho Ogawa¹, Akira Oikawa¹, Norihisa Miki^{1,2}

¹Keio University, Japan

²JST PRESTO, Japan

Corresponding Author: Masataka Ozawa

e-mail: ozawamasataka@a2.keio.jp

Adress: 25-221, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama, Kanagawa, 223-8522, Japan.

Tel: +81-45-566-1430

Keywords

Line-of-sight; Wearable; Dye-sensitized photovoltaic device; Information communication technology

Abstract

Line-of-sight (LOS) information acquired from the eye is quite valuable in information communication technology (ICT). LOS detection systems that do not impose physical or psychological stress are strongly demanded.

In this study, we fabricated and demonstrated a wearable LOS detection system that consists of micro-fabricated transparent optical sensors affixed on eyeglasses. The sensor array detects the difference in the intensity of light reflected from the pupil and the white of the eye (sclera) and then determines the view angle. The system is also equipped with a CCD camera to acquire the user's field-of-view (FOV) to deduce the LOS by using the detected view angle. This paper first presents the shapes and arrangement of the array of four cells on the eyeglasses. With only four sensor cells, we can detect the view angle in both the horizontal and vertical directions. We describe the LOS detection system and show experimentally that the error is as small as 1.5°. In addition, we deduce the characteristic output signals of the cells when the user blinks. Eye-blinking can be used as a trigger to initiate LOS measurement, select objects, etc. Finally, we successfully demonstrate the effectiveness of the proposed system to detect a user's LOS in applications that include the selection of objects to express the user's intent and tracking the point of regards to deduce the user's interest.

1. Introduction

Since we tend to switch our gaze toward an object of interest, the information acquired from the eyes is quite useful in information communication technology (ICT) [1-4]. For example, disabled or elderly people can communicate with others by using their line-of-sight (LOS). In addition, the LOS of customers helps retailers determine appropriate placement of their products to efficiently stimulate the customers' interests. To realize these applications, various LOS detection systems have been developed [5-10]. Currently, highly accurate detection of pupil position from a Purkinje image, which is the reflection of the near infrared light from the eye, is widely used [11-13]. However, this approach requires an external near infrared light source and cameras [14-18]. Therefore, LOS detection systems that allow the user to freely move without imposing either physical or psychological stress are strongly demanded. While the LOS displays an object of the user's interest, eye-blinks can be used to select it, i.e., like a mouse click. Therefore, development of systems that can detect a user's LOS and eye-blinks is mandatory [19-21].

We have proposed a wearable LOS detection system that has transparent optical sensors on the eyeglasses, as shown in Fig. 1. An array of dye-sensitized photovoltaic cells are patterned on eyeglasses as transparent optical sensors and they detect the differences in reflected light from the pupil and the white of the eye (sclera) to deduce the pupil position, which is further used to determine the user's LOS. This system is characteristic because it is wearable like eyeglasses and light-weight and does not have any CCD cameras facing to the user, which leads to little physical and mental stress to the user. The previously proposed system had a 2×5 array of 1.5 mm square cells on the eyeglasses and could measure the horizontal position of the pupil with an accuracy of 2.3° , but could not measure the vertical position accurately [22-23]. This is because our eyes are narrow in the vertical direction and the white parts above and below the pupil are covered by the eyelid. A limbus tracking system, which is another type of LOS detection system that uses a border of the white of the eye, also encounters this problem of low accuracy in the vertical direction [24]. While the accuracy of limbus tracking in the horizontal direction is 0.5° to 7° , that in the vertical direction is 1° to 7° [25].

In this paper, we first present the shapes and arrangement of the photovoltaic cells on the eyeglasses. The cells enable us to detect both horizontal and vertical directions with only four cells (Fig. 1). The differences of the cell outputs could be correlated to both horizontal and vertical view angles. The system is also equipped with a CCD camera to acquire the user's field-of-view (FOV) to deduce the LOS by using the detected view angle. Unlike other systems, which need other external cameras to detect the pupil position, our system is simple and light weight (60 g). In addition, since the number of the cells is smaller than that in the previous device, the difficulties in fabrication as well as calculation of the LOS are reduced. Second, we deduce the characteristic output signals of the cells when the user blinks and then we employ our proposed

system in applications, including using the detected LOS to select objects and to track the point of regards to deduce the user's interest.

