Biomedical Signal Processing and Control 5 (2010) 142–146

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

Note

A new method for calculating eye movement displacement from AC coupled electro-oculographic signals in head mounted eye–gaze input interfaces

Naoaki Itakura *, Kazutaka Sakamoto

Department of Systems Engineering, Faculty of Electro-Communications, The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu-shi, Tokyo 182-8585, Japan

ARTICLE INFO

Article history:
Received 1 December 2008
Received in revised form 18 December 2009
Accepted 21 December 2009
Available online 12 January 2010

Keywords:
Electro-oculograph
Eye–gaze interface
Head mounted display

ABSTRACT

Various eye movement measurement devices used in eye–gaze input interfaces are generally expensive or necessarily restrict the user's head motion. We proposed a novel eye–gaze input interface that combined a head mounted display with an electro-oculograph amplified via an AC coupling. Experiments were carried out to create a necessary calculation method for the displacement of an eye movement from an electro-oculograph amplified via an AC coupling. Offline and online analyses were performed to compare the new method of using integration to the previous method of using the maximum amplitude during an interval from 0 to 0 of the derivative AC-EOG. The mean accuracies of the choices increased from 88.8% to 96.7% in the case of 8 possible choices and from 72.8% to 86.4% in the case of 12 possible choices by using the integration instead of the maximum amplitude by the offline analyses. Moreover, the online analyses were done for confirmation of the calculation method of the displacement that was used with only the maximum displacement. For the designs with 8 and 12 possible choices, the mean accuracies of the choices were 95.3% and 88.5%, respectively.

1. Introduction

Human computer interactions (HCI) are an important field in computer science. Many computer interfaces are being developed for people with disabilities. One such computer interface is an eye–gaze interface. An eye–gaze interface is faster than a computer mouse for inputting users' selections. They are convenient in situations where keeping the hands free for another task is essential [1].

There are two main classes of eye–gaze interfaces: those that control a cursor by the user's gaze direction and those with direct input methods that rely on the user's gaze point. Eye movement is measured relative to the head's position with various oculography methods, such as infrared oculography [2–4], video oculography [5,6], and electro-oculography [7–15].

The gaze point is changed by the head's motion. When the eye–gaze monitor is a desktop display, the user's head movement must be restricted. To avoid restricting the user's head motion, a three-dimensional measurement system [16–18] can be used to measure the gaze point for direct input methods. The gaze direction can be easily obtained by infrared oculography (IROG), video oculography (VOG), and electro-oculography (EOG).

EOG is a method for measuring eye movements that is based on sensing the corneal-retinal potential. This potential arises from a steady electrical dipole, with a positive pole at the cornea and a negative pole at the retina. The potential can be estimated by measuring the voltage across electrodes placed around the eyes while the eyes move. Compared to other methods, EOG is low-cost and easy to develop, calibrate, and use [10].

The use of EOG with restricted head movement as a direct input method has been discussed in only one previous study [13]. In contrast, the control of a cursor by EOG without restricting head movement has been discussed in more studies [7–12,14,15].

Based on the two amplification methods used, DC coupled and AC coupled, there are two types of EOG: DC-EOG and AC-EOG. In DC-EOG, a voltage must be applied manually to the amplifier to adjust the baseline to zero in response to changes in the resting potential. On the other hand, AC-EOG does not require such adjustments [7–10,12].

The angle of the eye's position can be calculated as the sum of the displacements of the saccadic movements after saccadic movements have been detected [8]. This method calculates the displacement with an error of less than 2°. However, calculating the angle of the eye–gaze position would result in an error greater than 2°, even though the error in the calculation of each displacement is less than 2°.

The objective of this study was to create a necessary calculation method for the displacement of an eye movement from an electro-oculograph amplified via an AC coupling by using an eye–gaze

* Corresponding author. Tel.: +81 42 443 5248; fax: +81 42 443 5789.
E-mail address: ita@se.uec.ac.jp (N. Itakura).

