Development of a Method for Gaze Estimation Based on Planar Approximations of Voltage Ratios Calculated from Multiple Electro-oculogram Signals

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Abstract Gaze information has been used in numerous fields such as cognitive psychology research, input interfaces, and intelligent transport systems. In this study, we focused on electro-oculographic methods because of the low level of inconvenience to users, and developed a simple method for gaze estimation based on planar approximations of the voltage ratios (V_r) calculated from multiple electro-oculogram signals. The results suggest that V_r can be used for estimating gaze without being affected by the drift phenomenon that reduces the estimation accuracy. Numerical experiments using an eyeball battery model reveal that the proposed method can be used in yaw and pitch ranging from -40° to 40° and -30° to 30° , respectively, with an estimated error of approximately 3.5° , using at least nine electrodes arranged in an L shape.

Keywords: gaze estimation, electro-oculography, planar approximation, voltage ratio.

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1. Introduction

Eye gaze or eye movement is a useful interface that can be used in daily life. The eye-gaze input interface using eye movement as the input source has been developed as a communication device for patients with severe cervical spine injury or muscular dystrophy, because eye movement is highly voluntary and causes little strain to the patients [1–6]. Many patients have successfully communicated using this interface [7]. Here, we describe a method for gaze estimation using voltage ratios of electro-oculogram signals. These ratios are expected to reduce the influence of signal drift on measurement error. We investigated the characteristics of the method by numerical simulations.

In electro-oculography, electric signals are amplified by two different methods: direct current amplification [8] and alternating current amplification [9], given that changes in electro-oculogram signals during eye movement are very small [10]. Direct current amplification amplifies the original signal directly and can thus measure the absolute direction of eye gaze. However, the electric potential signals often drift independent of eye movement. This drift arises from diverse sources including electric potentials between the skin and electrodes, infinitesimal motions of eyes, and corneal–retinal electric potential differences due to retinal metabolism. Drift causes measurement error, reducing precision. To reduce the influence of drift, leaving the electrodes for 15 min after electrode placement [11] and applying a Karman filter to the multipoint electro-oculogram [12] have been recommended. Alternating current amplification only amplifies electric potential differences, which have no electric signal drift [13]. However,

electric potential is attenuated over time; therefore, correction by signal conditioning is required. In the present study, we developed a method of measuring the eye-gaze direction directly from electro-oculography, using direct current amplification.

As described above, leaving the electrodes for a period after electrode placement reduces electric signal drift. However, it is more practical to measure the electric potentials immediately after electrode placement. We accordingly developed a measurement method that allows measurement of the eye-gaze direction immediately after electrode placement, by monitoring the ratios of electric potentials obtained from a multipoint electro-oculogram. We previously reported a method for estimating gaze in the horizontal direction by line approximation of voltage ratios [14]. In this study, we developed a method for projection of the eye-gaze direction to horizontal and vertical planes using planar approximation of electric potential ratios. We then validated the effectiveness of the method using a battery model of the eyeball [15] combined with numerical experimentation for practical use.

2. Method

The retinal side of the eyeball always shows a negative potential, whereas the corneal side shows a positive potential [16]. Consequently, the eyeball always has a miniature bipolar static electric charge. Thus, when eye movement occurs, electric potential gradients around the eye socket change two-dimensionally with the magnitude of eye movement. This change in electric potentials can be measured by electrodes placed on the skin. The measurement of eye-gaze direction by this method is electro-oculography.

Here, we used the ratios of electro-oculograms obtained from more than three electrodes to measure the eye-gaze direction. The detailed measurement method is as follows:

1) We defined θ degrees in the yaw direction and ξ degrees in the pitch direction as the known eye-gaze direction. The electric potential (electro-oculogram) between two arbitrary electrodes selected from more than three was measured. The ratio of the electro-oculogram between the two electrodes was defined as V_r , which is approximated by the following plane equation:

$$V_r = C_\theta \theta + C_\xi \xi + C_B \quad (1)$$

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Fig. 1 An eyeball battery model. The origin of the coordinates is the center of the right eyeball.

