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A Method of EOG Signal Processing to Detect the Direction of Eye Movements

Manuel Merino, Octavio Rivera, Isabel Gómez, Alberto Molina, Enrique Dorronzoro
Electronic Technology Department.
University of Seville.
Seville, Spain.
manmermon@dte.us.es; octavio@dte.us.es; igomez@us.es; almolina@us.es; enriquedz@dte.us.es

***Abstract*— In this paper, a signal processing algorithm to detect eye movements is developed. The algorithm works with two kinds of inputs: derivative and amplitude level of electrooculographic signal. Derivative is used to detect signal edges and the amplitude level is used to filter noise. Depending of movement direction, different kinds of events are generated. Events are associated with a movement and its route. A hit rate equal to 94% is reached. This algorithm has been used to implement an application that allows computer control using ocular movement.**

Keywords: computer control; EOG signal processing: handicapped.

I. INTRODUCTION

Development of interfaces adapted to the user physical skills is necessary in some situations where users have different diseases. In most cases, some residual user movements are used to interact with these interfaces. Biosignals are useful to detect these movements, such as electrooculography (EOG) or electromyography (EMG) that are used in [1], where the aim is handled a computer through event and a virtual keyboard. An algorithm to manage the computer mouse based on EOG signal is discussed in [2]. Also the EOG signal has been used to handle a wheelchair [3].

In other cases, interfaces do not require user's movement. This kind of interfaces is based on the concept brain computer interaction (BCI), where electroencephalography is used. A system to type text based on the P300 paradigm is described in [4, 5] is described, while Mattiocco et al. described how is possible move a cursor through the mu-rhythm paradigm [6].

This paper describes an algorithm for processing EOG signal that allows the extraction of features in it to detect the direction of eye movement. This is separated in seven parts. The main properties of EOG signal are described in Section II. Section III focuses the preprocessing summary. The algorithm to detect the direction of eye movement is established in the Section IV. The next Section describes the tests realized. Finally, in Sections VI and VII are shown the results of tests and the conclusions.

II. FOUNDATIONS

EOG signal is based on electrical potential difference between the cornea and retina when eye movement is realized. The amplitude of this signal ranges between [50, 3500] µV and its frequency components go from 0 to 100Hz. On the other hand, the EOG signal is interfered by others, such as electroencephalography, electromyography, electrical network, speech, blink, etc. For these reasons, it is important the interference of noise is dimmed and the user is calm and relaxed.

An eye movement is related to a rise/fall of EOG signal amplitude. Two voltage levels, "low" and "high", can be defined in order to distinguish between a deliberate movement and a non deliberate one. Both, the "low" level and the "high" level, can be identified by a threshold value defined by equation 1, where "value" represents an absolute value of amplitude.

$$\text{classify(value)}\begin{cases}\text{value} \geq \text{Amplitude}_{\text{Threshold}} \cdot \mathit{Tolerance} \rightarrow \mathit{High} \\ \text{value} < \text{Amplitude}_{\text{Threshold}} \cdot \mathit{Tolerance} \rightarrow \mathit{Low}\end{cases} \quad (1)$$

In general, an event is made using two eye movements, one is used to generate the event and the other one is used to return a neutral position. Both movements are the same direction, but their senses are opposite. During these movements, three different stages can be recognized using EOG signals: the signal amplitude rises from the "low" level to the "high" level, then it stabilizes in the "high" level and finally, it fades until the "low" level (Figure 1).

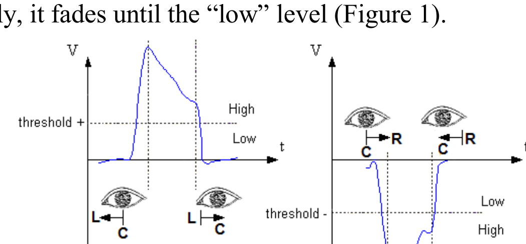

Figure 1. Eye movement components.

In this way, four different components could be identified: initial edge, final edge, area between edges and errors. This fact allows removing noise from the signals. For example, although the three stages are presented during a blink, the width of area between edges is much smaller. In this sense, a timer can be used in order to classify and remove blinks. A pulse is classified as a blink if the width of this area is smaller than 250ms.

III. PRE-PROCCESS

EOG signal information is mainly contained in low frequencies. For this reason a bandpass filter with a range between 0.1 and 30 Hz is applied and a sample rate of 128 Hz. Then an average filter is applied in order to remove some noise components.

