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Automatic Drift Calibration for EOG-based Gaze Input Interface

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***Abstract*— A drift calibration technique for DC-coupled EOG (electrooculogram) systems is proposed. It assumes a non-linear relationship between EOG and eye angle and estimates the absolute eye angle by the EOG differences during saccade. Drift is calibrated every saccade without user's explicit action, so it is especially suitable for long-term gaze input interfaces. An experiment confirms that it can estimate horizontal absolute eye angle with an error of about 5° in addition to accurate eye movement.**

I. INTRODUCTION

Since the eyes provide valuable information about the user, gaze input interfaces have been researched to enhance human computer interaction. They are essential for the disabled, such as those with ALS, and are becoming important for the healthy since they provide quick and direct access to surrounding objects.

For these interfaces, an effective eye tracking technique is crucial. The most popular approach to date uses infrared camera(s), for example, corneal reflection tracking [1] and pupil tracking [2]. Different from these techniques, EOG is the resting potential of the retina as measured by electrodes attached to the skin around the eyes to detect eye movement. It is relatively low cost and does not obstruct the user's visual field. Moreover, EOG provides wide ranging eye tracking, for example it can detect extremely large or quick eye movements, and it works even if the eyes are closed. Because of these features, EOG suits everyday interaction, and many studies have already used EOG to implement eye gesture or gaze input interfaces [3], [4], [5]. In practice, however, it is used only in specific fields such as interfaces for the disabled or clinical examinations.

Implementing an EOG-based interface raises several issues, among which drift is a major concern since it decreases the tracking accuracy. Drift is the baseline shift of EOG values. The amplifier's output involves not only eye movement components but many other factors, such as the electrode potential and environment light level, and the baseline shifts gradually with time. Even though the subject is gazing at the same target, the DC level of EOG does not remain the same. This means that the estimated eye angle changes even if the eye does not move. Since the drift changes the baseline slowly and it can be ignored over short periods, EOG offers accurate relative eye movement, e.g. saccade amplitude. Drift, however, can not be ignored over longer periods and EOG often provides inaccurate absolute eye angle.

Several strategies have been proposed to overcome the drift issue. The first strategy tries to lower the impact of the drift; examples include applying wavelet transform [6] and using multiple EOGs [5]. This strategy is effective in extending the period over which the drift can be ignored, however, it does not offer accurate estimation outside that period. Using AC-coupled EOG is an easy solution for the drift problem and absolute eye angle estimation was tackled in [7]. Unfortunately, slow eye movement is not captured and it will continue to provide inaccurate angle readings once an estimation error occurs.

The second approach involves calibration. Calibration is used to offset the effect of drift after it can not be ignored. Calibration is generally quite simple, for example the user is asked to gaze at a specific target; frequent calibration can ensure accurate eye angle estimation [8]. However, calibration requires the user's explicit effort and it often interrupts the main function of the interface. Calibration using visual evoked response (VEP) [9] is unique, but it is difficult to put into practical use because the user should gaze at flashing objects.

The third approach is tuning the interaction. The drift can be ignored when the interaction is based not on absolute eye angle but on short time relative eye movement (saccade) and its sequence (eye gesture). Many saccade-based interaction schemes have been developed [3], [4], [6]. These are effective in some applications, however they impose severe restrictions on interaction design. It is possible but hard to apply EOG to gaze-based interaction. The immediately prior eye gesture that includes calibration can be used to realize these interactions, however an additional gesture is necessary and the available period is short.

As stated above, no conventional strategy is effective enough to solve the drift problem; therefore, they are often combined for practical use. Nevertheless, the drift issue remains a major concern for EOG-based interaction. For the purpose of eliminating this issue, we propose a new automatic drift calibration technique and evaluate its accuracy.

II. PROPOSED TECHNIQUE

Our proposed technique adopts the second strategy mentioned above but calibration is performed automatically at every saccade. It differs from conventional alternatives in the following points; EOG is taken to be a non-linear function of eye angle, eye angle is estimated by multiple EOGs, absolute eye angle in addition to relative movement is output after

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each estimation (the drift is calibrated every estimation), and no intentional operation by the user is required.

