Automatic Electrooculogram Classification for Microcontroller Based Interface Design

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Abstract—In this paper, we present a simple and novel technique for classification of multiple channel Electrooculogram signals (EOG). In particular, a viable real time EOG signal classifier for microcontrollers is proposed. The classifier is based on Deterministic Finite Automata (DFA). The system is capable of classifying sixteen different EOG signals. The viability of the system was tested by performing online experiments with able bodied subjects.

I. INTRODUCTION

CLASSIFICATION of Electrooculogram (EOG) signals is a major concern for future development of multimode controllers, communication devices, and human computer interfaces [1-7]. This discipline of science and technology has a direct impact on the social well-being of human beings which fall into the strata of disabled and paralytic people. In particular, people suffering from Locked-in syndrome [8] (also known as Cerebromedullospinal Disconnection) have only control over their eye movements. This is the most prominent voluntary muscle activity in their body, and hence presents Electrooculogram as another possibility for use in development of such devices.

In the past few years, the focus on the development of assistive devices for people with severe disability has increased by improving the traditional systems. The Video Oculography (VOG) system and Infrared Oculography (IROG), based on detection of eye position using cornea or iris, are some of the developments made so far [9]. A number of possible methods of eye movements with its advantages and disadvantages have been reviewed by scientists [10]. The physical energy drained in moving eyes being minimal when compared to other gestures such as nodding head (dumb people), speaking or writing etc. also inspires the use of EOG signals for device control purposes. Lately, there have been much effort to develop EOG based assistive devices [11, 12].

In a companion paper [13], we introduced a methodology for estimating the maximum number of instructions that a microcontroller can process when EOG signal is an input. In this paper, we present a novel scheme where the EOG signal acquired from single/multiple horizontal and vertical channel is preprocessed, de-noised and continuously fed to a comparator network for extraction of key symbols. These symbols (explained later) are fed into a Deterministic Finite Automata (DFA) for extraction of another set of symbols (explained later) which are fed into another DFA for classification of the EOG signal. Our scheme based on DFA has a major advantage of being suitable for easy development of embedded (and hardwired) systems for EOG based multimode controllers.

II. EOG SIGNAL ACQUISITION

A resting potential is generated by an electric dipole formed by a positive cornea and a negative cornea [14]. Electrooculography is a technique for measuring this resting potential. The resulting signal called EOG is essentially a record of the difference in electrical voltage between the front and back of the eye that is correlated with eyeball movement and obtained by electrodes placed on the skin near the eye.

We used five silicon-rubber electrodes of impedance below 10 K-ohm, placed around the eye to obtain EOG signals. Due to the low impedance range starting from 40-200 Ω, the silicon-rubber conducting electrode is more suitable to sense the very low amplitude bio-signals as compared to other types of electrodes such as Ag-AgCl electrodes. Horizontal EOG is measured as a voltage by means of electrodes strategically placed as close as possible to the canthus of each eye. Similarly, vertical EOG is measured as a voltage by means of electrodes placed just above and below the eye as shown in Fig. 1. The reference electrode is placed on the forehead.

![Fig. 1. Electrode Placement for the present study](image)

With the eye at rest, the electrodes are effectively at the same potential and no voltage is recorded. The rotation of
the eye to the right results in a difference of potential with the electrode in the direction of movement, becoming positive with respect to the second electrode. The opposite effect results from the rotation to the left, as illustrated in Fig. 2.

EOG signal obtained by horizontal (left-right) eye movement is shown in Fig. 3. Visual analysis of EOG signal confirms the occurrence of well defined peaks. These peaks are very clear and can be detected using thresholding.

We performed analysis of EOG signals using LAB VIEW version 7.0. The PSD curve plotted for data shown in Fig. 7. shows that the prominent frequency components are up to 40Hz maximum where the maximum frequency components lie around 4Hz. Fig. 4 depicts the Fast Fourier Transform (FFT).

III. EOG CLASSIFICATION PROCESS FLOW

The EOG signal acquired from horizontal and vertical channel is preprocessed and de-noised to remove all unwanted frequencies. Then the de-noised signal is fed to a comparator and NOR Gate network for extraction of key symbols (here key symbols refer to digital output of the comparator and NOR Gate network) mapped onto set \( C \in \{CV+, CV-, CVo, CH+, CH-, CHo\} \). The symbols in this set correspond to different voltage levels in the EOG signal, which are shown in Fig. 5. Here \( V_{IH} \) and \( V_{IV} \) are amplitude of signal in vertical and horizontal channel respectively. THH, THL, TVH, and TVL are High/Low threshold levels in Horizontal/Vertical channel EOG signal respectively. We used Threshold levels as +/- 37.5% (This value was determined statistically while performing online experiments using LAB VIEW version 7.0, and may vary depending on the choice of electrodes and other factors such as sweat on the surface of skin etc.) of the highest positive/negative amplitude of the obtained EOG signal.