Eye movements are detected using an algorithm based on edge. The edges are detected through the derivative of the EOG signal. This one is calculated using discrete values of signal amplitude (eq. 2). So, two values are used, one represents the preceding value of amplitude (n samples before), e(t – n), and the other one represents the current value, e(t).

$$e'(t) = e(t) - e(t-n) \,/\, n \in \mathrm{N}, n > 1 \qquad (2)$$

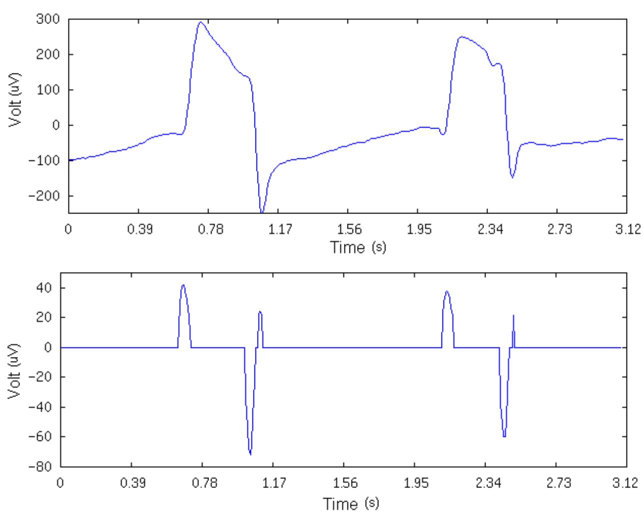

Figure 2. Filter Processing Result. (a) EOG signal. (b) Derivative.

A filter is applied to the signal derivative in order to remove some components without information. In Figure 2, the two steps of preprocessing are shown: first a smoothing filter is applied and in a second phase derivative is calculated.

IV. PROCCESS

Next, the algorithm to detect the direction of eye movements is described. The section is separated in two parts: the initial edge and final edge of them.

A. *Procedure*

A complex algorithm can be used to control the process. A flowchart representing the part of this algorithm associated with a pulse having positive amplitude is shown in Annex I. The states are described in table I.The input of this algorithm is the derivative of EOG signal that can have three different values: a value greater than 0, a value smaller than 0 and a value equal to 0. The values that are not equal to 0 are related to initial and final edges of a pulse having positive amplitude. The value equal to 0 is associated with the area between edges (no-activity area). State transitions are led by the values of signal amplitude at current moment and previous one, and by the value of the signal derivative.

TABLE I. STATES FROM A PULSE HAVING POSITIVE AMPLITUDE.

State	Description
INITIAL	Waiting an initial edge.
InitialEdge+	Initial edge detects.
Error-	Error.
FinalEdgeWait-	Waiting final edge.
FinalEdge-	Final edge detects.

The process starts in the INITIAL state. In this one, a non-zero input is waited. As mentioned above, this value can be related to an initial edge or a final edge. Next, the behaviour is described in detail. First, the part of algorithm associated with an initial edge is shown. Then, a final edge is considered.

B. *Initial Edge*

When an eye movement is started (Figure 3) the value of signal amplitude changes from the "low" level to the "high" level, obtaining a value of signal derivative that is greater than 0. At this moment, a transition from INITIAL state to InitialEgde+ state occurs. When area between edges is reached (derivative equal to 0), a transition to FinalEdgeWait- happens. It is necessary to consider some possible disturbances that could occur. Next, these ones are described.

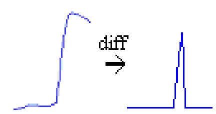

Figure 3. Initial edge.

1) *Horizontal initial edge*

In this situation a small area where the slope of signal is brought nearer to 0 is presented (Figure 4). Therefore two peaks are shown in the signal derivative. In this case there are two options:

a) The maximum value of signal amplitude in this area is lower than the value of set threshold. In this situation the first peak is rejected because the "high" level is not reached yet, so the machine is in INITIAL state. However the second one happens when the "high" level has been reached, therefore the transition from INITIAL state to InitialEdge+ state occurs.

b) The maximum value of signal amplitude in this area is higher than the value of set threshold. In this situation a transition from INITIAL state to InitialEdge+ state occurs because of the first peak. After that, the value of input is equal to 0 due to the horizontal noise and this fact causes a transition to FinalEdgeWait- state. When the second peak arrives, the preceding value, e(t – n), is set to the "high" level, so although the slope of signal derivative is positive, a change from the "low" level to the "high" level does not occur, this means a state transition does not occur. Therefore the second peak is rejected.