When the user is gazing at surrounding objects, saccades occur frequently because they follow fixations, whose periods lie in the range of 200-400ms [10]. Thus this technique is suitable for applications that utilize the user's gaze as the input interface.

The conventional linear model based gaze estimation, which gives accurate relative movement but inaccurate absolute angles without frequent explicit calibration, is described to highlight the proposed technique.

A. Linear model based estimation

It has been mentioned that the relationship between EOG and eye angle can be considered as linear for practical use. The linear model described below is used to estimate eye angle or eye movement in many studies including those mentioned above (e.g. [8]). In order to simplify the description, only horizontal eye movement is considered.

EOG is determined from E_0 and E_1 which are the potentials obtained at electrodes 0 and 1.

$$EOG(t) = E_1(t) - E_0(t) \tag{1}$$

The measured EOG includes the ideal retina driven potential, p, which is a function of eye angle of θ (the angle between the front of the face and the gaze direction, right side is positive), and noise components including DC offset $e(t)$.

$$EOG(t) \quad = \quad p(\theta(t)) + e(t) \tag{2}$$

$e(t)$ consists of various noise components, and its very low frequent component is called drift. Since the DC level of $e(t)$ is much larger than $p(\theta)$, the difference in EOG is used for eye angle estimation.

$$\begin{aligned} \Delta EOG(t_1, t_0) &= EOG(t_1) - EOG(t_0) & (3) \\ &= p(\theta(t_1)) - p(\theta(t_0)) + \Delta e(t_1, t_0) & (4) \end{aligned}$$

Conventional techniques assume $p(\theta)$ to be a linear function of θ using coefficient a, and generally $\theta(t)$ is represented as follows,

$$p(\theta(t_1)) - p(\theta(t_0)) = a(\theta(t_1) - \theta(t_0)) \tag{5}$$

$$\theta(t) = \frac{1}{a}\{\Delta EOG(t, t_0) - \Delta e(t, t_0)\} + \theta(t_0) \tag{6}$$

Assuming $\Delta e(t, t_0)$ to be zero (this can not be estimated),

$$\theta(t) \approx \frac{1}{a}\Delta EOG(t, t_0) + \theta(t_0) \tag{7}$$

Thus eye angle is calculated using the immediately prior measured $EOG(t_0)$, $\theta(t_0)$ and a. If $\Delta e(t, t_0)$ remains small enough, the above provides reasonable answers, which also means relative eye movements $\Delta\theta$ over short periods are accurately obtained. However, the offset due to drift worsens with elapsed time; Δe becomes significant and finally the estimation accuracy degrades. Thereafter, this equation always gives inaccurate answers. Updating t_0, the calibration step, is effective in suppressing the estimation error. Unfortunately, conventional calibration techniques are not suitable for everyday interfaces.

B. Relationship between EOG and eye angle

While the linear model is used by most studies, the relationship has been investigated in more detail to build a comprehensive model, and it is known that EOG and eye angle have a non-linear relationship. For example, Häkkinen et al. measured EOG by placing many electrodes very close to the eyes and reported that a simple mono polar model yielded a good match [11]. Itsuki et al. reported that EOG can be calculated by a dipole model [12]. Berg et al. investigated several models with one or two dipoles for each eye, and reported that the locations and orientations of the dipoles that offer reasonable fit depend on the type of eye activity [13]. These studies suggest that EOG and eye angle should be modeled as having a non-linear rather than a linear relationship.

C. Non-linear model based estimation

To explain the proposed technique, the i-th EOG from a series of EOG is given by equation (4),

$$\Delta EOG_i(t_1, t_0) = p_i(\theta(t_1)) - p_i(\theta(t_0)) + \Delta e_i(t_1, t_0) \tag{8}$$

Considering saccade, $\Delta e_i(t_1, t_0)$ becomes negligible because $p_i(\theta(t_1)) - p_i(\theta(t_0))$ becomes larger and the degree of drift is small due to the short time difference. Thus ΔEOG_i for the eye movement from θ_0 to θ_1, which corresponds to $\theta(t_0)$ and $\theta(t_1)$, can be represented as follows in the presence of saccade.

