Expert Systems with Applications 39 (2012) 10857–10866

Contents lists available at SciVerse ScienceDirect

Expert Systems with Applications

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

EOG-based visual navigation interface development

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ARTICLE INFO

Keywords:
Electrooculography
Human computer interaction
Virtual environment
Navigation
Fuzzy logic
Deterministic finite automaton

ABSTRACT

This paper presents an EOG-based (Electrooculography) interface for Human Computer Interface (HCI) purposes. The solution enables the filtering of the recorded signals and identification of characteristic peak amplitudes associated with eye saccades, blinks or winks by using a classifier based on a set of fuzzy logic rules and a deterministic finite automaton. The identified eye saccades were assigned to six low-level commands for navigation purposes. An experiment study was conducted in order to check the accuracy and the performances of the proposed interface compared with three traditional input control interfaces. Experimental results show that the developed interface has good performance and can be used for online communication and control in EOG-based HCI systems or even for first-person navigation metaphors in games industry.

1. Introduction

In the recent years, dedicated Human Computer/Machine Interfaces (HCI/HMI) have been developed for people with disabilities like Parkinson (Begnum, 2010), Quadriplegia (Kotzé, Eloff, & Adesina-Ojo, 2004), armless people and people who suffer from a motor skill disability but not a cognitive one (González, Muñoz, & Duboy, 2008). Thousands of people are currently suffering of Amyotrophic Lateral Sclerosis (ALS) or Motor Neuron Disease (MND) that leave them with no possibility to communicate, although the brain and eyes activities are not affected (Birbaumer, 2006; Wolpaw, Birbaumer, McFarland, Pfurtscheller, & Vaughan, 2002). Among the few ways of communication in these cases is the detection of the eye movement. The higher the precision of the eye movement detector is, the wider and richer the communication possibilities are. Therefore, the measurement of the eye movements and their precision are at this moment of highest interest in order to establish a robust communication channel with the disabled people.

One of the possibilities to detect eye movements is the EOG (Arden & Constable, 2006; Brown et al., 2006), which is a technique for measuring the resting potential of the retina. EOG signals have amplitude that normally varies from 50 to 3500 μV (Barea, Boquete, Mazo, & Lopez, 2002a; Deng, Hsu, Lin, Tuan, & Chang, 2010; Kim, Doh, Youm, & Chung, 2007). Besides this variation, further fluctuations occur even when similar recording conditions are achieved (Barea, Boquete, Ortega, Lopez, & Rodriguez-Ascariz, 2012). EOG was used for guiding and controlling a wheelchair for the disabled people (Barea, Boquete, Mazo, & Lopez, 2002b; Barea et al., 2002a; Tanaka, Matsunaga, & Wang, 2005; Wijesoma et al., 2006) or for using a virtual keyboard (Usakli & Gurkan, 2010; Yamagishi, Hori, & Miyakawa, 2006). Evaluation tests proved the viability of the EOG for HCI applications (Lv, Wua, Li, & Zhang, 2010), while Deng et al. (2010) went further and tested a specific HCI for operating a TV remote control and for a game.

In order to investigate the feasibility of EOG usage for a complex interaction task, in this paper an EOG-based visual navigation metaphor is proposed. For this purpose, an interface that uses the information provided by looking up/down, right/left and blinking/winking eye movements was developed and evaluated. Based on fuzzy logic and deterministic finite automata (DFA) theory, a classifier that can accurately distinguish between the user's eye movements was implemented. The classified eye movements are processed by the interface, associated with a set of commands and used for controlling the desired HCI application. The main objective of the present study was to develop a classification algorithm with high accuracy rates and a feasible navigation interface based on EOG signals. The interface was tested in a self-paced EOG-based application for a navigation task in a virtual environment (VE).

The paper is organized as follows: Section 2 describes the related work on the topic of eye-movement detection and its applications for people with disabilities. In Section 3 the proposed EOG-based eye-movement system is presented. The testing methodology and discussion for the experimental results are given in Section 4. Finally, in Section 5 the conclusions and future work are presented.

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http://dx.doi.org/10.1016/j.eswa.2012.03.007

2. Research background

Eye movement is the voluntary or involuntary movement of the eyes. Among the interfaces used for detecting eye movements are the infrared oculography (Kumar & Krol, 1992) and videooculography systems (Chan, Chang, Sang, & Won, 2006). The sclera search coil method (Collewijn, van der Mark, & Jansen, 1975; Robinson, 1963) is also used for measuring the position of the eye. A silicon annulus containing a coil of thin copper wire is placed on the user's eye. By placing the user in an AC (alternating current) magnetic field, the position of the eye is determined from the amplitude of the induction current in the coil. This method has high spatial (<<1°) and temporal (<<1 ms) resolution, but it is invasive and the experimental time is limited to around 30 min (Collewijn, 1998; Frens & Van der Geest, 2002). Another high precision and low-noise method is represented by the dual Purkinje image (DPI) eye tracker (Cornsweet & Crane, 1973; Crane, 1994), but the system is an expensive one.

EOG is a technique for measuring the resting potential of the retina by using pairs of electrodes (Deng et al., 2010; Lv et al., 2010). The human eye can be seen as an electrical dipole with a positive pole at the cornea and the negative pole at the retina (see Fig. 1). By measuring the voltage induced across a set of electrodes placed in reference positions around the eyes, we can measure the electric signal of the eye's dipole as the eye-movement changes (Barea et al., 2002a; Venkataraman, Prabhat, Choudhury, Nemade, & Sahambi, 2005).

