ENHANCED REAL-TIME CURSOR CONTROL ALGORITHM, BASED ON THE SPECTRAL ANALYSIS OF ELECTROMYOGRAMS

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ABSTRACT

This paper presents a new version of an EMG-based, hands-free, cursor control system, and compares its performance to that of a previous version [1, 2]. Both systems use classification algorithms that rely on the periodogram estimation of the power spectral density (PSD) of electromyogram (EMG) signals from muscles in the face. The older system requires three electrodes for EMG input, and utilizes an algorithm that calculates partial power accumulations over the frequency ranges of 0Hz – 145Hz and 145Hz – 600Hz in the PSDs of the EMG signals. The new system requires four electrodes for EMG input, and utilizes an algorithm that calculates mean power frequency (MPF) values to assist in distinguishing the cranial muscle that contracted. An experiment was devised to gauge the point-and-click capabilities of both systems. The experimental results were evaluated using Fitts' Law analysis. The results show that the new algorithm provides improved point-and-click performance over the old algorithm.

Keywords: Electromyogram, EMG, cursor control, Fitts' law

INTRODUCTION

One strong motivation for investigating alternative means for communicating with the computer is that there exists a population of individuals who are unable to use standard input devices due to some form of physical disability. It is estimated that there are 250,000 – 400,000 individuals in the United States living with spinal cord injury or spinal dysfunction [3]. Given the increasing pervasiveness of computer-based systems in most of our daily activities, it is clear that facilitating access of these individuals to Graphical User Interface (GUI)-driven computer systems is an important technical goal.

With today's GUI-based PC software, most of the human-to-computer interaction is based on selection operations, which consist of two steps:

- Pointing: Positioning the cursor at the desired location of the screen, over the appropriate area or icon.
- Clicking: Executing the Mouse Down/Up function that is interpreted by the computer's operating system as an indicator to complete the selection of the item associated with the icon at the location of the screen cursor.

A number of approaches have been attempted to allow individuals with motor disabilities improved access to GUIs, using mechanisms as diverse as voice input [4], eye gaze tracking [5], and biosignals, such as the electromyogram (EMG). The EMG is the electrical signal recorded by electrodes on the skin when a muscle contracts, due to the stimulation of several muscle fibers associated with different motor neurons innervating the muscle. In fact, the EMG is the spatio-temporal summation of these contributions. Therefore, the EMG signal provides an effective means of monitoring muscle activity.

EMG signals have been used for cursor control. This approach has been used in [6, 7] and [1, 2], with [1, 2] focusing specifically on the use of EMG from cranial muscles. The use of EMG signals from cranial muscles is an approach that would be suitable for individuals suffering from severe motor disabilities, who are paralyzed from the neck down.

The EMG system used in [1, 2] utilized three electrodes that measured EMG signals from muscles in the head of the user. The EMG signals were classified into cursor actions by performing real-time spectral analysis of these signals.

In analyzing the performance of the original three-electrode EMG system, it was found that it was occasionally inaccurate in discriminating between eyebrows-up and eyebrows-down EMG activity, used to command up and down cursor steps, respectively. To remedy this problem an additional electrode was added to the forehead region and a new classification algorithm was devised to work with this new input configuration.

The second section of this paper details how the new system was implemented and the methodology behind the new classification algorithm. The test program that was used to evaluate the old and new EMG systems is also described in this section. The results of these experiments are tabulated, analyzed and discussed. Conclusions based on the results are presented.

MATERIALS AND METHODS

A. Placement of Electrodes for the New EMG-based Cursor Control System

Figure 1 displays the placement of the Ag/AgCl electrodes on the head of the subject. The figure indicates that the electrodes were placed over the right frontalis muscle, the left temporalis muscle, the right temporalis muscle, and the procerus muscle respectively. An electrode was placed over the right mastoid as a reference.

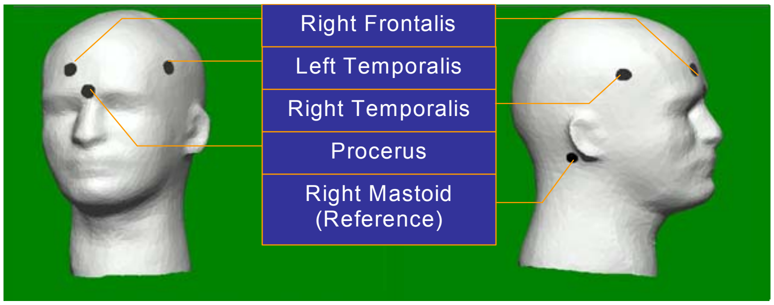

Figure 1. Electrode placement for the new EMG cursor control system

B. Hardware Components of EMG-Based Cursor Control System

The hardware components of the cursor control system are presented in Figure 2. The four EMG signals were amplified and preprocessed with analog anti-aliasing filters. The ADC64^{TM} DSP/AD board (Innovative Integration, Simi Valley, CA) performed analog-to-digital conversion on each signal at a sampling rate of 1.2 kHz, and then applied the classification algorithm to these digitized signals in real-time. The board was connected to the computer through the PCI bus. The output of the board was a series of TTL-compliant binary voltage sequences that were consistent with voltage sequences expected from a serial mouse. The Motorola® MC1488C RS-232C driver converted the TTL sequences into RS-

232C format and transmitted these sequences into the serial port of the personal computer (PC). The serial mouse driver of this computer communicated with the operating system to produce cursor actions consistent with the serial input.