The least-squares method was used to calculate the determination coefficients C_θ , C_ξ , and C_B . When the planar approximation of Vr was applied, maximum and minimum values of Vr were determined. To determine these, we calculated determination coefficients as the maximum values within ± 3 . We set a threshold value when planar approximation was applied for the determination of Vr , and only Vr values above the threshold were used for estimation of the eye-gaze direction. The direction components θ and ξ within the range of maximum and minimum Vr were recorded for each Vr value.

2) After obtaining Vr for which the determination coefficients for planar approximation were above the threshold value, the electro-oculogram was measured to determine Vr . The resulting Vr was applied to the linear equation (1) with variables θ and ξ .

3) When more than two equations (1) with different Vr were obtained, two equations were randomly selected. If the angle between the two equations exceeded the threshold value A_{th} , the simultaneous linear equations were solved for θ and ξ . When θ and ξ were within the range of approximated eye-gaze directions recorded in 1), θ and ξ were accepted as valid; if not, they were discarded. When several pairs of θ and ξ were obtained, mean values of θ and ξ were calculated as the measurement direction component values.

4) If there were fewer than two linear equations for θ and ξ , or all pairs of θ and ξ values were discarded, the measurement direction could not be determined.

We used a battery model of the eyeball [15] mimicking cornea–retina potential generation to evaluate the determination of the eye-gaze direction described above. In the battery model, we assumed that an electric current, I , runs from the retina to cornea within the eyeball and that the eyeball is filled with a uniform medium with electric conductivity, σ . As shown in **Fig. 1**, the X, Y, and Z axes are defined as forehead, horizontal, and vertical axes, respectively, and the yaw and pitch eye-gaze directions are defined as θ and ξ , respectively. When electrodes are placed at x , y , and z and the radius of the eyeball is a , the distances between electrodes and the positive pole r and the negative pole r' are expressed by equations (2) and (3), respectively:

$$r = \sqrt{(x - ak)^2 + (y - am)^2 + (z - al)^2} \quad (2)$$

$$r' = \sqrt{(x + ak)^2 + (y + am)^2 + (z + al)^2} \quad (3)$$

$$(k = \cos \theta \cos \xi, m = \sin \theta \cos \xi, l = \sin \xi)$$

The voltage between electrodes 1 and 2 around the eyeball is expressed by equation (4):

Fig. 2 Arrangement of electrodes. The origin of the coordinates is the center of the right eyeball.

$$\Delta V_{12} = \frac{I}{4\pi\sigma} \left\{ \left(\frac{1}{r_1} - \frac{1}{r'_1} \right) - \left(\frac{1}{r_2} - \frac{1}{r'_2} \right) \right\} \quad (4)$$

Previous studies showed that the calculated voltage between two points in the battery model of the eyeball closely approximates measured data [15]. Thus, the battery model is useful for simulating electro-oculography.

Changes in cornea–retina potential, which cause signal drift, are correlated with temporal changes in current density in equation (4). Thus, to avoid signal drift, the ratios of electric potentials obtained from several electrodes can be used to remove the current density term in equation (4). For instance, three electrodes are placed and the electric potential ratios between electrodes 1–2 and 2–3 are calculated by equation (5), removing the term of current density.

$$\frac{\Delta V_{12}}{\Delta V_{23}} = \frac{\left(\frac{1}{r_1} - \frac{1}{r'_1} \right) - \left(\frac{1}{r_2} - \frac{1}{r'_2} \right)}{\left(\frac{1}{r_2} - \frac{1}{r'_2} \right) - \left(\frac{1}{r_3} - \frac{1}{r'_3} \right)} \quad (5)$$

This can be used as an index of the eye-gaze direction with minimized signal drift.

We used only the right eye in the model. The electrodes were placed around the eyeball in an L-shape (**Fig. 2**). When the number of electrodes is N , the X, Y, and Z coordinates (x_i , y_i , z_i) [mm] of electrode i ($i = 1, \dots, N$) are expressed as follows:

$$(a + 5, 20 - 100(i - 1)/(N - 1), -15) \quad (6)$$

$$\text{for } i = 1, \dots, (N - 1)/2$$

$$(a, -30, -15 + 80(i - 1 - (N - 1)/2)/(N - 1)) \quad (7)$$

$$\text{for } i = (N - 1)/2 + 1, \dots, N$$

where N is an odd number, and a is the radius of the eyeball.

