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Eye Accommodation Sensing for Adaptive Focus Adjustment

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***Abstract*— Over 2 billion people across the world are affected by some visual impairment – mostly related to optical issues, and this number is estimated to grow. Often, particularly in the elderly, more than one condition can affect the eyes at the same time, e.g., myopia and presbyopia. Bifocal or multifocal lenses can be used, these however may become uncomfortable or disturbing and are not adapted to the user. There is therefore a need and opportunity for a new type of glasses able to adaptively change the lenses' focus. This paper explores the feasibility of recording the eye accommodation process in a non-invasive way using a wearable device. This can provide a way to measure eye convergence in real-time to determine what a person's eye is focused on. In this study, Electro-oculography (EoG) is used to observe eye muscle activity and estimate eye movement. To assess this, a group of 11 participants we each asked to switch their gaze from a near to far target and vice versa, whilst their EoG was measured. This revealed two distinct waveforms: one for the transition from a far to near target, and one for the transition from a near to far target. This informed the design of a correlation-based classifier to detect which signals are related to a far to near, or near to far transition. This achieved a classification accuracy of 97.9±1.37% across the experimental results gathered from our 11 participants. This pilot data provides a basic starting point to justify future device development.**

I. INTRODUCTION

The number of people worldwide suffering from eye refractive errors has been estimated to be over 2.2 billion [1], [2]. When they are affected by more than one refractive error, such as myopia, hyperopia, and presbyopia, they must wear more than one pair of glasses or use bifocal, multifocal, or progressive lenses [3]. These solutions however are uncomfortable, reduce the field of view, or force the user to move their head in different directions, often causing discomfort. The full field of view could potentially be restored using lenses with adaptive focus adjustment. In this way, the whole lens would provide the correct optical power depending on where the users gaze is, without the need to change glasses or move the head in an unnatural way.

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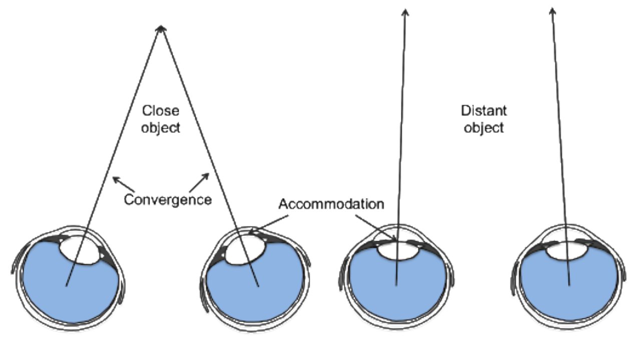

Fig. 1. Process of eyes vergence during accommodation. During near accommodation, eyes make an inward movement towards each other.

To understand what the user is looking at, and at which distance, it is important to know when accommodation occurs (or when it is intended). The latter is the process by which human eyes' lenses change optical power to keep focus on an object and to maintain a clear view when its distance from the eyes changes. It involves three responses that, working together, result in accommodation. These are: the *ciliary muscle contraction*, the *eyes convergence*, and *pupils constriction* [4]. In particular, the convergence is the simultaneous inward movement of both eyes towards each other. Each eye axe points towards the object of interest to focus it when the user is looking at a near object. Conversely, when someone is looking at a far object, both eyes simultaneously move outward, away from each other. This process is called divergence. Both vergence movements (convergence and divergence) are just in horizontal direction, and they are unique as they are the only eyes movements that are not associate. For this reason, vergence movements are called disconjugate eyes movements. The process of eyes vergence is illustrated in Fig. 1.

