Gaze Tracker by Electrooculography (EOG) on a Head-Band

Franco Simini, Andrés Touya, Agustín Senatore and José Pereira

Abstract—**A compact gaze tracker was developed by processing electrooculogram (EOG) signals taken from electrodes secured to an elastic head band. We confirmed that eye position is perceived by an observer in normal social interaction within 5°. We developed the prototype named PANTOJO after its pantographic potential to move a prosthetic eye following the healthy eye movements. We also confirmed that the EOG correlates with gaze angle. PANTOJO was implemented with a 1Hz to 20Hz bandwith, 66dB amplification and digital signal processing to output the position of the eye to within 2°. After initial calibration PANTOJO acts as a state machine, detecting and classifying eye movements according to saccades. A 75% success rate was achieved to detect transitions from discretized eye positions in 5° multiples from +40° to -40°. With its transport delay of 100 ms, update rate of 46Hz and an accuracy of 2.5° PANTOJO may prove to be a versatile gaze tracker for multiple applications, including communication devices for the disabled (e.g. tetraparesis), gait research or driving analysis in real life.**

I. Introduction

Eye movement research is an established field of work for physiologists and developers of biomedical instrumentation, with a growing share being taken by signal and image processing [1] [2]. Such areas as visual perception, reading technique determination, instrument panel layout design and driving analysis have all benefited from eye movement recordings [1]. Eye tracking has been implemented using a variety of technologies, ranging from a small coil affixed to the eye ball (using electromagnetic (EM) induction) to optic devices (using cameras to record sequences of images of the iris). A third technique -mostly used in clinical settings- processes the electrical signal detected on the skin by the eyes: the electrooculogram EOG.

The use of the data gathered strongly influences the technology to be selected to capture information. For instance a specific physiological study may include a somewhat cumbersome apparatus to record signals over short periods of time with great accuracy: this is the case of the 50 years old technique of a search coil put onto the sclera of the eye reported by Robinson as far back as 1963 according to later descriptions [1]. This scleral loop technique includes additionally two skull-sized field inducing spires located on both sides of the head to stimulate currents on the eye coil according to the area subtended by the EM field. In case vertical eye movements are also to be recorded, two more spires are installed horizontally in the vicinity of the patient. This set-up is clearly not suitable to study everyday life situations, let alone determine eye movements for prolonged periods of time.

Non contacting (and therefore less invasive) techniques to record eye movement were introduced when very small optical devices became commercially available. The optical elements are mounted on spectacles or similar light-weight structures secured onto the head of the subject under study. Infrared devices and webcams are used to obtain either simplified reflection of light or extensive video recordings to be processed. Very recently Schiavone et al. have described one such system to record normal activity of toddlers [3].

The most widespread modality to record eye movement in a qualitative way is called the electrooculogram (EOG) which displays electrical signals generated by the eyes on the skin. The EOG is embedded in multiple electrical interferences of both biological and EM origin [1]. Although the linearity of the EOG with eye position has been established, little was done [5], [6] to use it for purposes other than basic research or diagnostics.

The present project was initially motivated by the need to move a total eye prosthesis worn by patients. Subject to social discrimination despite the aesthetic quality of modern eye replacemet, patients may need the additional feature of a mobile artificial eye ball, whose movement should ideally follow the movement of the healthy eye. Our aim [4] was to record the eye position with a device that could be worn with minimal discomfort for a long time during the day. The prosthesic eye movement should be determined by some intelligent automatic guesswork based on the position of the healthy eye. An initial search for such devices was unsuccesful, all eye tracking solutions falling within the categories of either i) invasive, ii) externallly based or iii) head worn but cumbersome or heavy. We set ourselves the goal of developing a novel gaze tracker overcoming these difficulties, i.e. a portable, non invasive and lightweight eye position detector.

The device finally produced and tested has the additional

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F. Simini is Professor of Biomedical Engineering and Head of **nib** - núcleo de ingeniería biomédica de las Facultades de Medicina e Ingeniería of the UNIVERSIDAD DE LA REPUBLICA - URUGUAY (corresponding author´s telephone: +598 2487 1515 extension 2438; e-mail: simini@fing.edu.uy).

A. Touya, A. Senatore and J. Pereira hold a degree in Electronics Engineering and at the time of this research were students working in Biomedical Engineering applications at **nib** - núcleo de ingeniería biomédica de las Facultades de Medicina e Ingeniería of the UNIVERSIDAD DE LA REPUBLICA - URUGUAY (e-mail: adtouya@fing.edu.uy, agusen@gmail.com, josepereira@fing.edu.uy).

