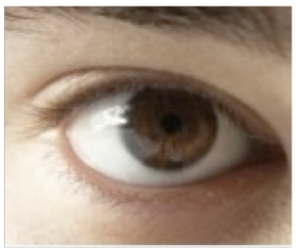
Wearable EOG Goggles: Eye-Based Interaction in Everyday Environments



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Abstract
In this paper, we present an embedded eye tracker for context-awareness and eye-based human-computer interaction – the *wearable EOG goggles*. In contrast to common systems using video, this unobtrusive device relies on Electrooculography (EOG). It consists of goggles with dry electrodes integrated into the frame and a small pocket-worn component with a powerful microcontroller for EOG signal processing. Using this lightweight system, sequences of eye movements, so-called eye gestures, can be efficiently recognised from EOG signals in real-time for HCI purposes. The device is self-contained solution and allows for seamless eye motion sensing, context-recognition and eye-based interaction in everyday environments.

Keywords
Wearable Computing, Context-Awareness, Human-Computer Interaction (HCI), Electrooculography (EOG), Eye Gestures, Eye Tracking

ACM Classification Keywords
C.3 [Special-Purpose and Application-Based Systems]: Real-time and embedded systems; H.5.2 [Information Interfaces and Presentation]: User Interfaces---Interaction styles; I.5.5 [Pattern Recognition]: Implementation---Interactive systems

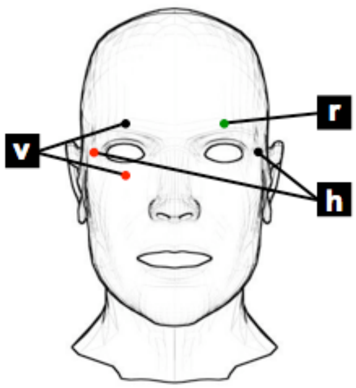

Figure 1. Schematic of the electrode positions used on the *wearable EOG goggles* for EOG data acquisition: Electrode pairs for the horizontal (h) and vertical (v) components of eye motion and the reference electrode (r).

Introduction

Similar to commonly used modalities such as hand-gestures or speech, the human eyes have emerged as an important input modality for HCI applications. Eye movements allow for privacy in situations where the hands or voice are not safe to use, such as in public places. Eye gaze has shown to be a good indicator of attention and intentionality, which makes it particularly interesting as an input modality for attentive user interfaces [17]. However, the commonly used method for implementing a "confirm" command based on the dwell time is limited in the maximum input speed that can be achieved. This is particularly irritating for trained users. Eye gestures that consist of several consecutive movements were proposed to provide a solution to this problem [7,20]. They naturally avoid the requirement of distinguishing between deliberate input and random eye movements, the so-called "Midas touch" problem (for details see [10]).

The common method to track eye gaze are systems based on video cameras. For stationary settings, a wide range of hardware is available that allows for precise gaze tracking. However, current mobile systems - such as the Mobile Eye from Applied Science Laboratories (ASL) or the iView X HED from SensoMotoric Instruments (SMI) - do not meet the requirements for unobtrusive long-term use and interaction in everyday environments. Video-based systems require bulky headgear and additional equipment to process the video streams. They are not geared for embedded online processing of eye motion, which is a crucial point for eye-based interaction. To our knowledge, at this stage no wearable eye tracking solution exists that is self-contained and unobtrusive and allows for long-term interaction in everyday environments.

Therefore, we investigate Electrooculography (EOG) as an alternative measurement technique for context-awareness and eye-based interaction. In contrast to vision-based gaze tracking, EOG is measured with body-worn sensors, and can thus be implemented as a lightweight wearable system. While accurate gaze tracking is still difficult to achieve, relative eye movements can be tracked robustly. Using a commercial multi-purpose device, we demonstrated that EOG is suitable for automatic recognition of natural reading activity in mobile daily-life settings [2]. These promising results lead to the design and implementation of a custom EOG-based wearable eye tracker with dry electrodes integrated into a glasses frame and EOG signals processed directly on the device, the so-called *wearable EOG goggles* [3]. The system is able to recognise eye gestures in real-time, which makes it particularly suited for eye-based HCI applications [4].

Related Work

Most studies in eye-based human-computer interaction so far focused on direct manipulation of user interfaces using video-based gaze trackers (e.g. [15,16,21]). A lot of research has been devoted to the development of eye-gaze based interfaces for text-entry [12,20]. While these studies used different basic characteristics of eye motion as an input, they did not investigate means to implement a versatile and fast interaction based on eye motion.