EOG was previously used for controlling a mobile robot (Kim et al., 2007) or a virtual robotic arm based on low-level commands (Postelnicu, Talaba, & Toma, 2011). EOG was also used for activity recognition (Bulling, Ward, Gellersen, & Troster, 2011), for controlling a multi-task gadget (Gandhi, Trikha, Santosh, & Anand, 2007, 2010) or a computer application (Estrany, Fuster, Garcia, & Luo, 2008, 2009). From the literature review, it can be observed that there are a number of EOG applications being developed, some of them with good solutions to specific problems. Still necessary algorithms and interaction metaphors need to be developed, evaluated and used to produce substantial improvements for the communication with disabled people by using eye movements. In the following sections the development and evaluation of a novel hybrid classification algorithm for eye movement recognition is presented. The algorithm was applied for the navigation in a VE using widgets.

3. Architecture of the EOG-based system

The proposed interaction technique uses input functions based on eye movement identification and visual widgets to mediate the human-computer communication. The system uses a self-paced EOG architecture which provides six commands associated with six recognized EOG eye movements. In addition, other EOG states that do not correspond to a command can be detected by the implemented classification algorithm. The system (see Fig. 2) assumes acquisition of EOG signals using electrodes placed on the user's skin, using a conductive gel. The recorded signals are filtered in a Simulink application and further sent to a XVR (eXtreme virtual reality, VrMedia) application through the localhost interface over an UDP port. Filtered signals contain information for eye saccades, blinks and winks. Relevant peak values are identified using an implemented recognition algorithm. If a correlation is made between parameters of a command and current identified values, then by using the classifier, a specific command is triggered. For each block involved in the system's flow details are presented in the following sections.

3.1. Interaction techniques based on EOG: eye saccades and widgets

An eye saccade is the movement of the gaze from one point to another point in the perceived space. Eye saccade is the primitive instance of eye movement based communication. Therefore, the identification of the eye saccade is fundamental. An eye saccade is characterized by its amplitude that is proportional with the amplitude of the corresponding angular eye movement. To identify the eye saccades in the application developed for the purpose of this research, users have to navigate in a VE using widgets (see Fig. 3). A widget is associated with an eye saccade and is drawn on the user's monitor as an arrow (see Fig. 3).

Horizontal arrows are drawn on the monitor at ±6° and ±12° (degrees of visual angle) for right/left commands (rotation of viewpoint with ±1° inside the application) and hard right/left commands (rotation of viewpoint with ±2°), considering the monitor's centre as reference. These angles are considered by placing the user at a distance of 50 cm in front of the monitor. A horizontal arrow has a width of 0.85 cm (≈1° – as is perceived by the user) and a height of 1.15 cm (≈1.3°). Vertical arrows are drawn at ±7.5° and represent the forward (moving the viewpoint forward with 5 units) and backward (moving the viewpoint backward with 5 units) commands. Their sizes are 1.15 cm (≈1.3°) for width and 0.85 cm (≈1°) for height. Widgets are permanently drawn on monitor as green arrows and, when a command is active, its corresponding arrow is drawn in blue colour (see Fig. 3 right side).

An eye saccade corresponds to a peak in the filtered signals (see Fig. 4), and has a characteristic amplitude associated with the visual angle for the eye saccade. A command sent by the user to the computer represents an eye saccade from the monitor's centre to a chosen widget. In addition to the eye saccade identification, the classification algorithm identifies blinks and winks in order to differentiate between useful peaks and artifact values. For

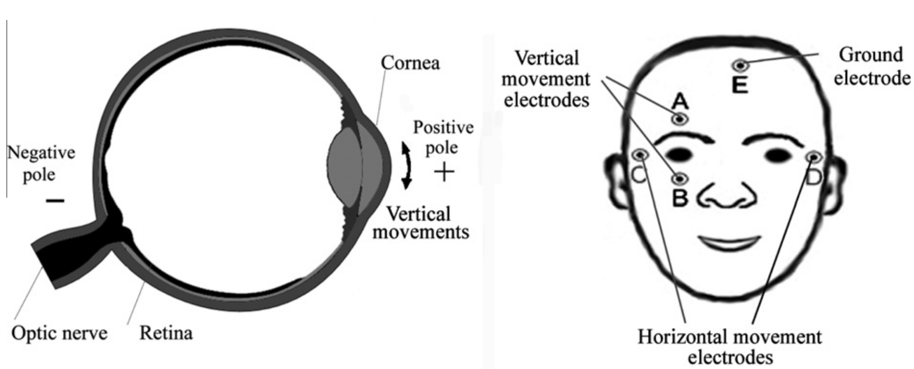

Fig. 1. Eye dipole and EOG electrodes.

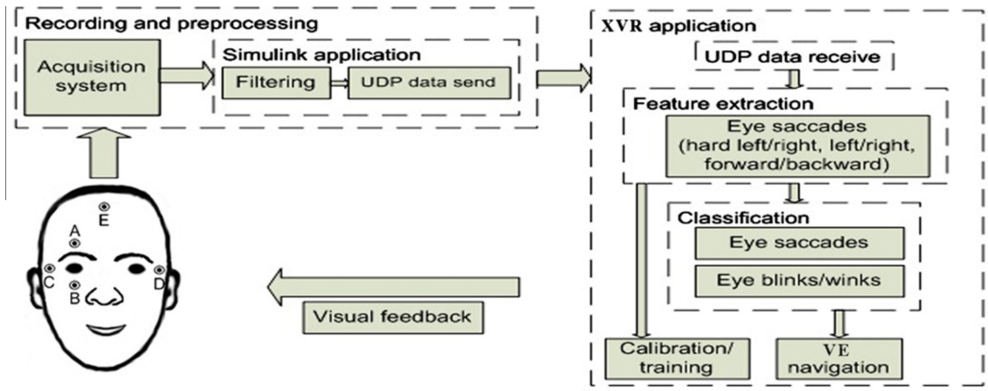

Fig. 2. EOG-based system architecture.