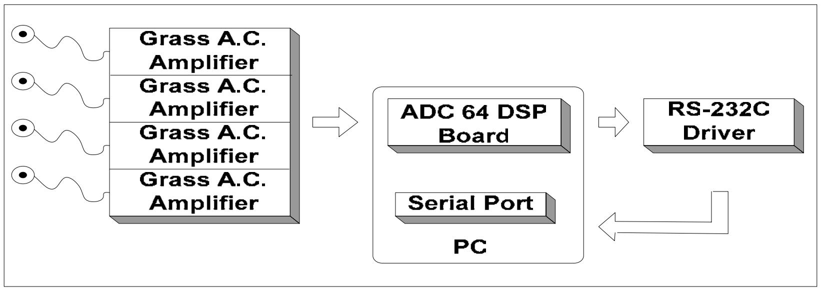

Figure 2. Block diagram of hardware components of EMG-based cursor control system

C. EMG Processing Algorithm for Muscle Contraction Identification

The desired relations between cursor actions, facial movements, and muscle contractions for the new system are given in Table 1.

Table 1. Relations between cursor actions, facial movements and muscle contractions

Cursor Action	Facial Movement	Muscle Contraction
Left	Left Jaw Clench	Left Temporalis
Right	Right Jaw Clench	Right Temporalis
Up	Eyebrows Up	Right Frontalis
Down	Eyebrows Down	Procerus
Left-Click	Left & Right Jaw Clench	Left & Right Temporalis

The purpose of the classification algorithm was to determine if a facial muscle contraction had occurred and if so, which specific muscle was contracted. Given the one-to-one correspondence between muscle contraction and cursor action, the output of an effective muscle contraction classification algorithm can be utilized in a hands-free cursor control system.

Both the classification algorithm of [1, 2] and the classification algorithm discussed in this paper, made use of the periodogram estimation of the power spectral density (PSD) of the input EMG signals. In both cases, the PSD indicated how the power of an EMG signal was distributed over a frequency range of 0 Hz – 600 Hz. Periodogram PSD estimations were taken every 256 consecutive samples (every 0.213s) from each of the four EMG channels.

The algorithm of [1, 2] only utilized three electrodes, placed on the left temporalis muscle, the right temporalis muscle, and the right frontalis muscle respectively, to record EMG signals. The classification algorithm adopted for this three-electrode system utilized partial accumulations of the PSD's and PSD threshold criteria. The partial power accumulations were calculated over the ranges of 0 Hz – 145 Hz and 145 Hz – 600 Hz of the PSD produced from each EMG channel. These partial accumulations were used to distinguish between the frequency characteristics of a temporalis contraction and those of a frontalis contraction. The threshold criterion was used to determine whether the contraction of a specific muscle was of a significant magnitude. The partial accumulation and threshold criteria were used to classify the facial movements: left jaw clench, right jaw clench, eyebrows up, and simultaneous left and right jaw clench. The eyebrows down movement used a partial accumulation over the frequency range 88 Hz – 250 Hz of the PSD calculated from the frontalis electrode. In addition, it was required that the PSD amplitude thresholds of the three electrodes not be exceeded.

Testing of this algorithm revealed that it did not always classify the eyebrows down movement efficiently. So it was proposed that an additional electrode be placed over the procerus muscle, because it is one of the muscles directly involved in the eyebrows down facial movement. This new four-electrode input configuration required a new classification algorithm, the details of which are described in the following paragraphs.

The new classification algorithm uses mean power frequency (MPF) values to distinguish spectral differences associated with each facial muscle contraction, instead of partial PSD accumulations. The MPF is derived from the PSD values as a weighted average frequency in which each frequency component, f, is weighted by its power, P. The equation for the calculation for the MPF is given by:

$$MPF = \left(\frac{f1 \times P1 + f2 \times P2 + \ldots + fn \times Pn}{P1 + P2 + \ldots + Pn} \right); \qquad n = 1, 2, \ldots, 256 \tag{1}$$

Empirically, we have determined that the typical MPFs for EMG from different muscles occur in characteristic ranges, e.g., [40Hz – 165Hz] for the frontalis, [60Hz – 195Hz] for the procerus, and [120Hz – 295Hz] for the temporalis.

For a unilateral muscle contraction to be correctly classified by the four-electrode algorithm all the following criteria must be satisfied:

1) The maximum PSD amplitude must exceed the threshold set for that electrode.
2) The complete sum of the PSD amplitudes for the given electrode must exceed the PSD complete sums of the other electrodes.
3) The mean power frequency calculated from the PSD must fall into a range consistent with the muscle associated with the electrode.