Efforts to miniaturise video-based eye trackers led researchers to consider EOG signals recorded with standard equipment for eye tracking in stationary settings [1,9]. Basic signal characteristics such as saccades, fixations and blinks have been used to

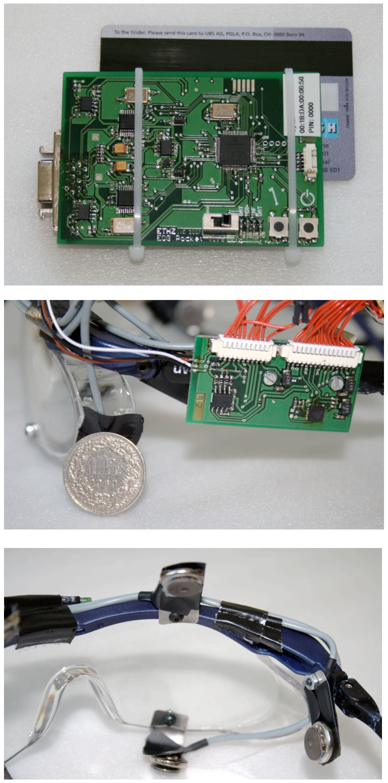

Figure 2. Detailed views of the signal processing unit *WEPU* with credit card size (top) and the *Goggles* with a small board containing a circuit for analogue signal amplification and an accelerometer, a light sensor and dry electrodes for EOG signal acquisition integrated into the frame (middle and bottom).

control robots with the person remaining stationary [5,19]. Others investigate novel electrode configurations for EOG recordings in mobile settings. Manabe et al. proposed a gaze detector that uses EOG electrode arrays mounted on ordinary headphones [13]. While this approach might be less obtrusive than electrodes stuck to the face, it raises other issues: Low signal-noise ratio (SNR) and poor separation of the movement components. Vehkaoja et al. presented a lightweight head cap with electrodes embroidered of silver coated thread [18]. A small device integrated into the cap allows for wireless data transmission. As yet it is still to be evaluated in operation.

Although novel devices for recording eye motion using EOG have been developed, none of them allows for embedded recording and analysis of eye motion and eye-based interaction using a standalone wearable device. The *wearable EOG goggles* are a highly miniaturised, autonomous wearable sensor particularly designed for this task. Low-power and lightweight implementation, real-time signal processing capabilities and additional sensors for the compensation of artefacts caused by physical activity make this embedded system a unique solution for robust eye-based interaction.

Background

The eyes are the origin of a steady electric potential field, which can be described as a dipole with its positive pole at the cornea and its negative pole at the retina. The magnitude of this corneoretinal potential (CRP) lies in the range of 0.4*mV* to 1.0*mV*. The CRP is the basis for a signal measured between two pairs of electrodes commonly placed above and below, and on the left and right side of the eye, the so-called Electrooculogram (EOG) (see Figure 1). If the eyes move from the centre position towards the periphery, this results in a change in the electric potential field. Inversely, by analysing these changes, the horizontal and the vertical component of eye motion can be captured.

In the human eye, only the central region of the retina, the fovea, is sensitive enough for most visual tasks. This limitation requires the eyes to move constantly as only small parts of a scene can be perceived with high acuity. Simultaneous movements of both eyes in the same direction are called *saccades*. Typical characteristics of saccadic eye movements are 400°*/s* for the maximum velocity, 20° for the amplitude and 80ms for the duration [8].

Design and Implementation

The *wearable EOG goggles* were designed to fulfil the following requirements:

1. To achieve a convenient and unobtrusive implementation and minimise user distraction the device needs to be *wearable* and *lightweight.*

2. To allow for autonomous long-term use in daily life the device needs to be *low-power*.

3. The device needs to provide *adaptive real-time signal processing capabilities* to allow for context-aware interaction.

4. To compensate for EOG signal artefacts caused by physical activity and changes in ambient light an *accelerometer* and a *light sensor* need to be added.

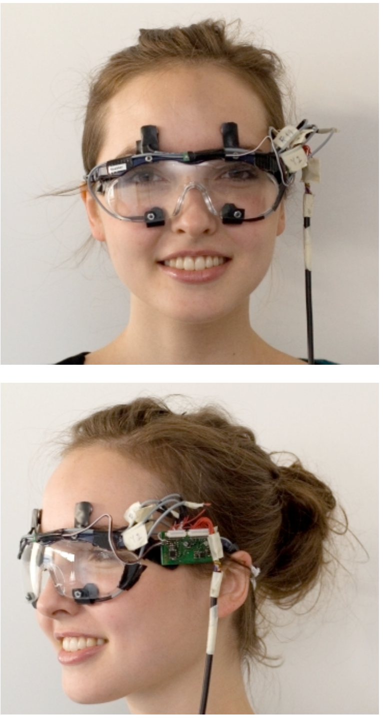

Figure 3. *Goggles* worn by a person with the small board for EOG signal amplification attached to the left side of the frame, dry electrodes capturing the horizontal and vertical components of eye motion and the light sensor at the front for adaptive compensation of changes in ambient light.

The hardware is made of two components (see Figure 2): *Goggles* with integrated electrodes and a small board for signal amplification and a wearable EOG processing unit (called *WEPU*) with credit card size worn on the body. The system weights 188*g* and allows for up to 7.2*h* of autonomous use.

The *Goggles* contain the light sensor, dry EOG electrodes and a small analogue amplification circuit board attached to the glasses frame. Four electrodes are arranged around the left eye and mounted on flat springs to achieve good skin contact. A fifth sensor above the right eye provides the reference signal. The light sensor is attached at the front of the frame between the eyes pointing forward in line of incident light (see Figure 3).