We assessed the eye-gaze direction by planar approximation from the ratios of voltage using the battery model of the eyeball with numerical calculation.

The range of eye-gaze directions was defined as follows: θ , -40 to $+40$ deg and ξ , -30 to $+30$ deg. For calibration for planar approximations of Vr , we used Vr values calculated from equation (5) at different θ and ξ at 5 deg intervals, and estimated the coefficients C_θ , C_ξ , and C_B in equation (1) by the least-squares method. We investigated the basic characteristics of gaze-estimation. The success rate of eye-gaze direction estimation and mean estimate errors within a range of eye gaze when subjects moved their eye-gaze direction by 1 deg intervals were evaluated. The success rate was defined as the proportion of times θ and ξ were successfully estimated to the total number of target points (4941, or 81×61 points). The mean estimate error was calculated as the mean absolute value of error among the estimated gaze directions.

We evaluated the influence of the number of electrodes used in estimation (5, 7, 9 or 11).

We also evaluated the effects of noise (fluctuations of contact impedance) added to electric potential at each electrode and to voltage between two electrodes (bias of the amplitude coefficient in whole amplification circuit). In the numerical simulation, the maximum noise added was 10–20% of the values of the electro-oculogram signals (note: the signal was approximately $400\ \mu\text{V}$ in the eyeball model when the eyeball radius a was 12 mm and $I/4\pi\sigma$ was $25\ \mu\text{Vm}$). Electric noise in each electrode was expressed as $N(0, \sigma_v^2)$. σ_v were set at 1, 2, 5, 10, 20, or $50\ \mu\text{V}$. We assumed that biased constant noise with a mean value of μ_{AV} was applied to the voltage between two electrodes. The same value of the biased noise was added to all the voltages, and μ_{AV} was set at 10 to $100\ \mu\text{V}$ for every $10\ \mu\text{V}$. (Note: addition of different values to each voltage included the addition of this random noise to each electrode).

We also evaluated the influence of the displacement of electrode location. Biased noise of a magnitude of μ_{EI} with random directions was applied to the electrode location. μ_{EI} were set at 0.1 to 1 mm for every 0.1 mm.

Programs for all the numerical simulations were written in the C language (gcc 4.2.1, MacOSX 10.7.5).

3. Results

In the battery model used, the eyeball radius a was 12 mm, $I/4\pi\sigma$ was $25\ \mu\text{Vm}$, and the origin of coordinates (0, 0, 0) was the center of the right eyeball. The coordinates of the electrodes were expressed as in equations (6) and (7).

Figure 3 shows the characteristics of voltage ratios when 5 or 11 electrodes were placed around the eyeball. The voltage ratios displayed two typical characteristics. The voltage ratios showed planar characteristics at the ranges of θ from 0 to +40 deg and ξ from +10 to +40 deg, (**Fig. 3a**) and θ from -40 to 0 deg and ξ from -30 to +30 deg (**Fig. 3c**). In contrast, the voltage ratio shows complex characteristics in **Fig. 3b** and **3d**.

The numbers of available voltage ratios from 5, 7, 9 and 11 electrodes were 90, 420, 1260 and 2970, respectively. When planar approximation gave determination coefficients of 0.9 and above, the numbers of voltage ratios were 53 (59%) for 5 electrodes, 246 (59%) for 7 electrodes, 727 (58%) for 9 electrodes, and 1693 (57%) for 11 electrodes. We estimated the eye-gaze direction using planar approximation with determination coeffi-

cients of 0.9 and above.

Figures 4 and 5 show the results of numerical experimentation using different numbers of electrodes. **Figure 4** shows the mean estimate error and success rate of eye-gaze direction estimation. **Figure 5** shows the results of estimate error within a range of eye-gaze direction.

The success rates were 45% for 5 electrodes, 95% for 7 electrodes, 100% for 9 electrodes, and 100% for 11 electrodes, indicating that more than 7 electrodes are sufficient for eye-gaze direction estimation to fall within the range of the eye-gaze direction. The mean estimate errors were 7.4 deg for 5 electrodes, 5.1 deg for 7 electrodes, 3.8 deg for 9 electrodes, and 3.2 deg for 11 electrodes, indicating that 9 or more electrodes yield mean estimate error of 3–4 deg.