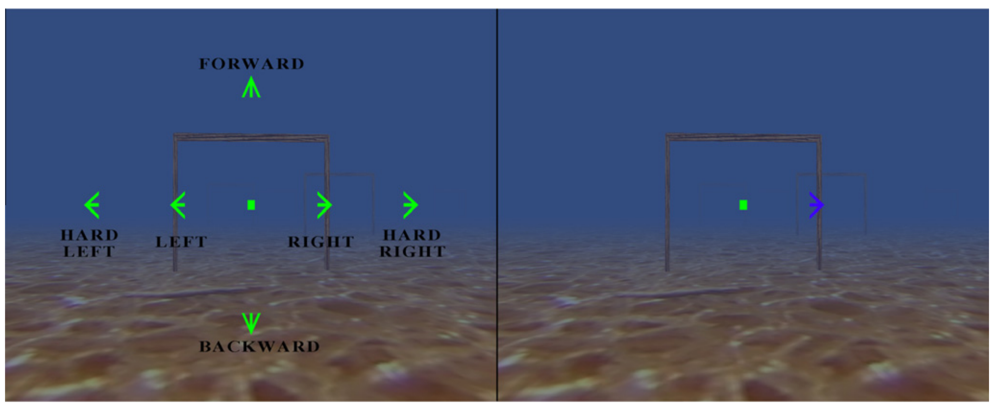

Fig. 3. The visual interface. Left – widgets drawn by the application in green colour (the idle state); right – a "right" command was activated and is drawn in blue colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

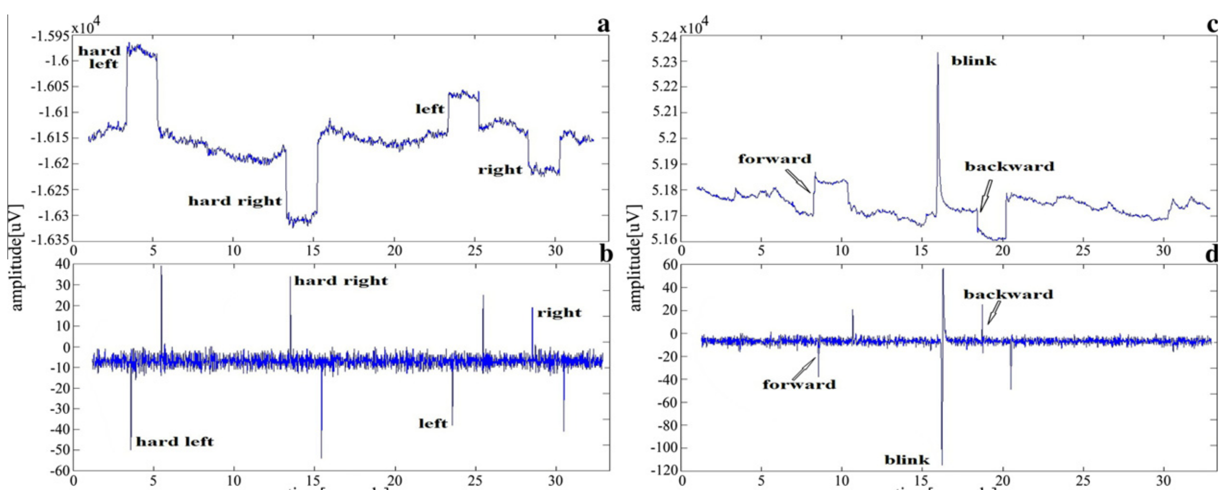

Fig. 4. a. EOG-horizontal channel low-pass filtered; b. EOG-horizontal (EOG-h) channel band-pass filtered (high-pass filter applied); c. EOG-vertical channel low-pass filtered; d. EOG-vertical (EOG-v) channel band-pass filtered (high-pass filter applied).

disabled people voluntary blinks are not a good option to generate control signals because their eye muscles are weakened (Deng et al., 2010). A blink represents an involuntary action and it generally appears when a person closes both eyes very quickly, naturally every few seconds without thinking about it. A wink represents the act of closing and reopening a single eye, in general a voluntary action. By analyzing the recorded signals a blink has amplitude changes on the vertical EOG channel, whereas a wink has in both horizontal and vertical EOG channels (see Fig. 5).

3.2. Acquisition

Neurophysiological signals were recorded and filtered using a Simulink application. For the present study, a g.USBAmp amplifier

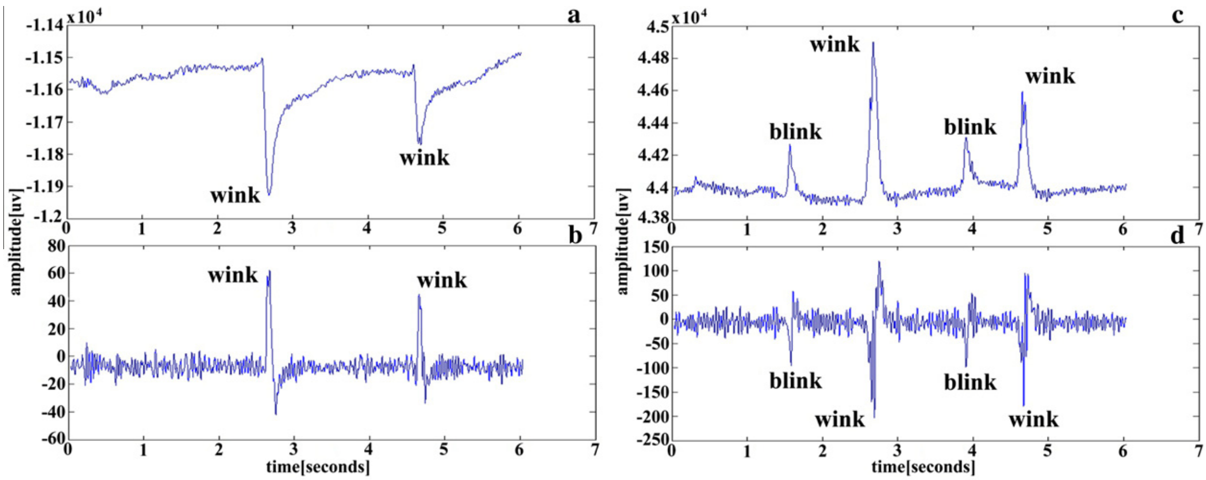

Fig. 5. a. EOG horizontal channel low-pass filtered; b. EOG horizontal channel band-pass filtered (as seen only winks have peaks in this channel); c. EOG vertical channel low-pass filtered; d. EOG vertical channel band-pass filtered (as seen both blinks and winks have peaks in this channel).