1746-8094/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.bspc.2009.12.002

input interface based on a combination of HMD and AC-EOG. Experiments were carried out, and the performance of the calculation method for the displacement of an eye movement during these experiments was assessed.

2. Materials

2.1. Interface design

The direct input method is ideal for eye–gaze interfaces because it is easy and fast to use. Thus, eye–gaze interfaces that use AC-EOG are convenient for people who use wearable computers. To accommodate these users, an input screen in the form of a head-mounted display (HMD) is used, thereby attaching the input screen to the user, rather than fixing the user to the input screen. This setup is useful for wearable computers [19]. Using IROG with an HMD requires remodeling of the HMD [20]. However, an interface that combines an HMD with AC-EOG is easy to create.

Since the possible choices available to be input by the eye–gaze interface are frequently arranged in a keyboard-like pattern over the whole screen, the entire screen is the input area. When the whole screen is used as the input area, unconscious fixations occur as the user searches for a selection, even though no selection is intended [21]. Discriminating between these unintended fixations and actual selections is called the "Midas touch problem". To avoid this problem, the display was divided into input areas and a guide area, as previously proposed [22]. This reduces the "Midas touch problem" because the eyes can search for selections while in the guide area without triggering a selection. However, it was difficult to identify eye movements due to large amplitude signals in the vertical AC-EOG measurements caused by blinking.

A new display based on measuring diagonal eye movements was designed. To determine the eye's position during diagonal motion, information about vertical eye movements is combined with the AC-EOG signals in the horizontal direction. An additional advantage of this display design is an increase in the number of possible choices in the vertical direction.

The display designs for 8 and 12 possible choices are shown in Figs. 1 and 2, respectively. These display designs have a guide area and input areas. The guide area, used to search for the location of a selection, was placed in the center of the screen. The input areas were placed on the right and left sides of the screen, separated by the same view angle. Gazes that correspond to selections can be clearly distinguished from the fixations that occur while searching for a selection while inside the guide area. To provide a reasonable width within which the eyes can search for the location of selections, the width of the guide area was chosen to be 6°.

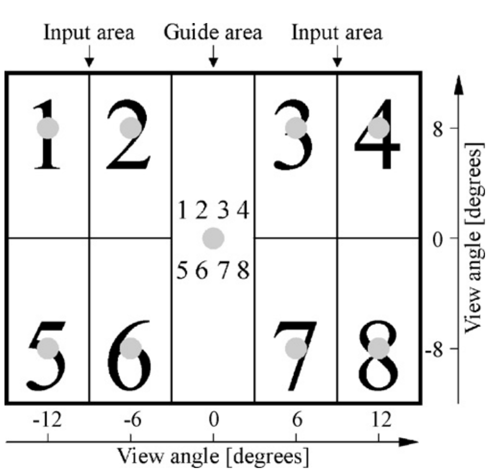

Fig. 1. Design of the display for an eye–gaze interface with 8 possible choices.

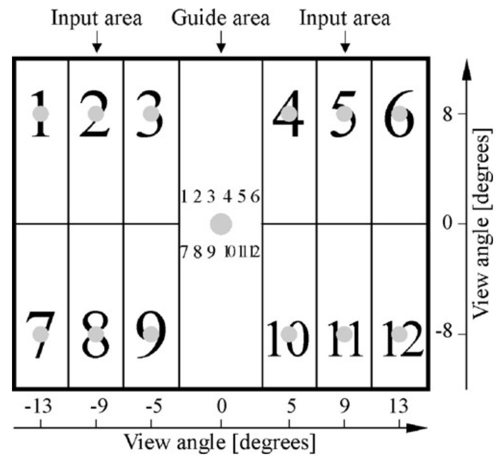

Fig. 2. Design of the display for an eye–gaze interface with 12 possible choices.