$$\Delta\mathbf{EOG}_i(\theta_1, \theta_0) \approx p_i(\theta_1) - p_i(\theta_0) \tag{9}$$

It is important to note that the above equation has no time-related components; previous techniques make ΔEOG a function of time t. In order to make clear the difference, $\Delta\mathbf{EOG}$ is used as a θ-oriented function in the proposed model. Considering that $p_i(\theta)$ is given as a non-linear function and multiple EOGs are measured (measured as $\Delta\overline{\mathbf{EOG}}_i$), we can get angles ($\theta_1$, θ_0) by solving the following formula ($m \geq 2$),

$$\sum_{i=1}^{m}\{\Delta\overline{\mathbf{EOG}}_i - (p_i(\theta_1) - p_i(\theta_0))\}^2 \rightarrow min \tag{10}$$

This formula shows that the absolute eye angle is calculated from just the multiple $\Delta\overline{\mathbf{EOG}}s$ over short periods, which means the offset due to drift is automatically compensated at every saccade without any effort by the user.

D. Estimation of the non-linear function

The proposed technique works well when EOG is represented using ideal function $p(\theta)$, a non-linear function of θ. The coefficients of $p_i(\theta)$ can be estimated by the measured signals when the function being used is known. When the user is asked to shift her/his gaze from θ_{k0} to θ_{k1}, the i-th EOG: $\Delta\overline{\mathbf{EOG}}_{i,k}(\theta_{k1}, \theta_{k0})$ is measured. By repeating this, K sets of $\{\Delta\overline{\mathbf{EOG}}_{i,k}, \theta_{k0}, \theta_{k1}\}$ are obtained, and the following formula gives the coefficients of $p_i(\theta)$.

$$\sum_{k=1}^{K}\{\Delta\overline{\mathbf{EOG}}_{i,k}(\theta_{k1}, \theta_{k0}) - (p_i(\theta_{k1}) - p_i(\theta_{k0}))\}^2 \rightarrow min \tag{11}$$

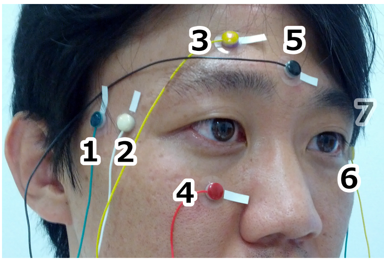

Fig. 1. Electrode arrangement
Examined arrangement of seven electrodes. #7 is not shown but is symmetrical to #1. Generally used positions are #2, 3, 4 and 6.

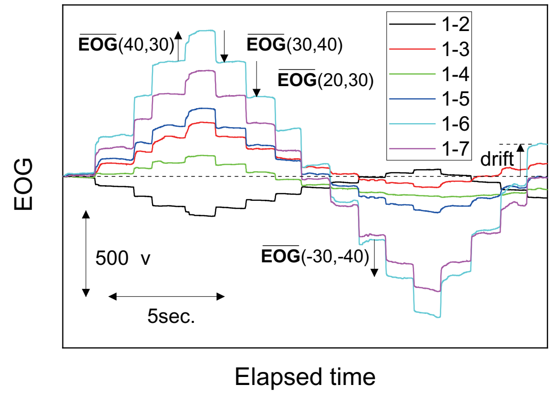

Fig. 2. Example of measured EOG
The user gazed sequentially at nine targets spaced at 10°. The difference in EOG is manually clipped for $\Delta\overline{\mathbf{EOG}}$.

Several models already exist to represent EOG, and they may be suitable for $p(\theta)$. However, these models often use complicated functions and the angle has to be calculated as an inverse problem. Since the objective is to get accurate eye angles rather than to use accurate models, simple polynomial equations of θ can be used. Using simple polynomial equations ensures that almost all cases will be well approximated, even though the electrode arrangement or the electrical property of facial tissue differs with the user. When using the n-th polynomial functions of θ as $p(\theta)$, the differential of the i-th EOG is represented as follows and $\{a_{ij}\}$ can be estimated from formula (11).