Symbols \( \{CV+, CV-, CH+, CH-, CHo\} \) are positive/negative region above/below threshold levels in vertical/horizontal channel respectively. Symbols \( \{CVo, CHo\} \) are rest zone areas in vertical/horizontal channel respectively. These signals are fed as primary input to the Peak Detection Deterministic Finite Automata (PDDFA), which based on these signals identifies positive/negative peaks and rest zone areas in EOG signals obtained from horizontal/vertical channel.

The output of PDDFA is mapped onto set \( P \in \{V+, V-, H+, H-\} \) (explained under the heading ‘PDDFA”), used as input by the Movement Classifier Deterministic Finite Automata (MCDFA) to determine which eye-movement was performed by the user, from its set of sixteen different eye movements. This output is then used by the O/P module (shown in Fig. 6) to display which eye-movement was detected, on the LCD display.
The functions governing digital values of the elements in set $C$ are shown in Table I. (only conditions for ‘Digital Logic 1’ are shown, value is ‘Digital Logic 0’ for all other cases).

**TABLE I
**

<table>
<thead>
<tr>
<th>Element of set $C$</th>
<th>Condition for which value is (Logic 1).</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CV+$</td>
<td>$V_r \geq TVH$</td>
</tr>
<tr>
<td>$CV-$</td>
<td>$V_r \leq TVL$</td>
</tr>
<tr>
<td>$CVo$</td>
<td>$TVL &lt; V_r &lt; TVH$</td>
</tr>
<tr>
<td>$CH+$</td>
<td>$V_n \geq THH$</td>
</tr>
<tr>
<td>$CH-$</td>
<td>$V_n \leq THL$</td>
</tr>
<tr>
<td>$CHO$</td>
<td>$THL &lt; V_n &lt; THH$</td>
</tr>
</tbody>
</table>

**IV. PDDFA**

The Deterministic Finite Automata, $PDDFA = (Q, \Sigma, \delta, q_0)$, was developed for triggering the detection of occurrence of positive/negative peaks and rest zone in horizontal/vertical channel of the EOG signal. The DFA is shown in Fig. 7. Here, $Q$ is the set of all states of finite automata, shown using $\bigcirc$ with the name of state written inside it, $\Sigma$ is the set of input signals $\Sigma \in \{C\}$, where $C$ is the set of all outputs from the comparator and NOR Gate network, $C \in \{CV+, CV-, CVo, CH+, CH-, CHO\}$ (explained under the heading ‘EOG CLASSIFICATION PROCESS FLOW’). $\delta_i$ is the set of all transition functions represented by arrows, if a transition function contains an element of set $P \in \{V+, V-, H+, H-\}$ (explained under the heading ‘MCDFA’) preceding with an “;” then that element from set $P$ is used as input by the MCDFA. $q_{0i}$ represents the start state as indicated in Fig. 7.

**V. MCDFA**

The Movement Classifier Deterministic Finite Automata, $MCDFA = (Q, \Sigma, \delta, q_{02}, F_2)$, was developed for classification of sixteen different EOG signals, acquired from horizontal and vertical channels (signal comprises of potential generated due to motion of eye with 2 degrees of freedom horizontal/vertical). The sixteen different eye movements with their abbreviations as shown in Fig. 8. Before performing any of these sixteen eye movements the eye should be centered such that both EOG signals obtained from horizontal/vertical channel lie in the horizontal/vertical rest zone respectively.
The eye movements shown inside curly braces using comma separated list in Table II. (column ‘Eye Movement’) must be performed simultaneously.