The fovea's field of view is approximately 1° [21]. The error in measuring the horizontal angle of an eye's position has been found to be less than 2° [23]. This error of 2° applies both to the position before motion and after motion when determining the displacement of an eye movement. Therefore, the actual eye position may differ by a maximum difference of 4° when the same displacement is measured. Thus, if the distance between possible selections is at least 4°, the selection at which the user is looking can be determined. Therefore, the maximum number of choices in the horizontal direction is 6.

However, it is difficult to determine the eye–gaze point for a given selection because of the width of a selection region on the screen. Therefore, it was decided that a user would gaze at a target circle (TC) at the center of each selection region. The width of the selection regions for 8 possible choices was 6°. The diameter of the TC was one quarter the width of the selection region. The letters were white on a black background.

2.2. Input procedure

The displacement of an eye movement is calculated by AC-EOG. To use AC-EOG to determine the eye–gaze position after an eye movement, the position before the movement must be known. Thus, users were instructed to look at the TC in the guide area after having found the location of the selection while looking only inside the guide area, and then they were asked to gaze at the TC of the appropriate selection region.

The determination of the selection was based only on the eye motion away from the TC in the guide area to a TC in a selection region. As a result, the user's selection can be determined by obtaining both the horizontal and vertical displacements.

2.3. Displacement calculation

The derivative of the AC-EOG signals (derivative AC-EOG) was calculated, and a low pass digital filter (30th order finite impulse response filter) with a cut-off frequency of 30 Hz was applied. The derivative AC-EOG signal was used to calculate the displacements of the eye movements. Fig. 3 shows an example of the derivative AC-EOG. The value of the derivative AC-EOG is directly proportional to the velocity of the eye movement.

A saccade is a rapid eye movement. During a saccade, the eye's velocity changes from zero to a large value and returns to zero. Therefore, an interval from 0 to 0 (a 0–0 interval) of the derivative AC-EOG with a large value, such as a h1 interval (as shown in Fig. 3), was considered to be an interval of saccadic movement.

The maximum amplitude (peak-amp) of a 0–0 interval of the derivative AC-EOG is used as the proportional value to the

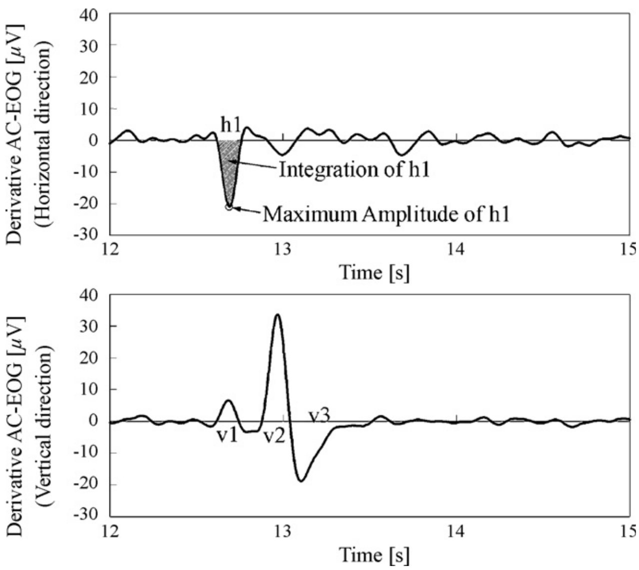

Fig. 3. An example of a derivative AC-EOG signal.

displacement of saccade in the previous studies [7,8]. On the other hand, we thought the integral of the derivative AC-EOG over the 0–0 interval of a saccade is directly proportional to the displacement. The displacement of a saccade is equal to the displacement of the eye movement if an individual will only make saccades during the eye movement.