The *WEPU* is the core signal processing unit of the system. It is based on a digital signal processor (DSP) and contains two 24-bit analogue-digital converters (ADC), a Bluetooth and a MMC module. EOG signals are processed in real-time and can either be transmitted using Bluetooth or stored on the integrated MMC card.

Eye Gesture Based Interaction

Eye gesture based interaction requires different signal processing steps to be performed on the EOG signals. This involves the detection and removal of blinks, the detection of saccades and their encoding into a string representation, and the recognition of eye gestures consisting of consecutive eye movements in this representation.

Blink Detection and Removal
Blinks need to be detected in the vertical EOG signal component for two reasons: For certain HCI applications they may be used as an additional input command to provide a more versatile input alphabet. For applications focused on eye gesture detection, however, blinks need to be removed because their characteristics are similar to those of saccadic eye movements. This would affect eye movement detection and may eventually render eye gesture recognition impossible. On the *wearable EOG goggles*, blinks are detected with a template matching approach: Using a template created manually from example blinks of different persons, blinks are detected by shifting this template over the vertical EOG signal component. For those segments of the signal where the similarity to the template is higher than a defined threshold, a blink is detected and removed from the signal.

Saccade Detection
Eye gesture recognition is based on the detection of consecutive saccades in the horizontal and vertical EOG signal component. The type of eye gestures is thereby defined by the order and direction of these saccades. On the goggles, saccade detection is performed using the so-called Continuous Wavelet Transform - Saccade Detection (CWT-SD) algorithm: The CWT-SD first computes the continuous 1-D wavelet coefficients from the signal at scale 20 using Haar wavelets. A saccade is detected for all samples where the absolute value of the coefficient vector exceeds a calibrated threshold.

Eye Gesture Recognition
For eye gesture recognition, the detected saccades are first mapped to eye movements in basic directions separately for each movement component. Basic directions are left, right, up and down, encoded into the symbols “L”, “R”, “U” and “D”. In a second step, diagonal eye movements are detected and combined

Figure 4. A person playing the computer game using eye gestures on a desktop computer screen. Movements of the head and the upper body in front of the computer are not physically constrained (top). Two example gestures used in the game and their corresponding string representations (bottom).

into one eye movement string sequence. Diagonal eye movements are characterised by simultaneous saccades in both EOG signal components. They are represented by the symbols "1", "3", "7" and "9".

To recognise eye gestures that consist of several consecutive eye movements, we follow a string matching approach. For matching, the combined string sequence is continuously compared with templates representing the gestures required by the specific interface (see Figure 4). If one of the templates is detected in the string sequence, the corresponding eye gesture is recognised.

Case Study

In [4] we evaluated the wearable eye tracker for eye-based human-computer interaction in a stationary setting. To investigate the use of explicit eye gestures as a control input, we developed a desktop computer game consisting of eight different game levels. In each level, subjects had to repeatedly perform defined eye gestures of different complexity as fast as possible until the first successful try (see Figure 4). To reach a high score, wrong eye movements, i.e. movements that were not part of the expected gesture, had to be minimised. In contrast to [7], no headrest was used, i.e. movements of the head and the upper body were allowed at any time in front of the computer.

We found that EOG signals can be efficiently processed for eye gesture recognition and that EOG is a robust modality for HCI applications over different subjects. While using the eyes as a control input was quickly learned, 30% of the subjects reported of having had problems to stay concentrated during the game. However, fatigue is an intrinsic problem not only for eye gestures but also for common input modalities such as speech or hand gestures. Eye gestures outperform these modalities if the hands cannot be used (e.g. during driving, during a surgery or while working on the computer) or if speech input is not possible (e.g. in very silent or very noisy surroundings).

Conclusion

In this work, we have described an autonomous and unobtrusive EOG-based eye tracker integrated into goggles. Its self-contained design enables wearable sensing and real-time analysis of eye motion and extends these to everyday environments. We found that the main characteristics of eye motion can be captured in an efficient way directly on the device. The detection of eye gestures enables a wide range of context-aware interactive applications, e.g. for mobile text-entry. Eventually, the *wearable EOG goggles* may allow for versatile interaction in mobile settings (see Figure 5). By connecting several eye trackers, concurrent eye movement recordings for several people and collaborative interaction may become possible.

The movement patterns our eyes follow in daily routine reveal much about what we are doing and what we intend to do. Our long-term objective is to investigate how much information eye motion can provide about the user's activity and context and how this can be exploited for novel human-computer interfaces. Unconscious eye movements are the result of cognitive processes in the human brain. These processes are related to the user's activities or environment, but also to internal aspects of visual perception such as memory [14] and learning [6]. The analysis of eye motion may allow deducing these aspects, which would give important input for future interactive systems.

Figure 5. Person using the *wearable EOG goggles* together with a head-up display (HUD) and a wearable keyboard (Twiddler2) for interaction in a mobile setting.

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