(g.tec Medical Engineering GmbH, Austria) was used. This device represents a multimodal amplifier for electrophysiological signals such as EEG, EOG, EMG and ECG. EOG signals were captured by 5 electrodes placed as in Fig. 1 and were recorded using a bipolar configuration. Horizontal movements are recorded by C-D pair and vertical movements by A-B pair. Electrode E, used as system's ground, is placed on subject's forehead. In the current system, a 256 Hz sample rate was used. Two filters were applied to extract relevant frequencies for the current system. Filtered signals were further sent through an UDP port (user datagram protocol) to a XVR application for classification.

3.3. Preprocessing

The signals were band-pass filtered between 0.05 Hz and 30 Hz by using a predefined low-pass filter with cut-ff frequency at 30 Hz integrated in the device and a high-pass filter with cut-off frequency at 0.05 Hz. An additional 50 Hz notch filter was applied to suppress line noise.

The high-pass filter was designed using the filter design & analysis tool (Matlab toolbox) and it represents a 27 order FIR filter (finite impulse response) using a Bartlett–Hanning window.The equation for computing the coefficients of a Bartlett–Hanning window is:

$$w(n) = 0.62 - 0.48|(n/N - 0.5)| + 0.38\cos(2\pi(n/N - 0.5)) \qquad (1)$$

where, $0 \leqslant n \leqslant N$.

The high-pass filter acts as a derivative block since it accurately highlights fast eye movements (eye saccades, blinks and winks) from the low-pass filtered signals (see Figs. 4 and 5). The filter is also used to reject the drift which usually appears in the EOG signals (see Fig. 4).

3.4. Features extraction

The EOG-based interface requires a calibration/training phase, whose purpose is to familiarize naive users with the interaction method and to extract values (features) for each command from the recorded signals. Each command is associated with an identified value that corresponds to a peak in the recorded signals. An example of association between commands and peak values is given in Fig. 4. Left, hard left, right and hard right commands are associated with values from the horizontal EOG channel, whereas forward and backward commands present activity on the vertical EOG channel. Each user has specific peak amplitudes for each command, thus a calibration is required before the effective use of the application starts. A peak is defined as the group of two ascending–descending or descending–ascending slopes starting and ending in the noise range (see Fig. 4b and d).

The former phase assumes the computation of the average for each EOG channel from the samples corresponding to an interval of 5 s while the user is gazing at the screen's centre. The average is used as reference for computing the command's corresponding peak amplitude values. The latter phase is the training phase during which a series of commands are presented to the user in

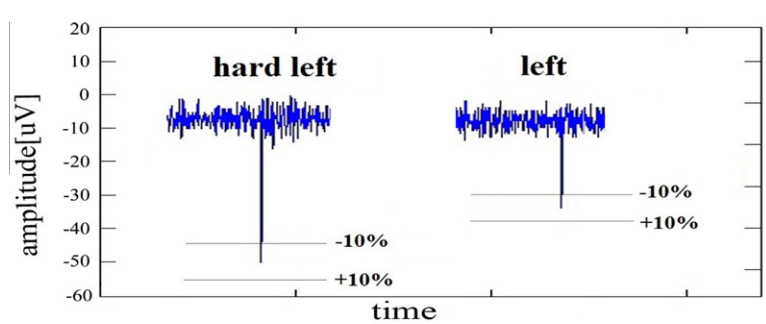

Fig. 6. Amplitude range accepted for commands; example given for commands ''hard left'' and ''left'' (percents are applied for the difference between the signal's average and the peak reference identified values from the calibration phase).

a synchronous manner. The user has to execute corresponding eye saccades for the presented commands, for training himself in using the current application and for calibrating the system. Commands are presented in a predefined order as following: hard left, forward, hard right, backward, left and right.

For each command, a positive or a negative peak will appear on its associated recording channel during a predefined maximum time interval of 2 s after the command was presented to the user. The application searches for maximum absolute values, positive or negative, and identified values are averaged separately for each command. A mean reference value is computed and used for the testing phase. If an artifact (blink or wink, see Fig. 5) is detected within a range of ±300 ms, considering the maximum absolute peak amplitude as reference, then the current peak value identified is rejected and the application will request another gaze at the command's corresponding widget. Such a method is used because the calibration is the most important phase in the application's flow. Eight values are computed after the feature extraction phase is finished: averageH (average for EOG-h channel), averageV (average for EOG-v channel), EOG-h-L, EOG-h-HL, EOG-h-R, EOG-h-HR, EOG-v-F and EOG-v-B (each command has a corresponding peak amplitude).

3.5. Classification

A real-time eye movement algorithm was implemented to recognize the commands sent by the user in a self-paced manner. The classification assumes the correlation between an identified peak value and a command by checking if the value fits in a specific range. For each command a variation of ±10° (see Fig. 6) is accepted since the accuracy rates of the EOG signals is of around 2° (Barea et al., 2012). The range is accepted because the signals are non-stationary and the user cannot hold his head still for the entire time interval when he uses the application. Another factor is represented by the widget's size, e.g. the user can look at the left/right or top/bottom sides, thus resulting small variations in the EOG signals.