The result of integrating the 0–0 interval of a saccade is a large value. Based on this observation, a saccade could be detected from the value of the integration. A 0–0 interval in which integration provides a value higher than a threshold determined during calibration was considered to be a saccade. A 0–0 interval in which integration yields a value below the threshold was considered to be a fixation. A state of prolonged fixation was considered to be an eye–gaze. Whenever an eye–gaze state was detected, the displacement of the preceding movement was calculated as the sum of the displacement values of saccades between the previous eye–gaze and the present eye–gaze.

2.4. Selection determination

Changes in the derivative AC-EOG signal during diagonal eye movement occur approximately simultaneously in both the horizontal and vertical directions. First, the horizontal displacement was calculated from the horizontal derivative AC-EOG, which had a large voltage change. Second, only the displacement value of the 0–0 interval in the vertical direction (v1 as shown in Fig. 3) that was the nearest to a corresponding horizontal 0–0 interval (h1 as shown in Fig. 3) that had the maximum horizontal derivative value was calculated from the vertical derivative AC-EOG. The vertical direction, either up or down, was determined from the sign of the vertical displacement value. Finally, the selection was determined by the eye's horizontal displacement and the vertical direction.

Following these algorithms for Fig. 3, it can be determined that the vertical direction was up, even though it is difficult to distinguish v1 (caused by a saccade) from v2 or v3 (caused by blinking) on the derivative AC-EOG for the vertical direction.

3. Methods

3.1. Subjects

Six healthy male subjects, with their ages ranging between 21 and 28 years (mean = 23.3 years, SD = 2.2 years), served as volunteers. None reported any medical or psychiatric problems at the time of testing. All volunteers were informed about the aims and the possible risks of the study.

3.2. AC-EOG signal acquisition

10-mm Ag-AgCl metal electrodes (NIHON KODEN Corp., Tokyo, Japan) were used. The AC-EOG signals were captured by seven electrodes placed around the eyes, as shown in Fig. 4. For the horizontal AC-EOG, two electrodes were placed 2.0 cm lateral to the outer canthi. For the vertical AC-EOG averaging the two vertical AC-EOGs, four electrodes were placed 2.0 cm above and 2.0 cm below the two electrodes for the horizontal AC-EOG. Finally, another electrode placed on the left ear served as a ground.

High-gain AC differential amplifiers (model AB-610J, NIHON KODEN Corp.) were used. These amplifiers had a gain of 10,000, a high pass analog filter (first order Butterworth filter) with a 0.08 Hz cut-off frequency, and a low pass analog filter (first order Butterworth filter) with a 30 Hz cut-off frequency. The AC-EOG signals from the amplifiers were fed into an analog to digital converter (model PCI-3153, Interface Corp., Hiroshima, Japan) in a PC. The amplified AC-EOG signals were sampled at a rate of 100 Hz with a 12-bit resolution.

3.3. Experimental procedure

An HMD (model Z800, eMagin Corp., New York, NY, USA) that delivers high-color, high-contrast images equivalent to a 105-in. screen viewed at 3.6 m (view angles of 32° horizontally and 24° vertically) was used in the experiments. The subject sat on a chair and put on the HMD, which filled the upper part of the subject's field of view.

A standard value for a movement of 1° was used to calibrate the interface prior to the experiments being carried out. During the calibration, the color of the TCs was changed from yellow to red in the following sequence: central TC, right TC at 6°, left TC at −6°, and central TC. The subjects gazed at the red TCs, thereby performing three eye movements. Since the TCs were red for 2 s, the time required for the calibration was 8 s. The standard value for 1° of eye movement was calculated as the mean of the three values obtained during the calibration. Conversion of a value to a change in view angle was carried out based on this standard value for a change of 1°.

