Biomedical Signal Processing and Control 30 (2016) 98–105

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

A human-machine interface based on single channel EOG and patchable sensor

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ARTICLE INFO

Article history:
Received 1 December 2015
Received in revised form 29 May 2016
Accepted 27 June 2016

keywords:
Flexible patchable sensor
Electrooculography
Human-machine interface

ABSTRACT

Goal: This study demonstrates that single channel electrooculography (EOG) recorded by ultrathin and flexible electrodes can be practically used to control computer or machine, with the aid of proper recognition algorithms and efficient controlling methods.
Methods: First, micro-fabrication process and transfer technology were used to develop a patchable sensor including three electrodes (a measurement electrode, a ground electrode, and a reference electrode). Each electrode was composed of golden ribbon in the form of a filamentary serpentine mesh to provide conformal contact of skin and stretchability. Second, EOG was recorded by the proposed sensor installed above the eyebrow. The peak and trough of eye movement signals were extracted as features to recognize three types of eye movements (blink, upward and downward) using a threshold-based recognition algorithm. Finally, a human-machine interface (HMI) system was realized by converting eye movements to computer commands including scroll up, scroll down, and close. To verify the effectiveness of the system, eight subjects were trained to use their eye movements to navigate a document on the screen.
Results: The sensor was approximately triangular with a 5 cm side-length and a 70 um thickness. The electrode can be stretched to 10% longer without any damage. The weight of the sensor was 180 mg. The demonstration system was capable of making continuous controls with an average accuracy of 84%.
Conclusion: Single channel EOG recorded with a patchable sensor is feasible for developing a wearable HMI system. The proposed system provides a comfortable user experience, a stable control method and a simple systematic framework for developing practical HMI systems.

1. Introduction

In recent years, due to the great advances in biomedical instrumentation, applications of bioelectrical signals are now widely used in monitoring human activities rather than medical diagnosis [1]. A number of human-machine interfaces (HMIs) based on bioelectrical signals have been proposed. For example, electroencephalogram (EEG) has been used to control external devices, such as a computer cursor [2] or a virtual helicopter [3]. Electromyography (EMG) is another approach for controlling output devices such as a prosthetic limb [4]. In addition, electrooculography (EOG) has been shown to be efficient for controlling a keyboard [5]. These bioelectrical signals-based HMIs provide new communication methods for both disabled and healthy people.

Traditional HMI systems are only suitable for subjects who stay still or have few motions. Wet electrodes, multi-channel biopotential signals and a series of hardware, which were used to induce or synchronize bioptentials, must be employed to ensure the feasibility and reliability of collecting bipotentials in the HMI. Although excellent performance can be achieved, these bulky HMI systems do not fit the requirements of a wearable system due to their uncomfortable user experience and unwieldy equipment.

There is a clear trend that the HMI system is getting smaller, lighter, and more comfortable to wear [6]. In order to solve the related problems in HMI systems, an extensive amount of work has been invested in recent years.

To facilitate preparation and removal of traditional wet electrodes, novel electrodes like dry-contact and non-contact electrodes have been developed. Forvi et al. fabricated a microneedle array based dry electrode [7]. It can achieve lower contact impedance without the use of conductive gel. However, this kind of sensor is slightly invasive as the microneedles penetrate the

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http://dx.doi.org/10.1016/j.bspc.2016.06.018
1746-8094/

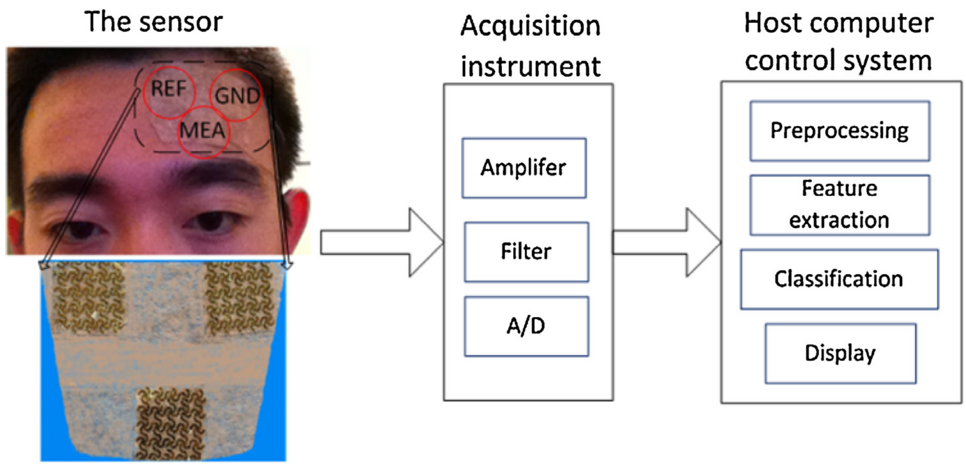

Fig. 1. A schematic diagram of the system.

stratum corneum and can cause minor pain or infection. Non-contact sensors fabricated by Matthews et al. can acquire signals without directly contacting the skin [8,9]; this kind of capacitive sensor is very sensitive to motion and relies on a complex amplifier to acquire signals due to high source impedance.