The classification is defined by two interlaced phases based on fuzzy logic and DFA theory. The former phase uses a set of defined rules for identification of peak amplitudes in the EOG signals (vertical and horizontal channels). During this phase the application identifies only a direction given from the vertical or horizontal signals (see Table 1 for the set rules). The identified commands (see Fig. 7 for transitions to set states S1) are not executed at this point. A value from the "mid" range can be evaluated as "mid", "low" or "high" value. The distinction is made based on the slope characteristics. If the slope has a high variation in its values then the "mid" value will be evaluated as a "low" or "high" value depending on the amplitude. This rule is useful when small saccadic movements below 3° are performed.

Table 1
Fuzzy distinction rules.

#	Rule
1	If EOG-h is low then LeftF
2	If EOG-h is high then RightF
3	If EOG-v is low then ForwardF
4	If EOG-v is high then BackwardF
5	If EOG-h is mid and EOG-v is mid then IdleF

The trailing 'F' (from fuzzy) is used to distinguish the intermediary states from the execution states (e.g. fuzzy command LeftF for execution state Left). The "mid" interval limits are automatically computed during the calibration phase and represents the interval in which the EOG signals vary due to contact or environmental noise (see Fig. 4).

The fuzzy commands are sent to the EOG Classifier Deterministic Finite Automaton (EOGCDFA) for validation. The EOGCDFA uses a timeout timer for validating each of the intermediate states. The timeout value, set at 150 ms, was chosen after the analysis of a set of initial tests. It is used especially for rejecting blinks and winks, e.g. for a wink in the EOG-h signal it will result a RightF and a LeftF command within a maximum interval of 150 ms (experimental value chosen). Although, winks are intentionally closures of a single eye representing rare events, our algorithm can identify them to accurately distinguish the eye movements. A wink's ascending slope might be misclassified as a right or hard right command (see Fig. 4b and Fig. 5b). If the EOGCDFA detects an artifact it will reject the command without executing it (see "Idle"-"RightF"-"Stall State" in Fig. 7).

In EOGCDFA = $(Q, \Sigma, \delta, q, F)$, Q represents all the states of the finite automaton and includes: "IdleH", "IdleV", "Stall", "Wait" and, sets S1 and S2. The q set represents the start states defined by the "IdleH" and "IdleV" as shown in Fig. 7. The two pathways starting from these states work independently until the automaton goes to a state from set S2 or to the "Stall" state. The alphabet Σ includes the fuzzy commands, the EOG-h and EOG-v signals, and the reference values obtained from the calibration for each command (EOG-h-L, EOG-h-HL, EOG-h-R, EOG-h-HR, EOG-v-F and EOG-v-B). The set of all transition functions δ is represented by the arrows used between the automaton's states (see Table 2 for details).

During normal activities, saccades tend to co-occur with blinks therefore the proposed automaton uses two start states in order to detect if such event occurred. The two EOG channels work independently and the fuzzy phase can return two values at the same time, e.g. ForwardF and LeftF may correspond to a diagonal eye movement to top-left side of the monitor or for a left saccade and a blink executed in the same time. None of these movements are valid for the present study because a command always corresponds to peak amplitudes in a single EOG channel. Each state from set S1 has a countdown timer assigned to it and the automaton goes to a next state only after the countdown has expired. The "ForwardF" state has a higher priority in S1 set because it identifies blinks and winks, causing the automaton to enter the "Stall" state, and therefore avoiding generation of erroneous commands. If the automaton detects activity on both EOG channels (multiple fuzzy commands detected while the countdown timer is active) it goes to the "Stall" state because no valid command would be detected.

The "Stall" state is used for inserting a break in the automaton's flow, to allow the user to change his gaze to the centre on the monitor for issuing another command. It uses a countdown timer with variable values, e.g. a timeout of 400 ms is used when a blink was detected. The "Wait" state is used for maintaining the current command active while the user keeps his gaze at the command's corresponding widget. Blinks and winks are automatically rejected, maintaining the automaton in the "Wait" state, and the automaton goes to the "Stall" state when the user performs any saccade (normally it should be a saccade back to the green rectangle).

4. Evaluation of the eye movement based interaction

An experiment study was conducted in order to evaluate if the EOG-based interface does fit for navigation tasks. In order to determine the performance of the proposed EOG visual navigation interface related to common desktop input devices, similar tests were conducted for three other classical input methods: keyboard, mouse and joystick. The desktop virtual reality environments are usually explored by keyboard and mouse, while the joystick is considered to be a first-rate interface for navigation purposes in