During the experiment, the selections to be made were randomly generated numbers. One of the numbers was displayed in red in the guide area. The following four instructions were given to the subject:

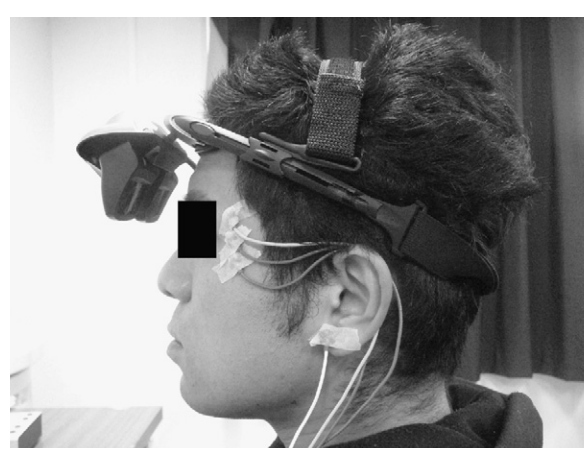

Fig. 4. Experimental setup.

1 After finding the location of the desired selection within the guide area, gaze at the central TC which is in red for 2 s in the guide area.
2 After the color of the central TC changes from red to yellow, gaze at the TC of the desired selection for 2 s.
3 While the TC is red, continue to look at the TC of the desired selection.
4 After the color of the TC of the desired selection changes from red to yellow, look back at the central TC in the guide area, and then continue the first instruction.

To obtain 5 observations for each possible selection when the numbers of possible choices were 8 and 12, then 40 and 60 selections were required, respectively. The subjects were trained once prior to the experiments done for each design. First, the experiments involving the 8-choice design were done, and then the experiments for the 12-choice design were done.

4. Results and discussions

Offline analyses were performed with the 6 subjects to compare the new method of using the integration to the method of using the maximum amplitude (peak-amp) in the previous studies [7,8].

Displacements were defined as having a size of more than 2°. The accuracy of a choice was defined as the success rate divided by the number of choices made. Table 1 shows the accuracies of the choices for all subjects with the sum of all the displacements.

In the case of 8 possible choices, the mean accuracy of the choices was 88.8% with the peak-amp. On the other hand, the mean accuracy was 96.7% with the integration. In the case of 12 possible choices, the mean accuracy of the choices was 72.8% with the peak-amp. On the other hand, the mean accuracy was 86.4% with the integration.

In the case of 8 possible choices, the mean accuracy of the choices increased from 88.8% to 96.7% (approximately 8%) with the integration instead of with the peak-amp. In the case of 12 possible choices, the mean accuracy of the choices increased from 72.8% to 86.4% (approximately 14%, as opposed to 8%). These results suggest that the integration can calculate the displacement more correctly than the peak-amp can.

In the case of 12 possible choices, however, the mean accuracy of the choices was 86.4%, as opposed to 90%. Displacements were defined as having a size of more than 2°. However, all displacements of more than 2° are not necessarily caused by eye movements because there is a possibility that there were artifacts involved in the EOG signals. Therefore, the accuracy of the choices was calculated with only the maximum displacement. Table 2 shows the accuracies of the choices for all subjects with only the maximum displacement.

In the case of 8 possible choices, the accuracy of the choices for all subjects was 90.0% with the peak-amp. On the other hand, the accuracy was 97.9% with the integration. In the case of 12 possible choices, the mean accuracy of the choices was 76.4% with the peak-amp. On the other hand, the mean accuracy was 91.4% with the integration.

Table 1
The accuracies (%) of choices for all subjects with the sum of all displacements.

	8 possible choices		12 possible choices	
	Integration	Peak-amp	Integration	Peak-amp
Sub.1	100	97.5	90.0	91.7
Sub.2	97.5	77.5	85.0	55.0
Sub.3	97.5	92.5	81.7	58.3
Sub.4	100	95.0	100	91.7
Sub.5	92.5	80.0	83.3	63.3
Sub.6	92.5	90.0	78.3	76.7
Mean	96.7	88.8	86.4	72.8

Table 2
The accuracies (%) of choices for all subjects with only the maximum displacement.