The standard ways to record accommodation are mainly focused on the change in curvature of the crystalline's anterior surface, adopting photographic recording. However, these devices are bulky and not wearable. During the past two decades, indirect and direct methods to record accommodation in a wearable form factor have been developed. For example, Richer et al. [5], and Domkin et al. [6] have found a correlation between ciliary muscle contraction and trapezius muscle activation during visual tasks. Other studies have developed glasses prototypes able to investigate the accommodation process and change the lenses optical power. While many of these require some form of manual control, others use automatic methods to record accommodation and

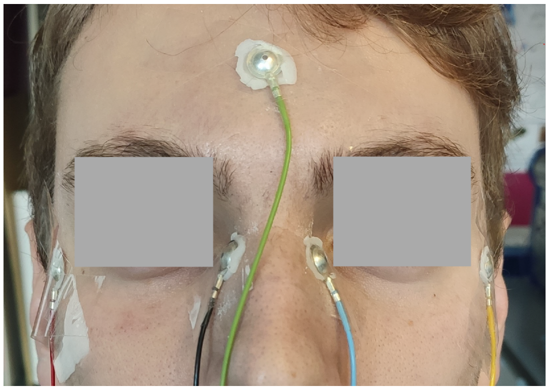

Fig. 2. Example of electrode placement for the EoG recording.

to send the information to the variable focus lenses. For example, Fujita et al. [7] has computed the distance of the object, measuring eyes convergence angles with a tunnel of light path device; Hasan et al. [8] has measured the distance of the object using a distance sensor based on the time of flight; Wang et al. [9] has used a simple manual control of the lenses optical power. All these solutions are either not fully automatic or not suitable for use during normal daily activities. To address this, Padmanaban et al. [10] has used a depth camera and an eyes tracker system to understand at which distance is the object that the user is looking at. Nonetheless, this system is not completely wearable due to the still large dimension.

This paper presents our pilot study aiming to develop a new technique to provide information on the distance of an object that the user is looking at. The work presented herein has been developed at the Centre for Bio-Inspired Technology (CBIT) at Imperial College London, UK.

II. Electroculography

The standard clinical electrooculography is an electrophysiological test in which the change of the electrical potential between the cornea and the ocular fundus is recorded during different room light conditions and during ocular movement tasks [11]. This potential can be considered as a dipole positioned on the same line of the eye axis. During standard EoG measurements, two small electrodes placed on the skin at each side of the eyes and one reference electrode on the forehead are attached. This test is typically used to evaluate possible disorders of the retinal pigment epithelium and the photoreceptor layer of retina. The potential amplitude depends on the light condition. With regards to this work, it is sufficient to use the recording system alone to detect the eyes movements. The purpose is to record the convergence during an accommodative eyes movement regardless of the light condition. The EoG system includes two channels, one for each eye, with the electrodes placed as in Fig.2.

A diagram of the horizontal movement of each eye is showed in Fig. 3. The aim is to acquire the signals from the two eyes separately and to compare them in order to evaluate the non-common component that represent the vergence components.

TABLE I

Study protocol listing the different gaze tasks requested.

Target configuration	Task (each repeated 4×)
X	Transition 1-2
X	Transition 2-1
Y	Transition 1-2
Y	Transition 2-1

III. Experimental recordings

As first step for the experiment, it is necessary to initiate the accommodation process in order to simultaneously record the eyes movements. To do this, a simple visual task protocol is developed. Two targets are used at two different distances (Fig. 4). The first target, 9x6cm in size, is positioned 30 cm far from the user's eyes. The second, is located at 4.3 m from the user's eyes and is 23×15 cm in size. The targets are placed at the same height of the eyes, with the user seated on a chair as in Fig. 5. For the experiment five reusable EEG adult cup electrode of silver/silver chloride (Philips) are used. For the electrodes attachment, a skin abrasive gel and a conductive/adhesive paste are used as advised in the EoG standard [12].

During the experiment, the user sits comfortable on a chair and is required to stay as still as possible with the body and the head to avoid external noise due to movement artefacts. Each recording lasts 15 seconds. Between each of them a rest of 30 seconds is provided. At the beginning of the recording, users are asked to fix one of the two targets. After half of the interval (7 seconds), they have to switch their gaze from one target to the other, and focus on it till the end of the interval. The protocol provides a total of sixteen recordings per patient. Half of them are done with the same target configuration of the Fig. 5, that is with the closest target positioned beneath the furthest (configuration X). In the other eight recordings the targets are inverted, positioning the closest above the furthest (configuration Y).