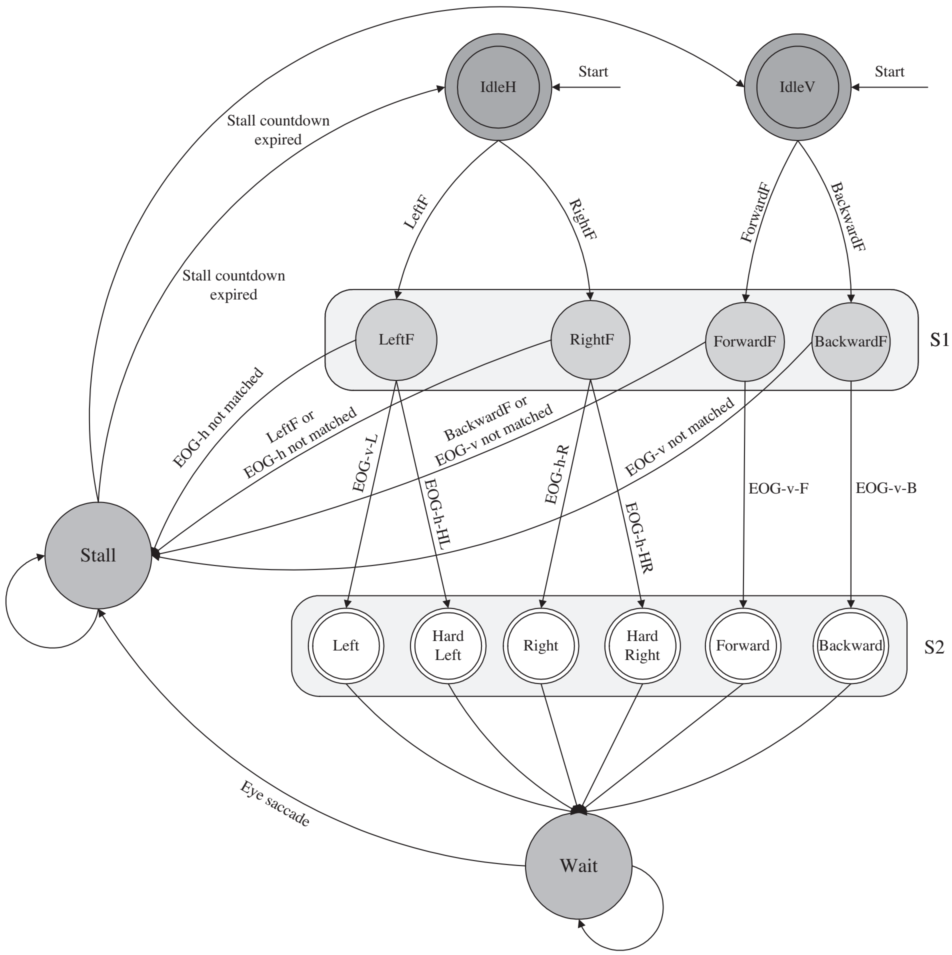

Fig. 7. EOG classifier deterministic finite automata.

Table 2
EOGCDFA transition details.

Start state	Target state	Details
IdleH	LeftF, RightF	The automaton goes to a state that defines a possible command
IdleV	ForwardF, BackwardF	The automaton goes to a state that defines a possible command
LeftF	Left	EOG-h amplitude is in interval of EOG-h-L
LeftF	Hard left	EOG-h amplitude is in interval of EOG-h-HL
LeftF	Stall	EOG-h amplitude wasn't valid for any interval or activity on both channels was detected
RightF	Right	EOG-h amplitude is in interval of EOG-h-R
RightF	Hard right	EOG-h amplitude is in interval of EOG-h-HR
RightF	Stall	EOG-h amplitude wasn't valid for any interval or activity on both channels was detected (it also includes the case of a wink, see Fig. 4b and Fig. 5b)
ForwardF	Forward	EOG-v amplitude is in interval of EOG-v-F
ForwardF	Stall	EOG-v amplitude wasn't valid for the interval or blink/wink was detected
BackwardF	Backward	EOG-v amplitude is in interval of EOG-v-B
BackwardF	Stall	EOG-v amplitude wasn't valid for the command
S2 states	Wait	A command is active and the automaton goes to the wait state
Wait	Stall	An eye saccade was detected (the user changed his gaze)
Stall	IdleH, IdleV	The automaton is reset to the start states when the countdown timer expires

terms of task completion time (Marchal, Pettre, & Lecuyer, 2011). The assigned commands are the following:

– For the keyboard and joystick interfaces were defined 4 commands: left (rotation to the left with 1°), right (rotation to the right with 1°), forward (moving forward with 5 units) and backward (moving backward with 5 units).
– For the mouse interface were defined the same 6 commands as for the EOG method (the supplementary hard left and hard right commands were enabled). A hard left commands is executed as a rotation to the left with 2° while a hard right command execute a rotation to the right with 2°.

During the tests with the keyboard, mouse and joystick interfaces the widgets are not drawn. The experiment was conducted for evaluating the number of commands and completion time required for navigate through a series of gates in a VE by using different input interfaces. The EOG method was supplementary evaluated for the eye movement classification accuracy.

4.1. Virtual environment

The experiment assumed the navigation in a VE based on different input control interfaces. The users were constrained to navigate through a series of 13 gates disposed in order to form a slalom (see Fig. 9). A fog effect was added to mask the gates and only 3 gates were visible for the user all the time (see Fig. 2). A collision detection algorithm was implemented in order to check if the user crosses correctly through the gates.

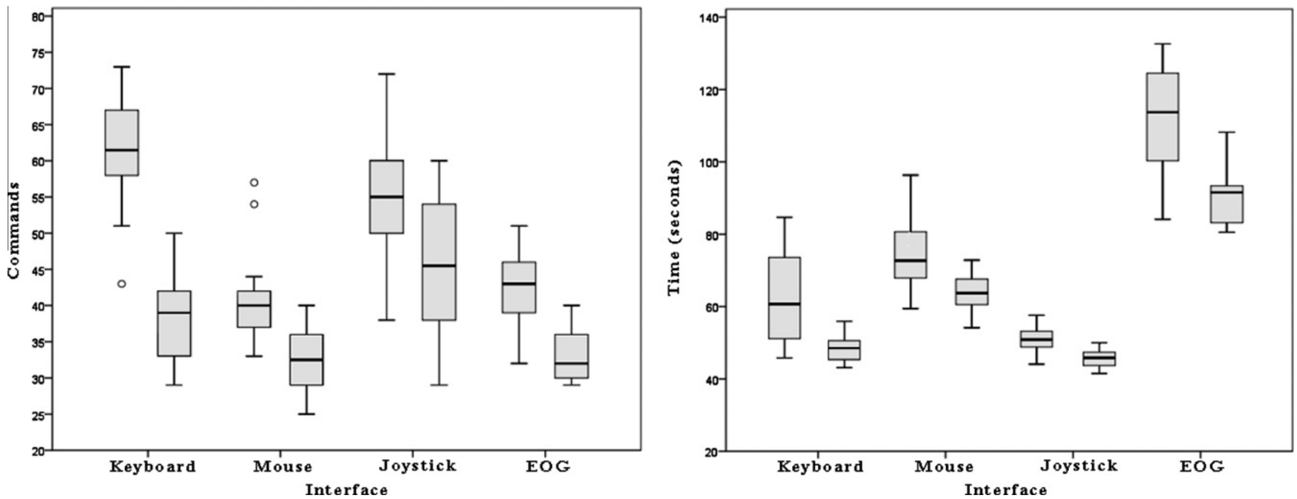

Fig. 8. Comparison between the number of commands used and completion time parameters obtained for the two tests (for each interface left box is used for Test1 and right box for Test2).