In $MCDFA$, $Q_2$ is the set of all states of finite automata, shown using $\bigcirc$ or $\bigcirc$. $\Sigma_2 \in \{P, T\}$ is the set of input signals, where $P$ is the set of output signals generated by PDDFA $P \in \{V^+, V^-, H^+, H^-\}$, and $T$ is the set of all output signals generated by timeout timers $T \in \{TV, TH, TD\}$, here $TV, TH, TD$ are vertical, horizontal, and diagonal timeouts respectively. $\delta_2$ is the set of all transition functions represented by arrows, $q_{02}$ represents the start state as indicated in Fig. 8., $F_2$ represents the set of all finish states shown by $\bigcirc$, with the name of state written inside it. All intermediate states between start and final states are divided into four groups $\{S_1..S_4\}$. When a transition to state $S_1, S_2, S_3$, or $S_4$ occurs the horizontal, vertical, or diagonal timeout timer is enabled respectively.
MCDFA works by taking a stream of inputs symbols (here elements of set $\Sigma$ are referred to as symbols). It accepts or rejects an EOG signal as follows. Starting in the start state, for each input symbol the automaton transitions to the next state following the transition function $\delta(q_0,a) = q$, where $p$ is the present state, $a$ is the current input, and $q$ is the next state. After making $n (n \in \{2,3,4\})$ transitions for an $n$-symbol EOG signal, if the automaton is in a final state, then it accepts the EOG signal. If it is not in a final state, or if at some point there was no appropriate input (i.e. no labeled edge to follow), it rejects the EOG signal, and resets the Automata to start state.

In Fig. 8, the sequence for detection of diagonal (down, left) → (up, right) eye movement is illustrated by highlighting all visited states and transitions by increased line width. Mathematically the input and transition sequence is represented as shown in Fig.9.

**VI. IMPLEMENTATION ON A MICROCONTROLLER**

We chose PIC16F877A [15] as the microcontroller for implementation of the aforementioned EOG Classification System. The transition $\delta(p,a) = q$ from state to state is completely determined by the input $a$ and initial state $p$. The algorithms merely follow the correct branches based on the information provided.

A. For PDDFA state transitions with and without output

1. **PDDFA_<p>:**
2. IF input = <a> THEN
3. GOTO PDDFA_<q>
4. ENDIF
5. GOTO PDDFA_<p>

Fig. 10. Algorithm for PDDFA state transition without output

1. **PDDFA_<p>:**
2. IF C = <a> THEN
3. PDDFA_OP = <p>
4. GOSUB MCDFA
5. GOTO PDDFA_<q>
6. ENDIF
7. GOTO PDDFA_<p>

Fig. 11. Algorithm for PDDFA state transition with output

Algorithms for PDDFA State Transitions with and without output are shown in Fig. 10 and Fig. 11 respectively. Here, $<p>$, and $<q>$ are the names of initial and final states for a given state transition in PDDFA. $<a>$ is the output from the Comparator and NOR Gate network, $<a>$ belongs to set $C$. Lines 2 - 4 in Fig. 10 and lines 2 - 6 in Fig. 11 must be repeated for each possible transition from state $<p>$ of PDDFA.

$<P>$ in Fig. 11 is the output from PDDFA. $<P>$ belongs to set $P$. Line 4 in Fig. 11 transfers program control from PDDFA module to MCDFA module which uses $<P>$ as input for its state transition functions. And after a successful state transition returns control back to PDDFA module.

B. For MCDFA state transitions to intermediate and final states

1. **MCDFA_<p>:**
2. IF PDDFA_OP = <a> THEN
3. MCDFA_STATE = MCDFA_<q>
4. RETURN
5. ENDIF
6. MCDFA_STATE = MCDFA_START
7. RETURN

Fig. 12. Algorithm for MCDFA state transition to intermediate states

1. **MCDFA_<p>:**
2. IF PDDFA_OP = <a> THEN
3. GOSUB EYE_MOVEMENT_<q>
4. MCDFA_STATE = MCDFA_START
5. RETURN
6. ENDIF
7. MCDFA_STATE = MCDFA_START
8. RETURN

Fig. 13. Algorithm for MCDFA state transition to final states

Algorithms for MCDFA State Transitions to intermediate and final states are shown in Fig. 12 and Fig. 13 respectively. Here, $<p>$, and $<q>$ are the names of initial and final states for a given state transition in MCDFA. $<a>$ is the output from the PDDFA and belongs to set $P$. Lines 2 - 5 in Fig. 12 and lines 2 - 6 in Fig. 13 must be repeated for each possible transition from state $<p>$ of MCDFA.

$<q>$ in Fig. 13 is the detected eye movement. Module EYE_MOVEMENT_<q> is used for displaying the detected eye movement on the LCD Display (number).

**VII. CONCLUSION**

To conclude, in this paper, we proposed a scheme for EOG signal classification which can be used as a mathematical model for development of EOG based medical instrumentation where device control is the main objective.
The sixteen classified signals provide a large range of input signals, enabling EOG to serve as a primary source of input to many multimode controllers. DFA being one of the most practical model of computation prove useful in development of linear-time, constant-space, online-algorithms (one that can process its input piece-by-piece, without having the entire input available from the start). The proposed scheme can be universally applied for development of embedded systems requiring real time EOG signals as primary input.

REFERENCES