For each target configuration, users have to perform two tasks. In the first, they focus on the closest target (target 1) when recording starts and switch their gaze to the furthest one (target 2) after seven seconds. In the second target configuration, they perform the same task, but starting from the furthest. These two tasks are performed for both target configurations X and Y. A scheme summarising the about described tasks is presented in Table I.

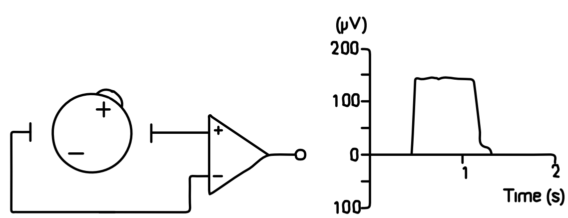

Fig. 3. Example of EoG single channel signal. When the eye moves horizontally a changing on the recorded signals occurs.

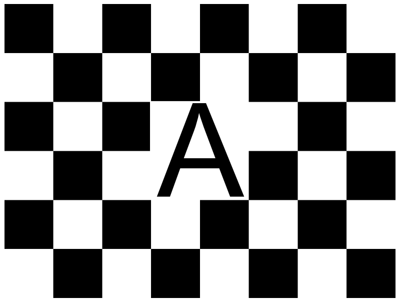

Fig. 4. Visual target used for the recordings.

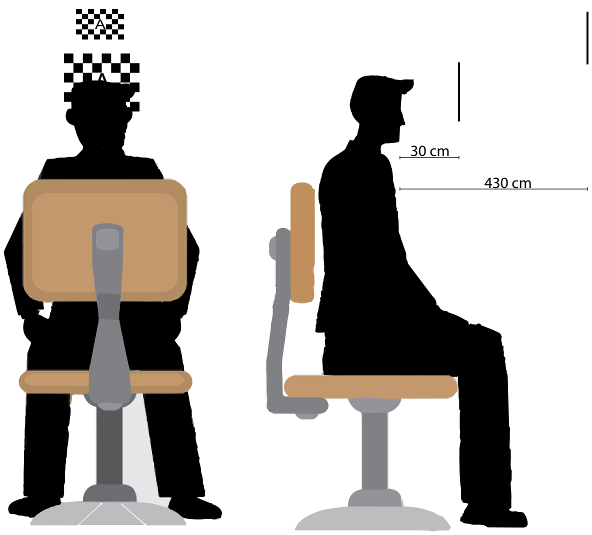

Fig. 5. Recording setup. The user is seated on a chair and the targets are placed in front of him at 30 cm and 4.3 m respectively.

A total of 11 volunteers have participated to the experiment (6 female, 5 male, aged 22-30). Written informed consent was obtained from subjects before the experiment in accordance with human subjects research rules. Each user was allowed to wear glasses if necessary. This does not affect the recordings. In total, 4 of the 11 users wore glasses during the experiment. None of the 11 participants were affected by disconjugate eye movement or strabismus.

IV. Signal processing

As introduced in Section I, convergence is a simultaneous inward movement of both eyes that occurs during accommodation. It is a disconjugate eyes movement, which means that eyes move in different directions. The purpose of this experiment is to understand when such non-common eyes movement occurs. Therefore, it is important that the electrodes are placed as symmetric as possible between the two eyes, in order to obtain two signals as similar as possible during non-accommodative movements. To extract the non-common components, the difference between the signals of both eyes has been computed. In this way, when eyes execute common movements (conjugate movement), the resulting signal would be negligible and approximated to zero. On the other hand, during a vergence movement, a signal different from zero is displayed. The EoG signal is mostly contained in the frequency band between 0 and 30 Hz. In this application, a sampling rate of 100 Hz has been used. In addition, first order low-pass and a high-pass filters have been used with respectively 30 Hz and 0.0001 Hz as cut off frequency. In order to avoid power line noise, a 50 Hz notch filter has been employed as well.