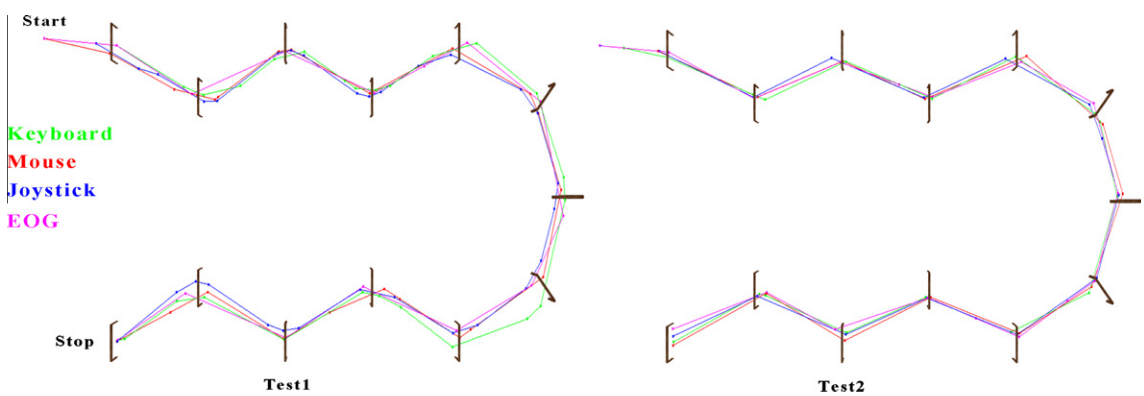

Fig. 9. Top view of the VE used for tests. Pathways used by a user during the tests.

4.2. Experimental conditions

The users were placed at a distance of around 50 cm in front of a 15 inches (38.10 cm) wide monitor with a visible area of 34.8 cm width and 19.7 cm height. The computed field of view is of 34.84° horizontally and 21.50° vertically. For the present study the origin of the system is considered the centre of the monitor, thus it results that the user can execute eye saccades for a maximum angle of 17.42° horizontally and 10.75° vertically because each command is executed from the origin. Maximum saccades of ±10° vertically and ±12° horizontally saccades are required for this study (see Fig. 10).

4.3. Experiment design

A number of 14 subjects aged from 23 to 30 (Mean = 25.92, SD = 1.97) took part at the experiment, all of them giving their informed consent. All participants had normal or corrected-to-normal vision by their own report. The conducted experiment was focused on completion time and number of commands used for completing the given task. All subjects were naive to the EOG interface and were asked to perform two group tests for each of the available interfaces as the following:

- For the first group of test they had to use the input interfaces for the navigation through the gates within the VE. Four navigation tests using the EOG, keyboard, mouse and joystick interfaces are performed. Each user was free to choose the order in which he was using the interfaces to avoid promoting a particular one.
- After the users finished the navigation by all interfaces they were allowed to familiarize with the VE. They could use each input interface for an interval between 5–7 min to freely navigate inside the VE. All the users were familiar with keyboard and mouse input interfaces, but only three of them had previous experience with a joystick and none of them had previous experience with the EOG interface. After this phase all the users were familiarized with the VE and all the input interfaces.
- The second group of tests was again performed for all the interfaces and the user was free to choose the order of the input interfaces.

The EOG calibration was performed for each user automatically when the test started. First the average for each EOG channel is computed from the samples extracted from an interval of 5 s during which the user has to gaze at the monitor's centre. The phase assumed the presentation for three times of each command under the conditions described in section "features extraction". A

Table 3
Results obtained for the conducted experiment (G – gender; M – male; F – female; n.c. – number of commands; SD – standard deviation).

Subject		Keyboard				Mouse				Joystick				EOG			
		Test1		Test2		Test1		Test2		Test1		Test2		Test1		Test2	
	G	n.c	Time (s)	n.c	Time (s)	n.c	Time (s)	n.c	Time (s)	n.c	Time (s)	n.c	Time (s)	n.c	Time (s)	n.c	Time (s)
1	F	64	81.774	33	48.379	41	84.228	32	66.593	59	48.913	59	47.393	46	114.531	29	84.214
2	M	43	46.958	33	44.485	33	68.713	25	54.141	54	53.196	29	44.55	39	100.286	30	80.581
3	M	69	51.117	50	48.345	40	80.666	32	68.462	72	44.816	57	42.604	46	132.595	31	91.547
4	M	59	68.512	43	55.937	57	73.424	33	67.596	61	51.711	54	45.639	44	126.428	30	91.696
5	M	66	45.803	43	43.131	40	72.006	34	63.732	69	44.056	60	43.726	41	102.964	32	83.207
6	F	67	84.666	42	49.878	37	96.341	29	72.843	38	57.62	35	47.858	36	117.685	29	102.305
7	M	54	49.434	29	44.304	36	70.381	26	64.324	55	50.017	37	44.441	51	120.413	32	83.207
8	F	73	67.743	42	45.391	33	66.665	31	58.889	48	48.826	38	46.072	38	112.876	36	89.965
9	F	69	77.348	40	50.568	40	88.452	34	61.526	50	52.397	45	46.175	39	107.759	33	91.523
10	M	60	56.706	38	50.138	44	78.955	38	63.724	55	56.235	48	50.017	32	84.108	32	83.207
11	M	58	57.863	35	50.625	54	73.568	40	68.455	60	52.781	39	41.526	48	131.215	37	95.71
12	F	63	73.563	40	46.375	39	67.865	40	62.453	56	48.451	49	43.608	46	124.536	40	108.227
13	F	51	62.548	30	52.152	42	59.452	36	57.526	49	54.649	46	46.893	50	90.863	35	92.843
14	F	59	58.884	34	48.624	40	66.545	25	60.523	51	49.734	45	47.638	42	95.348	38	93.364
Mean		61.07	63.065	38	48.45	41.14	74.804	32.5	63.627	55.5	50.957	45.78	45.581	42.71	111.543	33.14	90.828
SD		8.024	12.870	5.909	3.495	6.860	9.910	5.034	4.975	8.662	3.918	9.480	2.315	5.525	15.203	3.505	7.816