Figure 5 shows that estimation of the eye-gaze direction was not possible near the central region of the eye-gaze direction when 5 electrodes were used. Although estimates were possible in the entire range of the eye-gaze direction using 7 electrodes, the accuracy of estimation in the central region was low. When 9 or 11 electrodes were used, the accuracy of estimation was improved in the central region of the eye-gaze direction range. However, the estimation error became high for θ ranging from -20 to +10 deg and for ξ around ± 0 deg. In addition, regions with lower estimation accuracy were found around the center of the range.

Fig. 4 Results of gaze-estimation experiments with changing number of electrodes. a. Success rates. b. Mean error.

Fig. 3 Examples of voltage ratio characteristics. Numbers of electrodes are 5 (a and b) and 11 (c and d).

Fig. 5 Estimation errors with gaze range. The numbers of electrodes are 5, 7, 9 and 11 for a, b, c and d, respectively.

Fig. 6 Results of mean error of gaze-estimation in experiments with addition of random noise. Numbers of electrodes are 9 and 11 for a and b, respectively.

Fig. 7 Results of mean error of gaze-estimation in experiments with moving average of voltages. Numbers of electrodes are 9 and 11 for a and b, respectively. The solid or open circles indicate results with σ_v at 10 or 50 μV , respectively.

Based on the results of measurements using different numbers of electrodes, 9 electrodes were sufficient for estimating the eye-gaze direction. Accordingly, numeric experimentation with noise addition was performed using 9 and 11 electrodes. Estimation was evaluated by the mean success rate and estimation error from 100 measurement trials.

Figure 6 shows the results of electric potentials with $N(0, \sigma_v^2)$ noise added to each electrode. The success rate of estimation was 100% for all σ_v using 9 or 11 electrodes. Thus, we could estimate the eye-gaze direction within the entire range, whereas the mean estimation error was 8 deg or greater when σ_v was greater than 10 μV .

The addition-averaging method using signals obtained from multiple measurements is effective in eliminating fluctuations from the mean value of signals. However, this method is in practice not suitable for gaze estimation using electro-oculographic signals. Therefore, we decided to take the moving average of the measured electro-oculogram signals in the time direction for removing noise with a mean value of 0 from signals in which noise was included. Here the moving average of the measured electrical potential signal with the same gaze-direction at the N_a point was calculated, followed by eye-gaze estimation. **Figure 7** shows the results of estimation with σ_v at 10 or 50 μV . The success rate of estimation was 100%, and the mean estimation error became smaller with increasing N_a . When σ_v was 50 μV , the mean estimation error was less than 5 deg with N_a of 50.

Figures 8 and 9 show the results of estimation with biased noise applied to the voltage between two electrodes and to each electrode location, respectively. In both cases, the success rate of estimation was 100%, and the mean estimation error increased with increasing biased noise. The error became greater than 5 deg when bias noise of 20 μV was added to the voltage between two

Fig. 8 Results of mean error of gaze-estimation in experiments with addition of bias noise to voltages. Numbers of electrodes are 9 and 11 for a and b, respectively.

Fig. 9 Results of mean error of gaze-estimation in experiments with addition of bias noise to positions of electrodes. Numbers of electrodes are 9 and 11 for a and b, respectively.

electrodes and 0.5 mm displacement was added to the electrode location.

Next, we investigated the effect of changes in threshold angles, A_{th} , between the two linear equations for estimation of eye-gaze direction. **Figure 10** shows the results of estimation when random noise was added to the electric potential of each electrode and to voltage between two electrodes, and biased noise was added to electrode under random direction. When the angle threshold A_{th} increased, estimate error tended to decrease. For A_{th} between 0 and 30 deg, the addition of random or biased noise to measured electric potentials or voltages between two electrodes reduced the estimate error by 2 deg for electric potentials and 3 deg for the potential difference between two electrodes. However, when the angle threshold increased, the success rate of estimation did not reach 100% in some cases, but decreased by 5% when 9 electrodes were used for measurement.