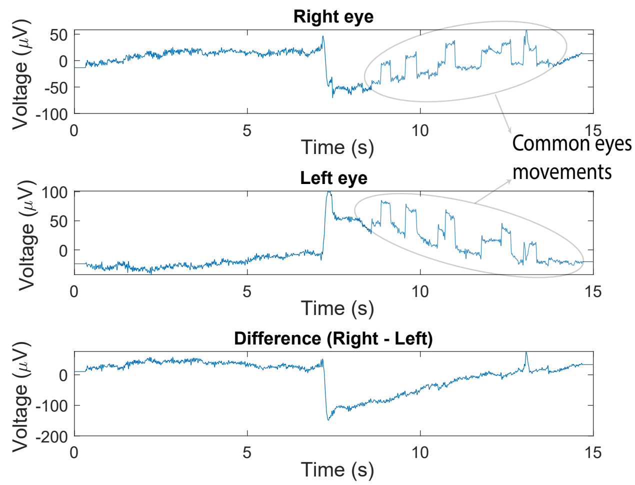

Fig. 6. An example recording. Two channels are recorded, one for each eye, and the difference between them is then computed (bottom). In this case the figure is related to a transition from the far target to the near target. As it is possible to see in the single eye channels, during the transition (middle of the x-axis) a step generates, and it has opposite polarity in the two channels. At the same time, during the final recorded seconds, other artefacts generate. In this case, they are the same in both channels, hence, they are minimised in the differential signal.

During the experiment, each user was trained with two recording trials in order for the process to be clear and learned by the user in advance. Such recordings are not part of the experiment data. Considering 16 signals per user, a total of 176 signals have been recorded.

Some of the recordings were not used at the processing stage, due to noise, interference, and artefact making the signal not suitable for processing. This was mainly cause by excessive eye blinking or eyes burning during the 15 seconds recording, where the user was supposed to stay as still as possible while fixing the target.

for this reason, a total of 24 signals have been excluded during the processing stage. Following time alignment, all the signals have been divided into two classes: the first is related to the visual transition from the near target to the far target (transition 1-2) and the second is related to the transition from the far to the near target (transition 2-1). An example of recorded signal is shown in Fig. 6, where common eyes movements are minimised in the difference signal, and non-common movements (i.e. convergence) are amplified.

A total of 152 signals have been used for the processing stage; 74 are related to the near to far transition (Fig. 7)

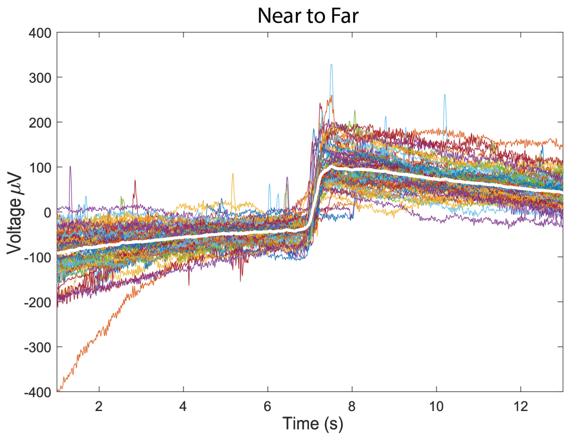

Fig. 7. Transition from near to far target. All recorded signals shown superimposed with average signal illustrated in white.

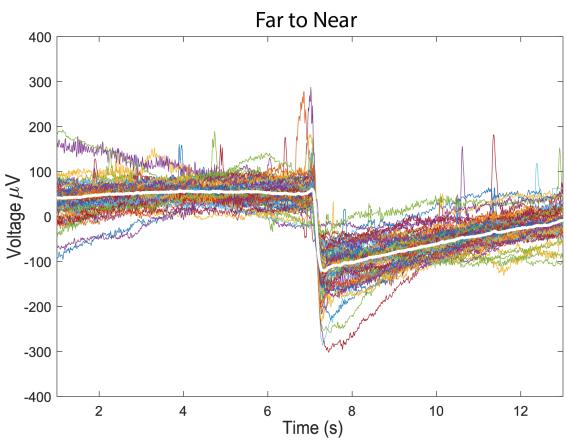

Fig. 8. Transition from far to near target. All recorded signals shown superimposed with average signal illustrated in white.

and 78 to the far to near transition (Fig. 8). As shown in the figures, there is a clear difference between the two transitions: during the far to near task, a decrease in the difference signal occurs during the transition, whereas a signal increase occurs during a near to far transition.

