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EOG-based eye movement detection and gaze estimation for an asynchronous virtual keyboard

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ABSTRACT

This work aims to develop a novel electrooculography (EOG)-based virtual keyboard with a standard QWERTY layout which, unlike similar state-of-the-art systems, allows users to reach any icon from any location directly and asynchronously. The saccadic EOG potential displacement is mapped to angular gaze displacement using a novel two-channel input linear regression model, which considers features extracted from both the horizontal and vertical EOG signal components jointly. Using this technique, a gaze displacement estimation error of $1.32 \pm 0.26^{\circ}$ and $1.67 \pm 0.26^{\circ}$ in the horizontal and vertical directions respectively was achieved, a performance which was also found to be generally statistically significantly better than the performance obtained using one model for each EOG component to model the relationship in the horizontal and vertical directions separately, as typically used in the literature. Furthermore, this work also proposes a threshold-based method to detect eye movements from EOG signals in real-time, which are then classified as saccades or blinks using a novel cascade of a parametric and a signal-morphological classifier based on the EOG peak and gradient features. This resulted in an average saccade and blink labelling accuracy of 99.92% and 100.00% respectively, demonstrating that these two eye movements could be reliably detected and discriminated in real-time using the proposed algorithms. When these techniques were used to interface with the proposed asynchronous EOG-based virtual keyboard, an average writing speed across subjects of 11.89 ± 4.42 characters per minute was achieved, a performance which has been shown to improve substantially with user experience.

1. Introduction

Computers are nowadays regarded as being ubiquitous, generally requiring very little effort to use. However, individuals with mobility impairments, such as those diagnosed with Amyotrophic Lateral Sclerosis (ALS) or paralysed stroke patients, may be seriously challenged in their autonomy and control of such devices. Despite the limitations imposed by the different conditions, the eyes are typically the last organs to be affected and hence, an eye movement-based human–computer interface (HCI) system could provide an alternative communication channel to such intelligent systems, giving the individuals suffering from these conditions more independence and an enhanced quality of life [1].

In recent years, such eye-based HCIs have been widely developed using videooculography (VOG)-based techniques, which use cameras and image processing algorithms to track the user's ocular pose. Although VOG-based techniques yield a better resolution than electrooculography (EOG)-based techniques, they are known to be computationally demanding, susceptible to the lighting conditions, sensitive to the user's movements and also normally require an external illumination source. Alternative eye movement recording techniques include infrared reflection oculography, which is generally restricted to the recording of horizontal eye movements only; or the scleral search coil technique, which is semi-invasive as it requires the user to wear contact lenses with embedded coils [2].

EOG, on the other hand, can offer a good alternative solution to these techniques by capturing the electrical activity generated by the human eye, which could be regarded to behave like an electric dipole, having the positive and negative poles at the cornea and retina respectively. In fact, this is known to create a potential difference varying in the range of 0.4–1.0 mV, referred to as the corneo-retinal potential (CRP), which creates an electrical field. Specifically, EOG captures the electrical activity generated by the CRP non-invasively, using a set of gel-based electrodes, attached to the face in peri-orbital positions around the eyes [2,3].

This work is concerned with the use of EOG signals to interact with a virtual keyboard application. State-of-the-art EOG-based

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virtual keyboards typically require users to perform repetitive up, down, left, right and possibly oblique saccadic movements to hover over icons in discrete fixed-sized steps [1,4,5], or to make subsequent icon selections by performing eye movements originating from the centre of the screen towards a set of icons placed at the periphery to transcribe each character [6,7]. In contrast, the proposed virtual keyboard allows users to reach any icon from anywhere on the screen. Specifically, this is implemented by modelling the voltage–angle relationship of eye movements in EOG signals to allow the subject's saccadic angular displacement to be directly estimated as opposed to simply detecting the direction of the saccade; thus, the subject can traverse from one target to a final target destination in one step, thereby eliminating the restriction of having to pass through intermediary locations or to repetitively originate eye movements from a central location on the screen. The proposed virtual keyboard is also controlled asynchronously, thus not requiring the eye movements to be performed within cued intervals [6,7]. Specifically, this is implemented by proposing a novel technique to detect the user's saccadic movements and distinguish them from blinks by processing the EOG signals in real-time. This also permits the user to perform specific blink sequences that are detected to address the Midas touch problem, an aspect which is typically neglected in the literature.