2. Design and Fabrication

We use dye-sensitized photovoltaic cells as optical sensors [26-28]. The fabrication processes are succinctly described in Fig. 2. We modified the electrolyte encapsulation processes. In our prior work, the cells were separated and the electrolytes for the cells were encapsulated individually [22-23]. Now, we are introducing processes such that all the cells are connected via a micro channel filled with the electrolyte. This design facilitated the electrolyte encapsulation and increased the yield while maintaining reaction efficiency. Other minor modification from our prior work includes we use titanium dioxide (TiO₂) nanoparticles (Ti-Nanoxide HT/SP, Solaronix), dye solution (Ruthenium535-bis-TBA, Solaronix), platinum (Pt-Catalyst T/SP, Solaronix), sealing films (SX1170-60, Solaronix) and liquid electrolyte (Iodolyte AN-50, Solaronix).

Fig. 3(a) describes the shapes and arrangement of the transparent photovoltaic cells. The system has only four cells. The small number of cells alleviates the difficulty in fabrication and leads to a high yield. The small number of cells also reduces the time for calculating view angles from the obtained sensor outputs. Given that the average width of the human eye is approximately 30 mm, we determine the total width of the cells to be 30 mm. Since the distance of the cell is sufficiently narrow (1 mm) and the transparent sensors are close to the eye, the user feels like he or she is wearing sunglasses with a blown color and does not see the patterns of the sensors.

Each cell has its own role. Cells #1 and #2 detect the view angle in the horizontal direction and cells #3 and #4 detect the angle in the vertical direction. As shown in Fig. 3(b), optical sensors detect the reflected light from the eye, which is stronger for white color than for black and can deduce the pupil position. For example, when the pupil moves left (A) to right (B). The output of cell #1 increases and the output of the cell #2 decreases. Then the difference of the cell output between cells #1 and #2 is used to deduce the view angle, and the vertical position is calculated by the outputs of cells #3 and #4. The gradient of the cell #3 output is used to detect the eye-blinks.

3. Experiments

3.1 Characterization of the device

We developed an algorithm to detect the view angle in the fabricated device by using the output voltages of the cells in an analog manner. As stated above, the view angle was correlated to the difference between the cell outputs. We defined the view angle as x , and the difference of the outputs as y . We first prepared a whiteboard with cross marks, as shown in Fig. 4. We placed the whiteboard 1.0 m ahead of the subject and measured the relationship as the subject moved his LOS in the horizontal direction. The subject wore the fabricated system and then gazed at each cross mark for 5

seconds while his face was fixed with his chin set on a holder. The horizontal view angle x_h was deduced by the voltages from cells #1 and #2. Fig. 5(a) shows the relationship between the view angle and the difference of cells #1 and #2 for subject A (an Asian man, age in 20s). The difference of the outputs and the view angle had a good linear relationship. Since our eyes are not symmetric, the relationship was different when x_h is greater and smaller than 0. The relationship is expressed as

$$\begin{aligned} y &= 0.13x_h & (x_h > 0) \\ y &= 0.15x_h & (x_h < 0) \end{aligned} \quad (1)$$

The vertical view angle x_v is deduced by using cells #3 and #4. Fig. 5(b) shows the relationship when the subject moves his LOS in the vertical direction. The relationship is expressed as

$$\begin{aligned} y &= 0.075x_v & (x_v > 0) \\ y &= 0.14x_v & (x_v < 0) \end{aligned} \quad (2)$$

By using Eq. (1) and Eq. (2), the view angle is correlated to the output of the cell; for example, when the difference in the output between cells #1 and #2 was 2 mV, the view angle was deduced to be about 15.4° . We define the lines described by Eqs. (1) and (2) as the calibration lines for subject A.

We experimented with five subjects to verify that the differences of the outputs and thus the view angle can be linearly correlated for other subjects. Fig. 6 shows the calibration lines for other subjects. Subjects A, B and C were Asian men in their 20s and subjects D and E were Asian women in their 20s. The individual relationships were linearly fitted, that is, expressed as $y=(a\pm\Delta a)x$, for all subjects,

$$\Delta a/a \times 100 = 4.99 \pm 3.34\% < 10\% \quad (3)$$

where Δa represents the standard deviation of a . These results, shown in Fig. 6, verified the linear relationship.