For practical application, it is necessary to investigate the influence of individual differences in size and shape of the eyeball and its surroundings on the success rate and estimation error. In the eyeball battery model, the radius of the eyeball, the current strength, the positions of positive and negative poles, and the distance between the poles and the center of the eyeball are modifiable parameters. We conducted numerical simulations by changing the values of these parameters by approximately 10%, and obtained results similar to those shown in **Figures 4–10**. These findings revealed that small individual differences in size and shape of the eyeball and its surroundings do not influence gaze estimation in model simulations.

4. Discussion

The use of planar approximation and L-shape placement of 9 or more electrodes reduces noise adequately, allowing estimation of eye-gaze direction with mean estimate errors within 4 deg, when

Fig. 10 Results of gaze estimation in experiments with changing angular threshold showing success rates (a, c, e, g, i and k) and mean error (b, d, f, h, j, and l), when random noise is added to potentials (a, b, g, and h), when bias noise is added to voltages (c, d, i, and j), and when bias noise is added to electrode positions (e, f, k, and l). Numbers of electrodes are 9 for a, b, c, d, e and f, and 11 for g, h, i, j, k and l. The solid or open circles indicate results with σ_V at 10 or 50 μV (a, b, g, and h), $\mu_{\Delta V}$ at 10 or 50 μV (c, d, i, and j), or μ_{EI} at 0.1 or 0.5 mm (e, f, k, and l), respectively.

the range of the eye-gaze direction was set between -40 to $+40$ deg in the horizontal plane and -30 to $+30$ deg in the vertical plane. The moving-average method with more than 50 points reduced random noise to a mean value of 0. We found that constant noise and the signal gap of electric potential between two electrodes or electrode location can be reduced by adjusting the angle

threshold of two linear equations to approximately 30 deg. For the constant noise with a mean value of 0, signal smoothing appears to render the noise component 0. For the signal gap, the estimation error increases with increased sensitivity of estimation of the eye-gaze direction to noise. When the eye-gaze direction is calculated by two linear equations, if the angle between the two linear equations reaches 0 (i.e., parallel direction), a small amount of noise greatly affects the solution of the two equations. When the angle between the two equations is less than the threshold angle, estimation is able to discard solutions that are markedly different from the true direction, and the accuracy of the estimation is improved. However, as shown in **Fig. 10**, if the threshold angle is set too large, the success rate of estimation of the eye-gaze direction decreases in some cases, owing to increased risk of discarding a solution. Thus, the angle threshold value and accuracy of eye-gaze direction estimation balance each other. It is necessary to set the threshold angle within a range that can maintain an acceptable balance between the threshold angle and accuracy of eye-gaze direction estimation.

This estimation method revealed the sensitivity of the electrodes to displacement (**Fig. 9**), although adjusting the angle threshold reduced the estimated errors by several degrees (**Fig. 10f and 10l**). It seems that displacement of electrodes by several millimeter in actual experiments leads to large estimation error. Therefore, for practical application, it may be necessary to consider the method of electrode placement and algorithmic solution to counteract the displacement of electrodes.

5. Conclusion

We confirmed that the eye-gaze direction can be readily estimated by measuring electric potential ratios using an electro-oculogram with planar approximation, which depends on temporal changes in electro-oculogram and improves the accuracy of electrooculography. L-shape placement of 9 electrodes allows estimation of the eye-gaze direction within 4 deg of mean estimate error. Using moving-averaging, random noise with a mean value of 0 can be removed from the acquired signal. Constant noise and a signal gap in electric potentials between two electrodes may be reduced by increasing the threshold angle between two linear equations.

To further improve measurement accuracy, analyses of the factors affecting estimation error and their countermeasures including displacement of electrodes are necessary. We also plan to conduct an experiment on human subjects to validate the effectiveness of this method of eye-gaze direction estimation for practical use. However, our method has not been tested for the effects of eye blinking, facial muscle activity, and crosstalk from the other eye during measurement. These effects have to be investigated to improve the stability.

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Conflicts of interest

We have no conflicts of interest relationship with any companies or commercial organizations based on the definition of Japanese Society of Medical and Biological Engineering.

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