$$p(\theta) \approx \sum_{j=1}^{n} a_j \theta^j \tag{12}$$

$$\Delta\mathbf{EOG}_i(\theta_1, \theta_0) \approx \sum_{j=1}^{n} a_{ij}(\theta_1^j - \theta_0^j) \tag{13}$$

III. Evaluation

An experiment was conducted to confirm the proposed technique. The arrangement of the seven electrodes used (8mm in diameter) is shown in Fig. 1. Three electrodes; horizontally far from the eye, #1 and #7 (not shown), and between the eyebrows, #5, were examined in addition to the general arrangement (#2, 3, 4, 6). The earth electrode was attached to the left side cheek. Nine targets were placed horizontally in line with 10° spacing from -40° to +40° (right side for the subject is positive). The subject placed his head into the holder and was asked to gaze at the targets sequentially (0,10,20,30,40,30,...-30,-40,-30,...,0). The EOGs were recorded using DC coupled amplifiers with 200Hz sampling, 50Hz notch filter, and 30Hz low pass filter. The recorded signals were then median filtered with window size of 250msec. to reduce high frequency noise. Fig. 2 is an example of the measured EOGs. Twenty one EOGs were calculated from seven channels (${}_7C_2 = 21$) and six EOGs from electrode #1 are shown in the figure. The EOGs have a stair-like form reflecting the subject's eye movements. The flat / rising part of the steps correspond to fixation / saccade and all saccades correspond to eye movement of $+10°$ or $-10°$. Five subjects, none of whom wear glasses, participated in this experiment. About twenty sets of eye movements (one set corresponds to Fig. 2 including sixteen saccades) were measured for each subject.

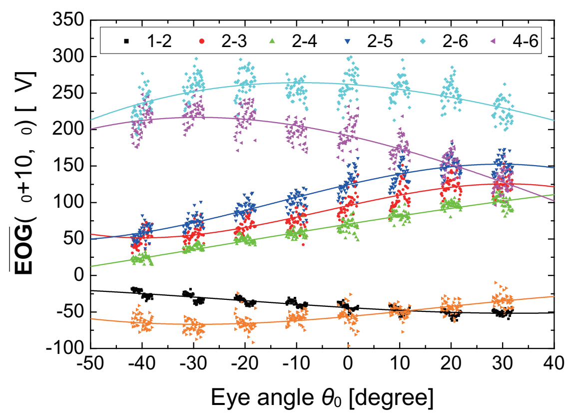

Fig. 3. Non-linearity of $\Delta\overline{\mathbf{EOG}}$
It is clear that $\Delta\overline{\mathbf{EOG}}$ depends on the eye angle, which means $\Delta\mathbf{EOG}$ and eye angle have a non-linear relationship.

A. Non-linearity of EOG

The EOGs, which were influenced by the saccades, were manually clipped to calculate $\Delta\overline{\mathbf{EOG}}$. $\Delta\overline{\mathbf{EOG}}$ values for one subject are plotted in Fig. 3. In the figure, $\Delta\overline{\mathbf{EOG}}(\theta_0 + 10, \theta_0)$ is directly plotted and $\Delta\overline{\mathbf{EOG}}(\theta_0 - 10, \theta_0)$ is inversed and plotted at $\theta_0 - 10$, because $\Delta\mathbf{EOG}(\theta_1, \theta_0) = -\Delta\mathbf{EOG}(\theta_0, \theta_1)$ (see equation (9)). For example, both $\Delta\overline{\mathbf{EOG}}(10, 0)$ and $-\Delta\overline{\mathbf{EOG}}(0, 10)$ are plotted at 0°. Note that each plot has been horizontally shifted to resolve overlap, the same as Fig. 4.

If $\Delta\mathbf{EOG}$ is assumed to be linear, the plot should be constant. Though the generally used EOG (#2-#6) shows that $\Delta\overline{\mathbf{EOG}}$ seems to be constant, it is clear that $\Delta\overline{\mathbf{EOG}}$ depends on θ. This means that EOG and eye angle have a non-linear relationship. The solid lines represent the results of $p_i(\theta)$ estimated by 4th order polynomial functions. While there are some differences between subjects, the rough tendency seems to be the same, for example $\Delta\overline{\mathbf{EOG}}$ for (#1-#2) decreases with angle.