Figure 4. Horizontal initial edge.

On the other hand, the effects of horizontal initial edge can be attenuated because the signal derivative is calculated by subtracting two non-consecutive components as mentioned above.

2) Overlapped amplitude peak in the initial edge

In this case three peaks are shown in the signal derivative (Figure 5). The behaviour is similar to the one shown in the previous section. If the amplitude of first peak does not overcome the set threshold, then a transition does not occur and the second peak is rejected. In this situation a transition from INITIAL state to InitialEdge+ state occurs when the "high" level has been reached.

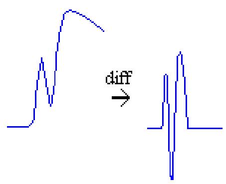

Figure 5. Overlapped amplitude peak in the initial edge.

On the other hand, if the amplitude of first peak overcomes the set threshold, then a transition to InitialEdge+ state occurs. When the second peak is received a transition to Error- state happens, meaning that it is probably an error. In this situation, the third peak tries to generate a transition to InitialEdge+ state; however that is only possible if the amplitude of this peak overcomes the "high" level.

3) Single edge

Figure 6. Single edge.

A single edge is an amplitude step like is shown in Figure 6. This causes a transition to InitialEdge+ state if the "high" level has been reached; else the single edge is rejected without effects. After the rise, the signal amplitude falls down. When the derivative is equal to 0, a transition to FinalEdgeWait- state occurs. In this situation two cases are studied: the single edge is followed by a pulse having positive amplitude; and the single edge is followed by a pulse having negative amplitude (Figures 7-8).

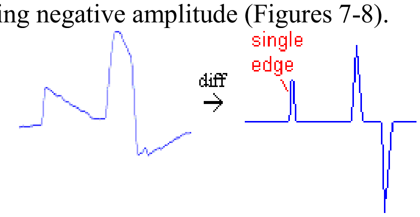

Figure 7. Single edge followed by a pulse having positive amplitude.

In the first case (Figure 7), the effect of the single edge depends on the value of preceding item, $e(t-n)$:

a) If $e(t-n)$ is associated to the "high" level: this means that the fall of single edge is not quick enough to reach the "low" level. So, the ascending slope of following pulse does not take effects, but the state of machine is correct. However, timer is reset when a transition to InitialEdge+ state is done, and this occurs with the single edge. Therefore, the timer value is not adequate and a misinterpretation could be made, e. g. if the second pulse is related to a blink and the timer value would be greater than 250 ms. This case is known as crest in the final edge which is described below.

b) If $e(t-n)$ is associated to the "low" level: this means that the fall of single edge is relatively quick. In this case, a transition to InitialEdge+ state could be done when $e(t)$ is related to the "high" level.

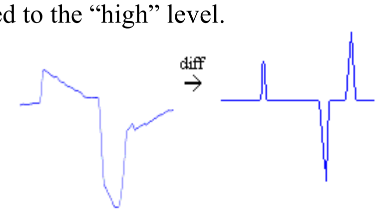

Figure 8. Single edge followed by a pulse having negative amplitude.

In the second case (Figure 8), the sign of initial edge is different to one of single edge. A transition to FinalEdge- state could be done. However, it is not an EOG movement. So before the transition occurs, it is necessary to check the preceding and current amplitude value.

On the other hand, a transition from FinalEdge- state to INITIAL state occurs when the value of signal derivative is equal to 0.

4) Abrupt fall before initial edge

Two examples of abrupt falls are shown in the Figure 9. In both cases, if the threshold value in negative case is reached then a transition from INITIAL state to InitialEdge- state occurs.

When the fall is abrupt as one that is shown in Figure 9.a, a transition to Error+ state occurs because the sign of second peak derivative is opposite to the one of first peak. Then, the area between edges is reached and the value of derivative is equal to 0. In such situation, two cases are possible: the pulse is a single peak of amplitude, leading to a transition to INITIAL state, or the second peak is a real initial edge. So if the current amplitude value is the "low" level (for a positive case), then a transition to INITIAL state (it is a single peak of amplitude) occurs. In the other case, a transition to FinalEdgeWait- state occurs.