For the classification of the bilateral contraction of the left and right temporalis muscles used to trigger the left-click cursor action, all the following conditions must apply:

1) The maximum PSD amplitude thresholds must be exceeded for both electrodes.
2) The complete PSD sums for both electrodes must be greater than the other two PSD complete sums.
3) The complete PSD sums for both electrodes must indicate a balanced bilateral contraction, that is, each PSD sum must be greater than 20% of the total of both complete PSD sums.
4) The mean power frequencies calculated from both PSD's must fall into a range consistent with the muscles associated with both electrodes.

D. Evaluation of EMG detection Algorithms

A test program was created in Visual Basic to evaluate the point-and-click capabilities of both cursor control systems. The program was displayed on a 17" color monitor. For each point-and-click trial, an 8.5 x 8.5 mm "Start" button was presented in a corner of the screen and a "Stop" button was presented in the center. The "Stop" button had four possible dimensions: 8.5 x 8.5 mm, 12.5 x 12.5 mm, 17 x 17 mm, 22 x 22 mm. Each subject was instructed to use the EMG-based system to click the "Start" button, in order to begin timing a trial, move the cursor to the "Stop" button, and click the "Stop" button as quickly as possible. The subject must then click a "Next" button to display another trial layout with the "Start" button appearing in another corner of the screen.

The real-time evaluations were divided in four sessions. During a session only one “Stop” button size was presented. The “Start” button was presented in one of the four possible corners for each trial. A trial that has a “Start” button in a specific corner is repeated five times per session. Therefore, there are twenty trials per session and 80 trials per subject. Six able-bodied, male subjects were involved in the real-time evaluations of the both systems.

RESULTS

The pointing task times found were (mean ± standard error) 16.36 ± 7.29 s for the three-electrode system and 13.24 ± 3.28 s for the four-electrode system. For Fitts’ law analysis, data was aggregated across subjects to give one data point for each task condition. The resulting data are shown in Tables 1 and 2, where D is the start-stop distance, W is the size (side) of the stop icon, ID is the index of difficulty, MT is the movement time and IP is index of performance.

Table 2. Aggregated point-and-click data for Fitts' law analysis of three-electrode system

D (mm)	W (mm)	ID =log2[D/W + 1] (bits)	MT (s)	IP = ID/MT (bit/s)
180	8.5	4.47	18.04	0.248
180	12.5	3.94	16.84	0.234
180	17	3.53	15.95	0.222
180	22	3.20	14.60	0.219

Table 3. Aggregated point-and-click data for Fitts' law analysis of four-electrode system

D (mm)	W (mm)	ID =log2[D/W + 1] (bits)	MT (s)	IP = ID/MT (bit/s)
180	8.5	4.47	16.12	0.277
180	12.5	3.94	14.89	0.265
180	17	3.53	13.37	0.264
180	22	3.20	12.85	0.249

The linear regression equation derived from the results of Table 1 was MT = 6.44 + 2.62*ID, $r = 0.979$, $F(1, 2) = 94.7$, $p < 0.0001$. The linear regression equation derived from the results of Table 2 was MT = 4.14 + 2.69*ID, $r = 0.984$, $F(1, 2) = 122.0$, $p < 0.00007$. The IP value for the three-electrode system was 0.38 bit/s, while the IP value for the four-electrode system was 0.37 bit/s. Figure 1 shows the linear regression plots for both systems.

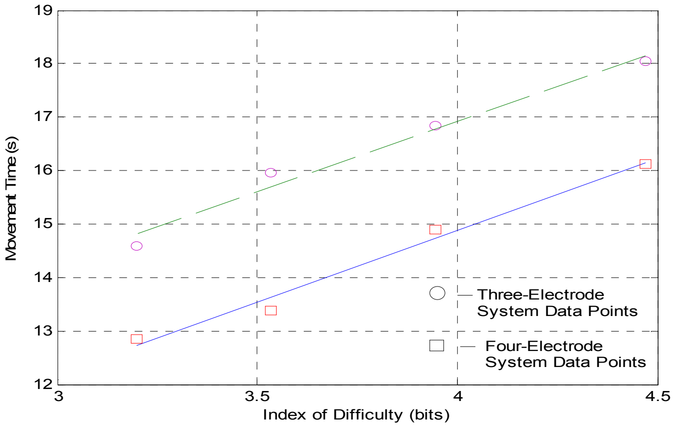

Figure 3. Fitts' law regression lines for both cursor control systems

DISCUSSION

The comparison of the mean task times for both systems showed that the mean task time is lower for the four-electrode system than the three-electrode system, this difference however was not statistically significant, $t = 1.048$, $p < 0.156$.

Overall, the tabulated results, regression line equations, and the plots produced by Fitts' law analysis suggest that the four-electrode algorithm produces a task time that is consistently ~ 2 seconds faster for a given task difficulty when compared to the three-electrode algorithm.

CONCLUSIONS

The results suggest that the four-electrode system is able to perform point-and-click tasks more quickly than the three-electrode system, and thus is a more efficient EMG-based cursor control system. The numerical results obtained with a small group of subjects (6) using both systems could not verify the statistical significance of this difference. Experiments involving a larger pool of subjects will be conducted to explore further the level of improvement in performance achieved by the four-electrode system and its associate algorithm.

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