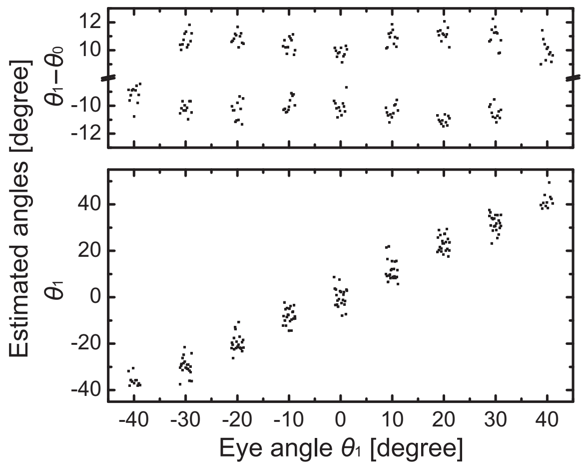

Fig. 4. Estimation of absolute angle and movement
Both absolute angle and eye movement are estimated correctly.

B. Estimation of eye angle

Eye angle was estimated using equation (10). The estimation was performed as follows, one half of the dataset was used to estimate $p_i(\theta)$ and the remainder was used for eye angle estimation; the datasets were swapped and the trial repeated. These processes yielded two angles (θ_0 and θ_1 in equation (10)), and eye movement $\theta_1 - \theta_0$ was then calculated. Fig. 4 shows the relation of correct and estimated θ_1 which are absolute angles, and movement ($\theta_1 - \theta_0$, correct data is $+10°$ or $-10°$) which are relative values. While conventional techniques estimate only the relative angle, both absolute and relative angle were estimated correctly by the proposed technique.

The average estimation error of θ_1 and eye movement was $3.2°$ and $0.7°$, respectively, for this subject. While all (twenty one) $\Delta\overline{\mathbf{EOG}}s$ were used for this result, even the six $\Delta\overline{\mathbf{EOG}}s$ yielded by the four generally used electrodes offer the small errors of $3.0°$ and $0.7°$, respectively. The errors for the other subjects were, for all seven electrodes, $5.0°$ / $1.3°$, $5.6°$ / $0.4°$, $6.4°$ / $1.1°$, and $5.5°$ / $0.7°$, and for the four commonly used electrodes $4.9°$ / $1.3°$, $5.1°$ / $0.4°$, $6.6°$ / $1.2°$ and $5.0°$ / $0.7°$. These values confirm that the proposed technique estimates the absolute angle with error of about $5°$ and offers highly accurate eye movement determination.

IV. Discussion

For some applications, e.g. input interfaces for the disabled where the user selects one of several choices [7], the obtained accuracy may meet the requirements. Many more applications can be created if the accuracy is improved. There are two approaches; improving this technique itself and more accurate estimation during saccade. The experiment showed that increasing the electrode number does not always yield an improvement and each $\Delta\overline{\mathbf{EOG}}$ has different distributions, which implies that improvement of this technique is possible. Estimating gaze during saccades is also important. Not all saccades offer accurate estimation, for example small saccades are easily swamped by noise. Gaze estimation during saccades will be effective in preventing a drop in accuracy. Conventional techniques will be helpful in offsetting this effect. Moreover, a technique to integrate them seamlessly is needed.

In order to implement this technique as a practical interface, more work is need. For example, we examined only horizontal angle performance and the vertical performance remains to be confirmed. The discrimination of horizontal and vertical components should be also considered.

V. Conclusion

An eye angle estimation technique that provides absolute eye angle at every saccade without user effort was proposed. It assumes the non-linearity of EOG and estimates eye angle by $\Delta\overline{\mathbf{EOG}}$ over short periods. An experiment confirmed that $\Delta\overline{\mathbf{EOG}}$ and eye angle have a non-linear relationship and that absolute eye angle can be estimated from $\Delta\overline{\mathbf{EOG}}$ with error of about $5°$ in addition to accurate estimation of eye movement. This technique provides a practical solution to the drift problem which has, up to now, made it difficult to realize EOG-based eye tracking schemes.

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