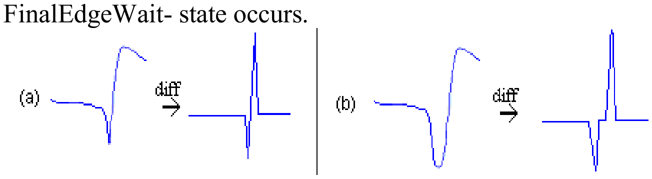

Figure 9. Abrupt fall before initial edge. (a) Pointed. (b) Round.

When the fall is not abrupt as one that is shown in Figure 9.b, the behaviour is similar to one that is shown when a blink is done. However, when the area between edges is reached, a transition from FinalEdge+ state to INITIAL state occurs. If current amplitude value is related to the "high" level, then a transition to FinalEdgeWait- state occurs. In other case, a transition to INITIAL state occurs.

5) Single peaks of amplitude

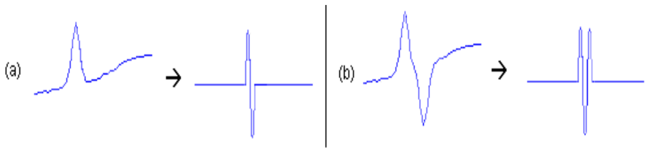

Figure 10. Single peaks of amplitude. (a) Even peaks. (b) Odd peaks.

There are two different cases:

a) Even number of peaks in the signal derivative (Figure 10.a). The final state is Error- when the processing of all peaks is completed.

b) Odd number of peaks in the signal derivative (Figure 10.b). The final state is Error- when the last peak is received. At this moment, the current amplitude value is checked in order to detect an overlapped amplitude peak. However, in this case a transition from Error- state to InitialEdge- state does not occur because the current amplitude value is related to the "low" level.

6) Crest in the initial edge

A crest is a rise of amplitude in the end of an edge. If this one is rounded (Figure 11.a) the pulse derivative is similar to one of a blink. However, the current amplitude value is related to the "high" level in the second peak, so there is not a state transition, i.e., the current state is FinalEdgeWait-. The problem is solved.

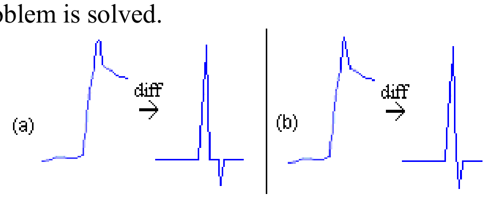

Figure 11. Crest in the initial edge. (a) Round. (b) Pointed.

On the other hand, if the crest is pointed (Figure 11.b) the signal derivative has an even number of peaks; such situation is similar to one shown in previous section. However, the pulse is a real movement. So, first it is necessary to check if the current amplitude value is related to the "low" level. In the considered case, the current amplitude value is related to the "high" level, and therefore a transition to FinalEdgeWait- state occurs. In other case, it is a single peak and a transition to INITIAL state occurs.

C. Final Edge

The end of an eye movement leads to a falling edge due to change from the "high" level to the "low" level. A negative peak is shown in the signal derivative. This fact can be used to detect the end of an EOG movement (Figure 12).

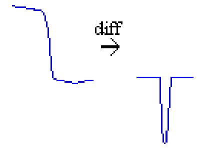

Figure 12. Final edge.

1) Horizontal final edge

This disturbance is similar to one presented in subsection 1, but in final edge. As then, there are two options:

a) The maximum value of signal amplitude in this area is higher than the value of set threshold. Both, the current and previous amplitude value, are related to the "high" level, so the state does not change. A transition to FinalEdge- state occurs when the next peak arrives, because the preceding amplitude value is related to the "high" level and the current amplitude value is related to the "low" level. So the pulse is associated with an EOG movement if the duration of pulse is greater than 250ms. In other case it is associated with a short pulse (noise).

b) The maximum value of signal amplitude in this area is lower than the value of set threshold. The current amplitude value is related to the "low" level in the first peak of signal derivative, and the preceding amplitude value is related to the "high" level, so a transition to FinalEdge- state occurs, obtaining an output value equal to 1 if the width of pulse is adequate. Now, a transition to INITIAL state occurs because of horizontal noise. Finally, the second peak could be identified as an initial edge. However, current amplitude value is related to the "low" level and therefore, a transition does not occur.