Second, we evaluated the error of the view angle resulting from the errors Δa in calibration. The errors in the view angle Δx can be described as

$$|\Delta x| = \left| \left(\frac{\partial x}{\partial a} \right) \Delta a \right| = \left| \frac{y}{a^2} \Delta a \right| = \left| \frac{\Delta a}{a} x \right| \quad (4)$$

Therefore, when presuming the error in the calibration is 5%, the error in the view angle $\Delta x/x$ is 5%. By using Eq. (4) and $\Delta a/a$ of each calibration line, the expected error is calculated. Fig. 7 shows the expected error with respect to the view angle. Δx_h represents the expected error in the horizontal direction and Δx_v represents the expected error in the vertical direction.

In this graph, Δx_{exp} , which is the expected error in both the horizontal and vertical directions, is calculated as

$$\Delta x_{exp} = \sqrt{(\Delta x_h)^2 + (\Delta x_v)^2} \quad (5)$$

In fact, we calculated the error of the view angle from the originally detected output. The error in the horizontal direction was 1.5° and that in the vertical direction was 1.3° . As shown in Fig. 7, the

results were not much different from the expected error.

3.2 LOS detection

We conducted experiments with the proposed system. A subject was asked to stare at the points on the whiteboard ahead. The subject's view angle was deduced from the sensor outputs and the calibration line obtained in advance, as shown in Fig. 8(a). The front image of the subject was acquired by the mounted CCD camera, and then the view angle was superimposed onto the acquired image to deduce the LOS, as shown in Fig. 8(b). The average detection accuracy of the view angle was 1.5° . The results verified that the proposed cell design achieved highly accurate LOS detection in both horizontal and vertical directions by using only 4 cells. The errors are considered to originate from the errors in calibration, as stated in 3.1, and the effect of the eyelid, particularly when the subject gazed at marks in the lower positions. *Since this system detects the light reflected from user's eye, the system is affected by user's surroundings. In our previous work, we designed cells for gauging the intensity of illumination, which are not influenced by the motions of users' eye. The light intensity obtained by the reference cells can be used to calibrate the cells and enabled us to detect the under various illumination conditions, which improved the detection accuracy [29].*

We also evaluated the delay of the cell reaction. Fig. 8(c) shows the reaction rate in this experiment. To reach 100% of the cell reaction, the device needs 1.49 s on average while it takes 0.64 s to reach 80 %. Our next challenge is to develop an algorithm to deduce the pupil position in a shorter period.

3.3 Eye-blink detection

Eye-blinking can be used as a trigger to initiate LOS measurement, select objects, etc. We investigated characteristic output signals of the cells when the user blinked, as shown in Fig. 9(a). Fig. 9(b) shows the cell #3 output when the subject blinked every 2 seconds while wearing the manufactured LOS detection system. Since the light reflected from the eyelid was stronger than that from the eyeball, the cell #3 output increased when the user blinked. The gradient of the cell #3 output while blinking was higher than that while the pupil was moving, and the cell #3 output steeply increased when the user blinked. The system judged an eye-blink when the gradient surpassed a threshold of 7.0 mV/s (the red line in Fig. 9(b)), which was experimentally determined. In this experiment, each of the eye-blinks contained a delay of 0.1 s to cut off the effect of noise.

We naturally blink our eyes every several seconds. To distinguish such natural eye-blinks from the intentional eye-blinks to trigger a process, we categorized types of eye-blinks, such as “double blink” (two blinks in a short period) and “long blink” (closed eyes for longer than 1 s).

3.4 Applications using the developed system

We successfully demonstrated applications of the user's LOS detected by the proposed system. The applications included a selection of objects to express the user's intent and tracking the point of regards to deduce the user's interest.

We first developed an eye-controlled human interface system using the subject's LOS, FOV and eye-blinks. The subject could select an object on the screen by his LOS and eye-blinking (like mouse clicks). Fig. 10 shows an application of the user's LOS and eye-blink. The LOS was projected as a yellow mark, as shown in Fig. 10(a). When the subject blinked, the yellow mark turned red, as shown in Fig. 10(b). The detection of an eye-blink was successful and could be used for the process of selecting. The system detected that the user first looked at a cup, then looked at a bottle of tea. The intention of the user that he wanted to drink tea was successfully expressed in real time.