Many groups try to simplify the biopential-based HMI systems by reducing the number of electrodes, developing more efficient control paradigms and signal processing algorithms. Abdelkader et al. proposed a classification algorithm based on two channels of EOG, which can identify six classes of eyes movements [10]. However, there is still room for improvement in the accuracy (85.2%) and sensitivity (77.6%). Abo-Zahhad et al. proposed a HMI system based on single channel EOG recorded with a commercial headset (NeuroSky, CA, US) [11]. High accuracy (97.3%) was achieved, but the information transfer rate (ITR) was limited because the system can only identify one type of eye activity. Ma et al. designed a hybrid HMI system that can send 28 commands to four robots based on EOG and EEG [12]. The system required 11 channels and the operation method was relatively complex. Overall, these HMI systems are still not convenient to use.

From the above analysis we can see the traditional wet electrode is not suitable for long-term recording. In order to ensure good signal quality, users need to replace electrode frequently. In addition, traditional HMI systems use numerous recording channels, therefore, users need to spend a lot of time to prepare electrodes and ensure the stable wear. Those troubles make users reluctant to use the HMI system. As far as we know, these two problems were always studied separately. Very few studies combined the advantages of dry electrode and a small number of recording channels to solve these problems. For example, in Ref. [13], Tejz et al. designed a four-channel EOG-based assistive system using thin copper plates as dry electrodes. The proposed system could reach 100% accuracy in the classification of three kinds of eye movements (blink, left and right). To further reduce the amount of the channels, systems were developed with a single-channel commercial headset (NeuroSky, CA, US) [11,14,15]. The sensor was a dry electrode made of stainless steel. The system could only detect one type of eye activity (i.e., eye blink). In Ref. [16], with an optimized algorithm, the system designed by Shen et al. could classify two different eye-blink signals with the accuracy of 95% using the same headset. Only a small number of types of eye activity can be classified in these studies. In addition, the stainless steel electrode is sensitive to head movements.

This study pays more attention to the user experience and ergonomic factors for developing a wearable HMI system for practical applications. On the one hand, we design a flexible dry electrode to replace the traditional wet electrode or rigid dry electrodes. It can acquire good signal quality comparable to the wet electrode. On the other hand, we manufacture a flexible sensor, which integrates a measurement electrode, a reference electrode and a ground electrode, to realize a single-channel EOG-based control paradigm. It can significantly reduce system preparation time and improve user comfort. The proposed HMI system used a flexible patchable sensor attached above the eyebrow to record single-channel EOG. A new control paradigm and an efficient classification algorithm are combined to implement the HMI system, which can recognize three kinds of eye movements (upward, downward, and blink) with high accuracy and ITR.

2. Materials and methods

2.1. Control paradigm

EOG is the difference of the corneal-retinal potential in the process of eye-movements. The researcher takes the fundus as the negative pole and the cornea as the positive pole. The amplitude of EOG ranges between 50 uV and 3.5 mV with a frequency range of dc–100 Hz [17].

Traditional EOG recording needs four or more electrodes pasted around the eyes, which is uncomfortable. And if traditional electrodes are used, it is inconvenience for the subjects wearing these devices. In this study, we present a new control paradigm based on a novel patchable sensor. The sensor, which can be stuck on the forehead above the eyebrow, includes three electrodes (namely measurement (MEA), ground (GND), and reference (REF) electrodes), each in the form of a filamentary serpentine mesh with exposed gold that contacts the skin directly. Three types of eye movements including upward, downward, and blink can be recognized from the single-channel EOG recorded by the sensor and converted into computer commands (i.e., scroll up, scroll down, and close) to navigate a document on screen.

2.2. System architecture

As illustrated in Fig. 1, the system can be divided into three modules. The first module is the sensor for EOG acquisition. Fig. 2 shows the sensor's structure, which consists of a base elastic tape layer and three electrodes made with filamentary serpentine gold mesh. The size of the patchable sensor is approximately 5 cm, and the thickness is about 70 um.The size of each electrode is 2 cm × 2 cm. Three electrodes are distributed in an equicrural triangle manner with a center-to-center distance of 3 cm. The sensor