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advantage of being a general purpose *gaze tracker* for other applications, such as communication devices for the disabled (e.g. locked in syndrome, tetraparesis or patients in Intensive Care Units who cannot otherwise communicate, etc.) [5] gait research or driving analysis in real life.

II. SPECIFICATIONS OF *PANTOJO*

PANTOJO (from Pantographic and ojo=Spanish for eye), was named to convey the idea that the eye prosthesis could be moved as if tied to a pantograph to copy the movement of the healthy eye. The device to be developed should be portable, cause no discomfort to the bearer, be lightweight, non invasive and capable of instant determination of the healthy eye position. Ideally located on a pair of spectacles, the output of PANTOJO should deliver an angular position at all times. To achieve this, we first determined the necessary precision (Section III), then developed the position/voltage equivalence (Section V) and finally build a practical prototype (Section IV).

III. JUST NOTICEABLE EYE POSITION DIFFERENCES

In order to track the position of the eye, a preliminary determination was performed to estimate the necessary resolution of the device to be designed. It was felt that a high resolution in the quantification of the eye position was not needed for social purposes. Possibly behind a pair of spectacles, the exact position of the eye was of no concern to an external observer in normal colloquial interaction. To determine this, a series of photographs were taken of a healthy eye looking at a target directed at set angles with respect to the central position. The photographs were taken at 2.5° intervals, then 5° and finally at 10° intervals from the central position (0°) to the extreme 45° lateral sight on both sides. The photographs showing each a full eye (Fig 1) were then shown to four persons to be classified in groups of "identically looking photos". The observers were blinded as to the angle the proband´s eye was looking at. The result was that photos of gazes within 5° or less were systematically classified together while 10° were distinct enough to suggest different eye positions. The resolution of the gaze angle determination goal was therefore set at 2,5°, since better resolutions would have little effect -if any- on the usability of the device. This result is in agreement with the surgical goal of 5° bilateral gaze difference used in strabism correction.

IV. BUILDING BLOCKS OF *PANTOJO*

PANTOJO was built with the following blocks:

-- electrodes, amplification and filtering
-- A/D and signal processing
-- output of eye position and input of parametres
-- power supply

In order to reduce noise, amplification was put very close to the original EOG signal. We therefore located it 5 cm away from the electrodes (Fig. 2). An overall amplification of 66dB with a bandpass of 1 Hz – 20 Hz (resulting in a 7dB attenuation at 50 Hz) was implemented.

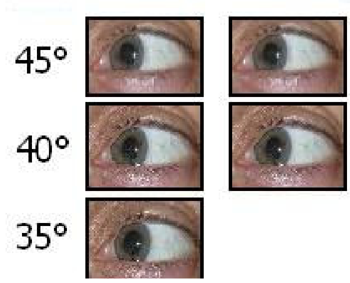

Fig. 1. Photographs of a normal eye looking at different angles. A series of 64 photos obtained in two different sequences -away from the centre and towards the central position- were analyzed. In the first column the eye goes from 0° towards greater angles (sideways) and in the second column the same position but while going back from wider angles towards the central position. The result is that eye directions within 5° cannot be distinguished.

A/D and processing was located in the main unit –to be worn at the belt- and includes a Microchip PIC 18F2553. The digital eye position is output with a Bluetooth KC21 element by "KC wirefree Ltd.".

Power supply is a set of AA batteries and the weight of the prototype is 120g (band) plus 280g (belt module).

The electrodes and the amplificator are located on an elastic head-band secured with velcro at the nucha (Fig. 2). The EOG signal is taken differentially from an electrode on the nasal septum and one on the temple on the side of the healthy eye. The other temple electrode is used as the reference electrode.

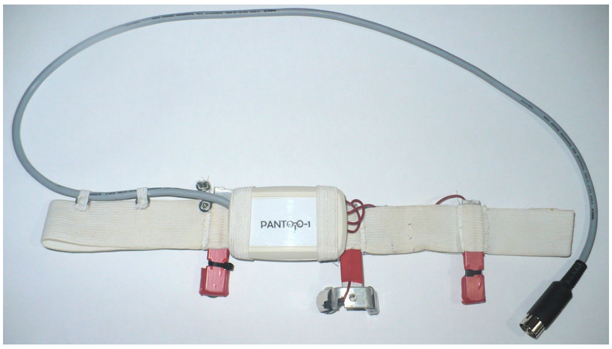

Fig. 2. Head-band of PANTOJO. Note the amplifier circuit is located only a few centimetres away from the electrodes. The central electrode is applied on the nasal septum and the two lateral electrodes on the temples, one for EOG of the healthy eye, the other as electrical reference.