Fig. 11 shows the trajectory of the LOS when the subject saw a web page. The attention to a specific position of the page was deduced from the length of time that the LOS remained on a certain position. The subject paid more attention to the position where the red was displayed, as in the pictures in the figure. Such results can be fed back to improve the design of the webpage.

Fig. 12 shows the attempt to select a product in a vending machine on a street. The subject glanced at the beverage that he wanted to drink, and then selected it by using his eye-blink. It should be noted that the experiment was conducted under sunlight. Thus, the system is readily applicable to ICT outside of a laboratory.

4. Conclusion

We developed the LOS detection system, which enables us to detect both horizontal and vertical directions with only four transparent optical sensors affixed on eyeglasses. We experimentally confirmed that our system had an average detection accuracy of 1.5° for the view angle. The results verified that the proposed cell design achieved highly accurate LOS detection in both the horizontal and vertical directions. Eye-blinks can also be deduced from characteristic output signals of the cells when the user blinks. By using both the LOS and eye-blink detection, practical applications in ICT were demonstrated. We also confirmed that the system was reliable outside a building. We believe that this system will prove profitable in various fields in ICT.

Acknowledgement

This work was supported in part by JST PRESTO (Information Environment and Humans).

Fig. 1. LOS detection system, which has transparent optical sensors on eyeglasses.

Fig. 2. Fabrication processes and operation principles of the system.

(a)

(b)

Fig. 3. The designs of the device. (a) Shapes and arrangement of the cells. (b) Way to detect the view angle.

Fig. 4. Specific experimental equipment.

(a)

(b)

Fig. 5. Characterization of the device. (a) Horizontal direction. (b) Vertical direction.

(a)

(b)

Fig. 6. Calibration lines of five subjects. Subjects A, B and C are Asian men in their 20s and subjects D and E are Asian women in their 20s. (a) Horizontal direction. (b) Vertical direction.

Fig. 7. The expected error.

(a)

(b)

(c)

Fig. 8. LOS detection. (a) View angle. (b) LOS projected onto the whiteboard. (c) Evaluation of the cell reaction time.

Fig. 9. Eye-blink detection. (a) Video image when the subject blinked. (b) System detects the gradient of the cell #3 output.

Fig. 10. Eye-controlled human interface system. The intention that subject wanted to drink a cup of tea was successfully expressed.

Fig. 11. Attention to a specific point of the web page.

Fig. 12. Selection of the drink from the vending machine on a street.

References

- [1] N. Murray, D. Roberts, Comparison of head gaze and head and eye gaze within an immersive environment, in: 10th IEEE International Symposium on Distributed Simulation and Real-Time Applications, Malaga, 2006, pp. 70–76.
- [2] R. Stiefelhagen, J. Yang, Gaze tracking for multimodal human–computer interaction, in: IEEE International Conference on Acoustics, Speech, and Signal Processing 1997, Bavaria, vol. 4, 1997, pp. 2617–2620.
- [3] R.J.K. Jacob, The use of eye movements in human-computer interaction techniques: what you look at is what you get, *ACM Transactions on Information Systems* 9 (2) (2002) 152–16.
- [4] A. Jaimes, N. Sebe, Multimodal human–computer interaction: a survey, *Computer Vision and Image Understanding* 108 (2007) 116–134.
- [5] A.T. Duchowski, A breadth-first survey of eye-tracking applications, *Behavior Research Methods, Instruments, & Computers* 34 (4) (2002) 455–470.
- [6] W.M. Smith, P.J. Water Jr., Eye movement and stimulus movement: new photoelectric electromechanical system for recording and measuring tracking motions of the eye, *Journal of the Optical Society of America* 50 (1960) 245–250.
- [7] W.J. Ryan, A.T. Duchowski, S.T. Birchfield, Limbus / pupil switching for wearable eye tracking under variable lighting conditions, *System* (2004) 61–64.
- [8] D.A. Robinson, A method of measuring eye movements using a search coil in a magnetic field, *Transactions in Biomedical Engineering* 10 (1963) 137–145.
- [9] R.W. Ditchburn, B.L. Ginsborg, Involuntary movements during fixation, *The Journal of Physiology* 119 (1953) 1–17.
- [10] M.F. Marmor, M.G. Brigell, D.L. McCulloch, C.A. Westall, M. Bach, ISCEV standard for clinical electro-oculography (2010 update), *Documenta Ophthalmologica*. 122 (2011) 1–7.
- [11] D.W. Hansen, A.E.C. Pece, Eye tracking in the wild, *Computer Vision and Image Understanding* 98 (1) (2005) 155–181.
- [12] C. Morimoto, D. Koons, A. Amir, M. Flickner, Pupil detection and tracking using multiple light sources, *Image and Vision Computing* 18 (2000) 331–335.
- [13] K. Nguyen, C. Wagner, D. Koons, M. Flickner, Differences in the infrared bright pupil response of human eyes, in: 2002 Symposium on Eye Tracking Research & Applications, 2002, pp. 133–138.
- [14] Z. Zhu, Q. Ji, Novel eye gaze tracking techniques under natural head movement, *IEEE Transactions on Biomedical Engineering* 54 (2007) 2246–2260.
- [15] D. Li, J. Babcock, D.J. Parkhurs, OpenEyes: a low-cost head-mounted eye-tracking solution, in: Symposium on Eye Tracking Research & Applications, 2006, pp. 95–100.
- [16] C. Hennessey, B. Nouredin, P. Lawrence, A single camera eye-gaze tracking system with free head motion, *Measurement* 1 (2006) 27–29.