In order to implement a system that recognise at which transition each signal belongs, thus identifying the change in accommodation and focus, a simple classifier has been developed. It is based on correlation between signals: signals belonging to the same class have more correlation with each other, with respect to the signals belonging to the other class.

The main steps in the algorithm are as follows:

- Random separation of the data-set in training (60%) and test-set (40%);
- Computation of the cross-correlation sequences: taking a generic ith signal from the test-set, the cross correlation sequences with all the training-set signals are computed;
- Selection of the maximum value of each cross correlation sequences;
- Calculation of the mean value of all maximum values for each class separately (means for classes 0 and 1);
- Comparison between the means of classes 0 and 1. If the first is higher than the second, the ith signal is allocated in class 0. Otherwise, it is allocated in class 1.

The accuracy, defined as the number of correct classified data over the total number of data, is 97.9% $\pm$1.37 (mean $\pm$ standard deviation). To test the performance change depending on the amount of training sets, different fractions of training and test set have been investigated. Specifically, keeping the same test-set (40%), different fractions of training set have been tested, starting from 5% to 60%, as shown in Fig.9. As expected, the accuracy increases with the increasing of the training fraction, saturating at a value of $\sim$98% corresponding to a percentage of training set of 20%.

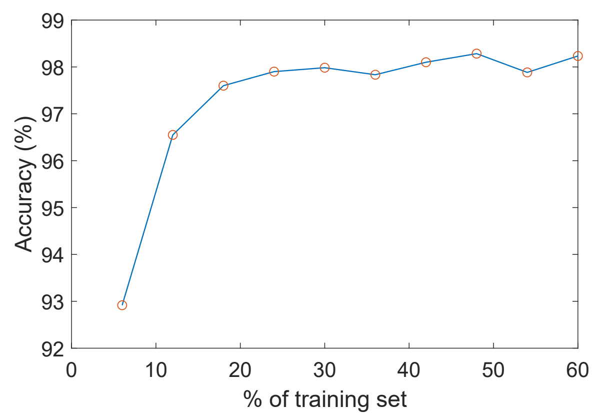

Fig. 9. Algorithm performances, changing the fraction of training set. The test set has been kept fixed at 40%.

V. Conclusion

The core objective of this work has been to verify the feasibility of recording the accommodation process, to inform future development of a pair of glasses able to change lens' focus depending on the object that the user is looking at.

A protocol was developed and an experiment performed, during which 11 participants were each asked to switch their gaze from a near (30 cm) to a far (4.3 m) target and vice-versa, to stimulate eye accommodation. Signals were recorded with a Electro-oculography system and were processed and classified with MATLAB. The implemented classifier is based on the correlation between signals pertaining to the same class. Starting with a training set fraction of 20% of total recorded signals, the performances remain above 97%, saturating at $\sim$98%.

We have shown that, with a setup based on EoG recordings and with a simple correlation classifier, it possible to identify with high accuracy when the participant is switching their gaze from a near target to a far target, or from a far target to a near target. Moreover, considering the location of the electrodes, a wearable device may be implemented based on a form factor similar to typical eyeglasses. The typical

EoG electrodes used in our experiments are not suitable for integration in wearable glasses, therefore more advanced and miniaturised electrodes should be employed for such application, both to reduce the contact resistance - thus the signal quality - and the comfort for the user.

Moreover, significant sources of noise have been identified during the experiment: sudden eyes movement, eye blinking, eyes burning, etc, which cause the activation of muscles around the eye. A more accurate front-end recording system and digital filtering will allow in further iterations of the system to reduce the impact of such sources of noise and amplify the accommodation signal.

Finally, with new advancement in materials that are able to change focal length depending on the electrical voltage applied, adaptive multifocal lenses will be implemented to help people suffering from eye refractive errors, avoiding the need for multiple glasses, multiple lenses, or fixed multifocal lenses. Systems aiming at measuring intended accommodation with a simple, effective, and low-power method will be required. We believe what we presented hereby is one of them.

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