V. ANGLE TO VOLTAGE CONVERSION

The EOG reflects eye movements with varying sign and amplitude of the signal. When the eye moves sideways, the EOG voltage on that side increases. The EOG voltage is proportional to the angle spanned within 30° from the central position. We have taken measurements of both (i) the target angle seen by normal volunteers and (ii) the filtered EOG output to verify the linearity within +/- 30 degrees and to determine our transfer function. Fig. 2 shows the curve fit (3rd order polynomial) on normalized data. The linearity is thus verified and the region from 30 to 45 degrees can be represented by a more complex relation [4].

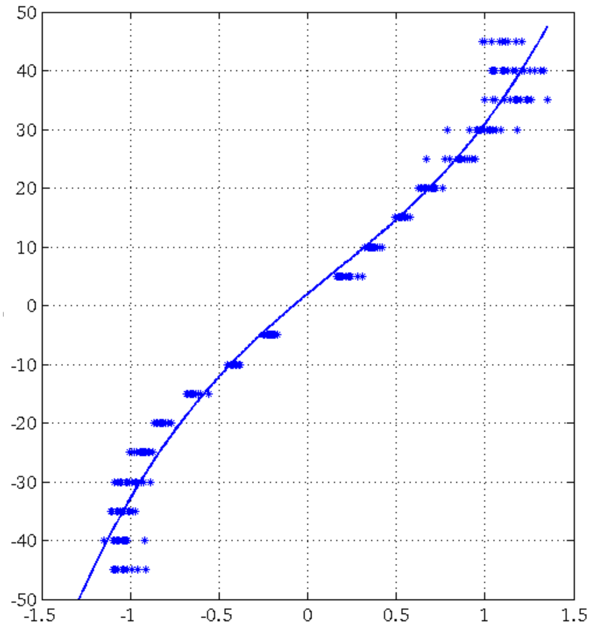

Fig. 3. EOG voltage and eye angle. Normalized EOG voltage on the horizontal axis and eye angle in the vertical axis. A 3rd order polynomial is fitted to the data taken from a healthy volunteer. $\varphi = 6.9*v^3 - 2.9*v^2 + 25.0*v + 1.9$ is the polynomial fit obtained [4]. Note that within 30° the correspondence can be assumed to be linear, with deviations for larger angles: as the angle increases, EOG fails to follow linearly.

PANTOJO implements an ***angle to voltage conversion*** as described in Fig 3. A fragment of conversion is shown in Fig. 4. The heavily filtered EOG exhibits a pulse every time a transition is detected from an eye position to another. These pulses are detected by PANTOJO which outputs a new eye position as a square wave (Fig. 4).

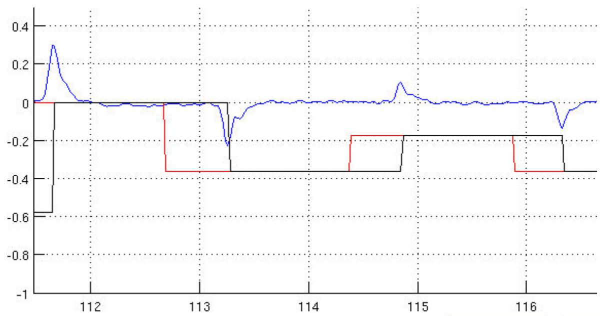

Fig. 4. Target position as it moves, resulting EOG and PANTOJO output. The square waves are the target and –with a 350 ms delay- the eye position as determined by PANTOJO. The analog signal is the filtered and amplified EOG. Note that PANTOJO determines the eye position analysing the EOG pulses. Normalized amplitude on the y-axis and time (seconds) on x-axis.

The determination of eye movements was tested in order to evaluate the accuracy of PANTOJO as a gaze tracker. Not all EOG signals look as noise-free as the fragment shown in Fig. 4 and sometimes the available information is not enough for PANTOJO to report the true eye position.

Following a protocol of target tracking by volunteers, the output of PANTOJO was compared to the real eye position, with data described in the RESULTS section.

VI. Calibration

A calibration arm was developed to obtain EOG signals of known angles of view. This calibration is necessary because EOG signals vary from subject to subject, vary with different electrode contacts and according to surrounding light as well as with perspiration on the patient´s temples. The calibration arm is a LED rod held in place by the subject in front of him at a fixed distance from the forehead. The separator is a 32cm long rod to keep the LED rod at a distance which keeps LEDs flashing at 30° right, central and 30° left gaze.