- [17] T. Ohno, N. Mukawa, A. Yoshikawa, FreeGaze: A gaze tracking system for everyday gaze interaction, in: 2002 Symposium on Eye Tracking Research & Applications, 2002, pp. 125–132.
- [18] T. Ohno, N. Mukawa, A free-head, simple calibration, gaze tracking system that enables gaze-based interaction, in: 2004 Symposium on Eye Tracking Research and Applications, 2004, pp. 115–122.
- [19] K. Grauman, M. Betke, J. Gips, G.R. Bradski, Communication via eye blinks - detection and duration analysis in real time, in: Computer Society Conference on Computer Vision and Pattern Recognition 2001, vol. 1, 2001, pp. 1010–1017.
- [20] G.R. Bradski, K. Grauman, M. Betke, J. Lombardi, J. Gips, Communication via eye blinks and eyebrow raises: video-based human-computer interfaces, Universal Access in the Information Society 2 (2003) 359–373.
- [21] Z.R. Cherif, A. Nait-Ali, J.F. Motsch, M.O. Krebs, An adaptive calibration of an infrared light device used for gaze tracking, in: 2008 Conference on Human System Interactions, vol. 1, 2002, pp. 287–291.
- [22] T. Shigeoka, T. Ninomiya, T. Muro, N. Miki, Wearable pupil position detection system utilizing dye-sensitized photovoltaic devices, Sensors and Actuators A: Physical 146 (2010) 103–108.
- [23] A. Oikawa, N. Miki, MEMS-based eyeglass type wearable line-of-sight detection system, in: 2011 IEEE International Conference on Robotics and Automation, 2011, pp. 3640–3645.
- [24] C.H. Morimoto, M.R.M. Mimica, Eye gaze tracking techniques for interactive applications, Computer Vision and Image Understanding 98 (2005) 4–24.
- [25] A.J. Glenstrup, T. Engell-Nielsen, Eye controlled media: present and future state, Laboratory For Psychology. BSc (1995) 82.
- [26] B. Oregan, M. Graetzel, A Low Cost, high-efficiency solar cell based on dye sensitized colloidal TiO₂ films, Nature 353 (1991) 737–740.
- [27] A. Hagfeldt, M. Graetzel, Light-induced redox reactions in nanocrystalline systems, Chemical Reviews 95 (1995) 49–68.
- [28] L. Han, N. Koide, Y. Chiba, T. Mitate, Modeling of an equivalent circuit for dye-sensitized solar cells, Applied Physics Letters 84 (2004) 2433.
- [29] M. Ozawa, A. Oikawa, N. Miki, Line-of-sight detection using micro-fabricated transparent optical sensors on eyeglasses under varying illumination, in: 2012 IEEE Asia-Pacific Conference on Transducers and Micro-Nano Technology, 2012.