	8 possible choices		12 possible choices	
	Integration	Peak-amp	Integration	Peak-amp
Sub.1	100	95.0	90.0	90.0
Sub.2	97.5	77.5	85.0	51.7
Sub.3	100	97.5	91.7	63.3
Sub.4	97.5	92.5	100	91.7
Sub.5	95.0	82.5	93.3	70.0
Sub.6	97.5	95.0	88.3	91.7
Mean	97.9	90.0	91.4	76.4

Two-factor repeated measures ANOVA was used to assess the main effects of group 1 (integration vs. peak-amp) and group 2 (the sum of all displacements vs. only the maximum displacement). The accuracies of the choices were significantly higher with the integration compared to the peak-amp in the cases of 8 possible choices ($p = 0.004$) and 12 possible choices ($p = 0.012$). There were no significant differences in the accuracies of the choices between the sum of all displacements and only the maximum displacement in the cases of 8 possible choices ($p = 0.619$) and 12 possible choices ($p = 0.417$). The interaction between group 1 and group 2 was not significant.

In the case of 12 possible choices, the maximum mean accuracy of the choices was 91.4% with only the maximum displacement. Therefore, online analyses were performed with the 5 subjects, except for subject 2, for confirming the calculation method of the displacement that was used with only the maximum displacement. For the designs with 8 and 12 possible choices, the mean accuracies of the choices were 95.3% and 88.5%, respectively.

Previously, Kuno et al. [13] reported that the accuracy of the choices was 85% for an eye–gaze interface using the direct input method with DC-EOG and 6 possible choices. In the present study, the accuracy of the choices with 12 possible choices was more than 85%. In future studies, experiments dealing with the practical use of this design will be carried out, and the impact of the results will be assessed.

5. Conclusions

To create a necessary calculation method for the displacement of an eye movement from an electro-oculograph amplified via an AC coupling by using an eye–gaze input interface based on a combination of an HMD and AC-EOG, offline analyses were performed with the 6 subjects to compare the new method of using the integration to the previous method of using the maximum amplitude. In the cases of 8 and 12 possible choices, the mean accuracies of the choices increased from 88.8% to 96.7% and from 72.8% to 86.4%, respectively, with the integration method instead of with the maximum amplitude method. These results suggest that the integration can calculate the displacement more correctly than the maximum amplitude can.

In the case of 12 possible choices, the maximum mean accuracy of the choices was 91.4% with only the maximum displacement. Online analyses were performed for confirming the calculation method of the displacement that was used with only the maximum displacement. For the designs with 8 and 12 possible choices, the mean accuracies of the choices were 95.3% and 88.5%, respectively.

References

[1] L.E. Sibert, R.J.K. Jacob, Evaluation of eye gaze interaction, in: Proceedings of Conference on Human Factors in Computing Systems (CHI 2000), 2000, pp. 281–288.