2) Overlapped amplitude peak in the final edge

This disturbance is shown in Figure 13. A single peak of amplitude is overlapped with the final edge of the pulse. An odd number of peaks are presented in the signal derivative. If the current value of amplitude of the first peak is related to the "high" level a transition does not occurs. The next two peaks are identified as a crest in the final edge which is processing using the method described in the next subsection.

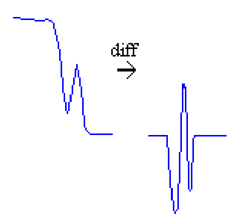

Figure 13. Overlapped amplitude peak in the final edge.

On the other hand, if the current value of amplitude of the first peak is related to the "low" level a transition to FinalEdge- state occurs. This state is kept until the values of signal derivative are equal to 0. So, the next two peaks are filtered without problems.

3) *Crest in the final edge*

There are two cases in this disturbance that are shown in Figure 14. The processing is the same in both cases. A transition from FinalEdgeWait- state to InitEdge+ state does not occur when the first peak of signal derivative is received because the current and preceding amplitude values are the same (the "high" level), so the process is in FinalEdgeWait- state. Then, a transition to FinalEdge- state occurs when the second peak is received due to the current amplitude value is related to the "low" level and the preceding amplitude value is related to the "high" level.

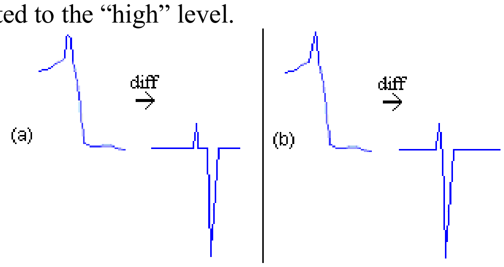

Figure 14. Crest in the final edge. (a) Round. (b) Pointed.

V. EXPERIMENT DESIGN

The algorithm was tested through different kinds of tests. Next, these tests are described.

A. *Participants*

Some tests were made to the system. Three users without visual disabilities between 25 and 42 years old participated on these trials.

B. *Tests*

We used BCI2000 [7] and the amplifier gUSBamp of g.tec [8]. The EOG signal was recorded through four sensors of Ag/AgCl placed around the eyes (Figure 15). The difference between the sensors 1 and 3 was used to register the vertical eye movements, and the difference between sensors 2 and 3 was used to register the horizontal eye movements.

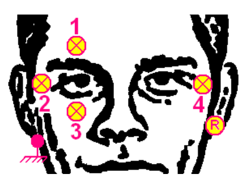

Figure 15. Sensors.

Four targets were placed around the computer screen (Figure 16). Users were asked to move their eyes from central position (C) to one of the extreme side (right (R), left (L), up (U) or down (D)) and then the eyes returned the initial position (C). This is shown in Figure 17.

Six tests were completed by each user. First of them was used to calibrate the system. In this one 12 movements were done (R - U- L - D - R - U- L - D - R - U- L - D). The users were asked to move 6 times their eyes in a unique direction in the followed four tests. In the last one, they had to move their eyes in different directions that were set previously.

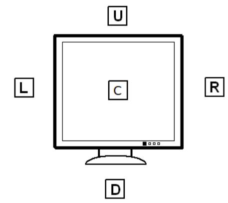

Figure 16. Targets of eyes movements.

Figure 17. Eye movements.

VI. RESULTS

Test results are shown in Table II. Average hit rate is of 94.11%. This high hit rate shows that the people with disability could handle a computer through events detected for the system when he/she does an eye movement.

TABLE II. TEST RESULTS.

Character	Correct (%)
Individual 1	100
Individual 2	95.83
Individual 3	86.49

VII. CONCLUSION AND FUTURE WORK

A system used to detect eye movement based on the EOG signal is proposed. So the system objective is to detect when a movement of eyes is realized and the route described. The main goal of this algorithm is reduce both initial calibration and detection errors. In this form, events generated for the system when an eye movement is done can be used to handle computer applications causing as less fatigue as possible to the user. This allows handicapped people are able to access the computer in an easy and comfortable form. So, in the future, we will use the EOG signal as communication interface to handle an application based on augmentative and alternative communication. Also, we will detect the stress and fatigue of user in order to use these results in ambient living application.

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ANNEX I: COMPLETE FLOWCHART OF A PULSE HAVING POSITIVE AMPLITUDE