VII. Results

The performance of PANTOJO as a gaze tracker was evaluated considering the transitions that occur between eye positions. In normal life a person would look at some point in space and occasionally shift to another point during social life. The positions of the eye were shown here to be satisfactory if limited to a set of angles, multiples of 5°. We measured the ability of PANTOJO to detect correctly the transition from a left gaze of 20° to a left gaze of 10°, for instance, and similarly all possible –and physiological- transitions. Table I shows the mean percentage results of over 420 comparisons of the eye position as detected by PANTOJO with the real eye position of three volunteers.

Four different processing criteria were used to compare real with calculated posotion:

- -- 10° steps with "continuous" previous position
- -- 10° steps with "discrete" previous position
- -- 5° steps with "continuous" previous position
- -- 5° steps with "discrete" previous position

TABLE I
CORRECT DETERMINATION OF EYE POSITION TRANSITIONS IN 10° SPACING, DISCRETE PRIOR VALUE (PERCENTAGES)

Final angle of saccade or eye position (°)

Initial °	-40	-30	-20	-10	0	10	20	30	40
-40					95				
-30	85		81	88	55				
-20	82	68		69	82				
-10		89	58		68	61			
0			85	80		84	77		
10°				73	81		80	67	
20°					74	78		72	72
30°					50	62	64		73
40°					79				

Rows show the initial position of the eye ending at a position given by columns. Figures given in percentage of successful determination.

Note only movements within each half plane are shown. The overall accuracy of PANTOJO gaze tracker with this method was 76.6%.

In “continuous” criteria the exact angle is kept, while in “discrete” criteria it is quantized to either the 5 º or 10 º closest steps. For each strategy, results were different, ranging from 37.7% to 76.6% of correct determinations (Table I). As a gaze tracker, PANTOJO performs as follows:

-- accuracy 2.5º
-- resolution 5º
-- precision 2º
-- range -40º to +40 º horizontally
-- eye position update rate 46Hz
-- bandwith 1Hz to 20Hz
-- transport delay 100ms

VIII. Conclusions and Discussion

We have verified with our own data that the EOG amplitude has a linear behaviour with respect to the angle subtented by the eye, within 30° on either side of the central line of sight. Outside this range, a smaller EOG voltage/angle increase is found. We have developed a device, called PANTOJO, which treats the EOG close enough to the skin so as to minimize noise, then processes the digital EOG detecting peaks to output information as to the eye position. This algorithm is based on stable eye positions, resulting in a “state machine” logic. PANTOJO detects transitions of definite eye positions or saccadic movements of single saccades. Smooth pursuit eye movements (those that take over one second to describe 40°) are not detected by PANTOJO because it will be assimilated to a drift in electrical baseline. This limitation is nevertheless of lesser importance as it is well known that saccadic movements and quick shifts in gaze from fixed points are more frequent than smooth pursuits, let alone complex reflexes such as optokinetic compensatory eye movements. We believe that a device that would only keep track of quick transitions could fulfill the need for a continuous gaze tracker, provided a periodic automatic check and synchronization with the real position of the eye is provided.

This takes us to the calibration issue, a necessary procedure, which was included in our prototype as a time consuming task, which clearly needs to be eliminated. To this end the statistics of the EOG signal could be used to create an automatic calibration. It is well know that the central position is the most common in everyday life, and therefore the mode of the EOG indications could be periodically assigned to such central position or optical axis. By an adaptive matching of standard eye angle distributions with the measured EOG distribution, one could determine the calibration constant by assigning, say 45° to the extremes of the present uncalibrated distribution.

The use the information output by PANTOJO to drive a full eye prosthesis has the drawback of the delay to deliver the eye position: about 100 ms are needed in the present version to output a new eye position after the saccade has taken place. Despite a saccade is a very quick movement (a 10° saccade can occur in 50 ms [2]) the prosthetic device driven by PANTOJO would have an additional mechanical inertia of similar duration. It can therefore be estimated that the prosthesis would follow some 200 ms after the saccadic movement of the healthy eye, which is a reasonable result.

PANTOJO can be the starting point for the development of a new device, not as a gaze tracker, but included in a closed loop system to command the position of a token in the field of view of the bearer: such as a computer monitor. If shown the output of PANTOJO, the user can quickly learn to fix his gaze to a given point, thus implementing a commanding tool dependent only on the eyes. This derivation of PANTOJO could benefit from an additional source of information since the subject would normally have binocular vision, a plus denied to the present version of PANTOJO.

Several improvements can be planned for PANTOJO now that it produces eye position information after manual calibration. Further miniaturization, standard mobile phone power supply, automatic calibration, closed loop command for the disabled and behavourial research set up. New processing of the EOG signal with wavelets will allow to detect eye movements of a broader nature than the saccades.

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