[2] L. Chern-Sheng, H. Chien-Wa, C. Wen-Chen, C. Chuang-Chien, Y. Mau-Shiun, Powered wheelchair controlled by eye-tracking system, Optica Applicata 36 (2006) 401–412.
[3] L. Chern-Sheng Lin, C. Chao-Ning Chan, L. Yun-Long Lay, L. Jyh-Fa, Y. Mau-Shiun Yeh, An eye-tracking human–machine interface using an auto correction method, Journal of Medical and Biological Engineering 27 (2007) 105–109.
[4] T.E. Hutchinson, K.P. White, W.N. Martin, K.C. Reichert, L.A. Frey, Human–computer interaction using eye–gaze input, IEEE Transactions on Systems Man and Cybernetics 19 (1989) 1527–1534.
[5] K. Abe, M. Ohyama, S. Ohi, Eye–gaze input system with multi-indicators based on image analysis under natural light, Journal of the Institute of Image Information and Television Engineers 58 (2004) 1656–1664.
[6] K. Itoh, T. Ifukube, Image processing with video capture for eye movement measurement and its application to eye control system, Electronics and Communications in Japan Part 2 (Electronics) 89 (2006) 50–59.
[7] R. Barea, L. Boquete, M. Mazo, E. Lopez, System for assisted mobility using eye movements based on electro-oculography, IEEE Transactions on Neural Systems and Rehabilitation Engineering 10 (2002) 209–218.
[8] R. Barea, L. Boquete, M. Mazo, E. Lopez, Wheelchair guidance strategies using EOG, Journal of Intelligent & Robotic Systems 34 (2002) 279–299.
[9] R. Barea, L. Boquete, L.M. Bergasa, E. Lopez, M. Mazo, Electro-oculographic guidance of a wheelchair using eye movements codification, International Journal of Robotics Research 22 (2003) 641–652.
[10] D. Borghetti, A. Bruni, M. Fabbrini, L. Murri, F. Sartucci, A low-cost interface for control of computer functions by means of eye movements, Computers in Biology and Medicine 37 (2007) 1765–1770.
[11] J. Gips, P. DiMattia, F.X. Curran, P. Olivieri, Using EagleEyes—an electrodes based device for controlling the computer with your eyes-to help people with special needs, in: Proceedings of ICCHP: 5th International Conference on Computers Helping People with Special Needs, Vol. 1, 1996, pp. 77–83.
[12] J. Hori, K. Sakano, M. Miyakawa, Y. Saitoh, Eye movement communication control system based on EOG and voluntary eye blink, in: ICCHP 2006 Proceedings (Lecture Notes in Computer Science, Vol. 4061), 2006, pp. 950–953.
[13] Y. Kuno, T. Yagi, I. Fujii, K. Koga, Y. Uchikawa, Development of eye–gaze input interface using EOG, Transactions of the Information Processing Society of Japan 39 (1998) 1455–1462.
[14] J.J. Tecce, J. Gips, C.P. Olivieri, L.J. Pok, M.R. Consiglio, Eye movement control of computer functions, International Journal of Psychophysiology 29 (1998) 319–325.
[15] J.J. Tecce, L.J. Pok, M.R. Consiglio, J.L. O'Neil, Attention impairment in electro-oculographic control of computer functions, International Journal of Psychophysiology 55 (2005) 159–163.
[16] E.D. Guestrin, M. Eizenman, General theory of remote gaze estimation using the pupil center and corneal reflections, IEEE Transactions on Biomedical Engineering 53 (2006) 1124–1133.
[17] B. Noureddin, P.D. Lawrence, C.F. Man, A non-contact device for tracking gaze in a human computer interface, Computer Vision and Image Understanding 98 (2005) 52–82.
[18] S. Sheng-Wen, L. Jin, A novel approach to 3-D gaze tracking using stereo cameras, IEEE Transactions on Systems, Man and Cybernetics Part B (Cybernetics) 34 (2004) 234–245.
[19] F. Mizuno, T. Hayasaka, K. Tsubota, S. Wada, T. Yamaguchi, Development of hands-free operation interface for wearable computer-Hyper Hospital at home, in: Proceedings of the 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (IEEE Cat. No.03CH37439), 2003, pp. 3740–3743.
[20] H. Shimoda, Y. Nikaido, N. Umeda, N. Hayashi, H. Yoshikawa, A prototype of head-attached interface device and its functional evaluation, Transactions of the Society of Instrument and Control Engineers 36 (2000) 972–979.
[21] 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 (1991) 152–169.
[22] H. Ban, I. Sugamata, N. Itakura, K. Sakamoto, T. Kitamoto, Proposal of eye–gaze character input interface with guide area, Electronics and Communications in Japan Part III-Fundamental Electronic Science 86 (2003) 36–42.
[23] C. Chi, C. Lin, Aiming accuracy of the line of gaze and redesign of the gaze-pointing system, Perceptual and Motor Skills 85 (1997) 1111–1120.