In the literature, the voltage–angle relationship of eye movements in EOG signals is typically modelled by analysing the horizontal and vertical EOG components separately, specifically by adopting one model for each EOG component to model the relationship between the gaze angles and EOG potential in the horizontal and vertical directions separately [8–10]. The correctness of this method however, depends on the assumption that the horizontal EOG signal component is only a function of the horizontal ocular displacement, and similarly the vertical EOG signal component is only a function of the vertical ocular displacement, which may not be typically the case in practice, such as due to misalignment between the horizontal and vertical EOG electrode pairs and the horizontal and vertical ocular dipole axes [11]. This was observed by Lee et al. [12] wherein each EOG component was represented by a linear model depending on both the horizontal and vertical displacements. Here the dependence of each EOG component on the horizontal and vertical ocular displacements is further studied. Consequently, this work investigates whether both components ought to be used individually or jointly when estimating the gaze angles, specifically by proposing a two-channel input linear regression model, using features extracted from both EOG components jointly, and by comparing this against state-of-the-art methods comprising one model for each EOG component.

On the other hand, the limited literature available with regard to asynchronous eye movement detection from EOG signals is typically restricted to the detection of blinks and a discrete set of saccadic movements of one particular displacement in four [1,4] or eight directions [3,5] only. This restricts users to hover over the screen in fixed-size steps in discrete directions only, as previously indicated. State-of-the-art blink and saccade detection techniques are typically based on amplitude and duration thresholds [3–5]. Template-matching based approaches are also typically used, particularly for blink detection [1,11], which however suffer from a long labelling delay as they have to wait for the acquisition of the entire EOG segment prior to labelling the eye movements. In view of this, we propose a novel technique which exploits the saccade and blink EOG peak-gradient feature distribution to distinguish between blinks and saccades, of any displacement and direction, from EOG signals in real-time.

Thus, in summary, the main contributions of this work include: (i) a statistical analysis of the dependence of each EOG signal component on the horizontal and vertical ocular displacements, henceforth referred to as the dependence test; (ii) a two-channel input regression model to estimate the ocular pose; (iii) a novel technique to detect and label eye movements by processing the EOG signals in real-time; and (iv) the combined use of these techniques to interact with a virtual keyboard. The rest of the paper is divided as follows; Section 2 focuses on the acquisition and processing of EOG signals, followed by Section 3 which presents the dependence test as well as the proposed two-channel input regression model. The proposed real-time eye movement detection and labelling technique is presented in Section 4, while Section 5 presents the ocular pose estimation and eye movement labelling performance obtained using the proposed techniques. Finally, an asynchronous EOG-based virtual keyboard is presented in Section 6 together with its performance as tested by a number of subjects. Section 7 concludes this paper.

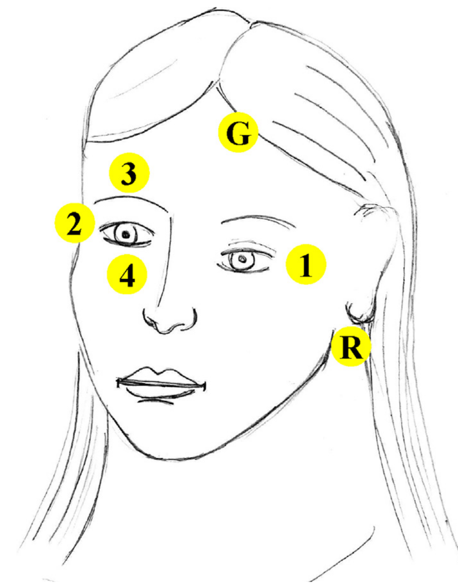

Fig. 1. EOG electrode configuration.

2. Acquisition and processing of EOG signals

2.1. Acquisition of EOG signals

The acquisition of EOG signals was approved by the University Research Ethics Committee (UREC) at the University of Malta and before each recording session subjects had to provide their informed consent. Subjects were placed approximately 60 cm away from a 24 in. LCD monitor, with their head held immobile by means of ophthalmic chin and forehead rests. During these sessions, they were instructed to follow onscreen instructions as will be discussed further in the sections which follow.

The EOG electrode configuration was set as shown in Fig. 1, with two electrodes placed to the left and right of the respective outer canthi and another pair placed above and under the right eye. A ground ('G') and a reference ('R') electrode were also placed on the forehead and on the mastoid behind the left ear respectively, as shown. EOG data was recorded using the g.tec g.USBamp biosignal amplifier (g.tec medical engineering GmbH, Austria) with a sampling frequency of 256 Hz. The potential differences between the horizontally- and vertically-aligned electrodes were computed to yield what are referred to as the horizontal and vertical EOG components, denoted by $EOG_h(t)$ and $EOG_v(t)$ respectively:

$$EOG_h(t) = V_1(t) - V_2(t) \quad (1)$$

$$EOG_v(t) = V_3(t) - V_4(t) \quad (2)$$