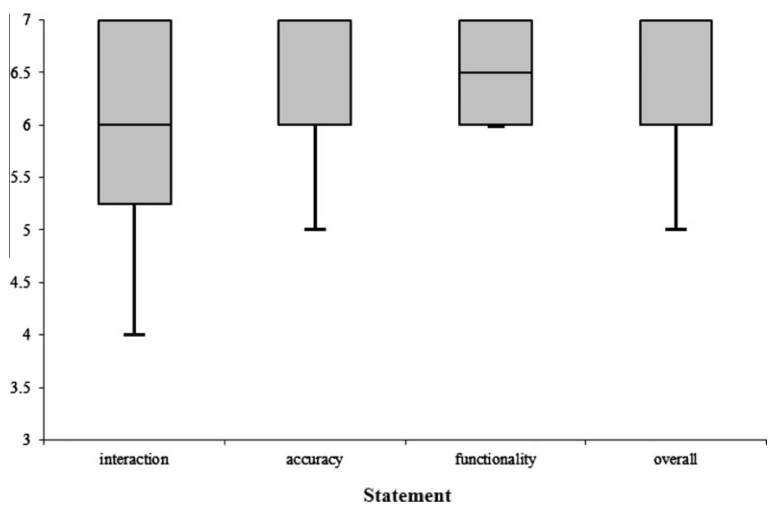

Fig. 10. Results for the subjective questionnaire.

minimum of 18 stimuli (3 trials × 6 commands) were presented to the user, but the total value could vary if a blink overlapped an eye saccade. The timing used was: 2 s for the execution of the command (during which the user changes his gaze to the activated command) and 2 s waiting time (during which the user keeps his eye gaze on the centre of the monitor – focusing on the green rectangle) resulting a calibration time of around 77 s.

4.4. Results and statistical evaluation

For each participant, the task completion time and the number of command used for each test were measured (see Table 3 and Fig. 8). A one-way ANOVA was performed on the different input interfaces, number of commands used, time of completion and the two tests. For the number of commands the ANOVA revealed statistically significant difference between interfaces for the first test (Test1): $F(3,52) = 24.457$, p-value < 0.05. A Tukey post-hoc test revealed that the number of commands required for keyboard (61.07 ± 8.024, p-value < 0.05) and joystick (55.5 ± 8.662, p-value < 0.05) interfaces were statistically significant higher compared to the EOG (42.71 ± 5.525) one. There were no statistically significant differences for mouse (41.14 ± 6.86) – EOG (p-value = 0.942) and keyboard – joystick (p-value = 0.201) pairs. Significant differences were also found for keyboard-mouse (p-value < 0.05) and joystick-mouse (p-value < 0.05) pairs, were the mouse interface required less commands (41.14 ± 6.860).

For the second test (Test2) significant differences were found between all the interfaces (Welch test, p-value < 0.001). A Games–Howell post-hoc test revealed a significant difference between EOG (33.14 ± 3.505) and joystick (45.79 ± 9.480) interfaces resulting in a lower number of commands used for the EOG-based navigation (p-value < 0.05). Significant differences were also found for the mouse–joystick pair (p-value < 0.05), all other pairs having no significant differences (p-value > 0.05). It results that EOG, keyboard and mouse interfaces have comparable performances for the number of commands used after the users were familiarized with them.

Considering the time of completion parameter, for Test1 were revealed significant differences between the EOG and other interfaces ($F(3,52) = 75.194$, p-value < 0.05). The EOG (111.54 ± 15.2 s, p-value < 0.05, according to the Games–Howell post-hoc test) interface had higher completion times compared to the keyboard (63.06 ± 12.87 s), mouse (74.8 ± 9.91 s) and joystick (50.95 ± 3.91 s) interfaces. Significant differences are also found for keyboard–joystick and mouse–joystick pairs (p-value < 0.05). Similar values were obtained for keyboard–mouse pair (p-value = 0.056).

Table 4
Ranks obtained by the interfaces (mean is computed by subtracting the mean values for the second test from the mean values obtained for the first test).

Interface	Test1 rank		Test2 rank		Mean rank			
	Number of commands	Time	Number of commands	Time	Mean commands difference	Rank	Mean completion time difference (s)	Rank
Keyboard	#4	#2	#3	#2	23.07 ± 5.65	#1	14.615 ± 11.78	#2
Mouse	#1	#3	#1	#3	8.64 ± 6.03	#4	11.177 ± 7.48	#3
Joystick	#3	#1	#4	#1	9.72 ± 7.34	#2	5.376 ± 3.28	#4
EOG	#2	#4	#2	#4	9.57 ± 5.80	#3	20.715 ± 13.93	#1

For Test2, significant differences between the EOG and other interfaces ($F(3,52) = 232{,}249$, p-value < 0.05) were determined. According to Games–Howell post-hoc test the EOG (90.82 ± 7.81 s) had higher completion times (p-value < 0.05) compared to all other interfaces: keyboard 48.45 ± 3.49 s, mouse 63.62 ± 4.97 s and joystick 45.58 ± 2.31 s. The keyboard–joystick pair had no differences (p-value = 0.077), while the keyboard-mouse and mouse–joystick (p-value < 0.05) had significant differences.

A classification based on the statistical analysis is presented in Table 4, were the interfaces are ranked according to their mean values. The EOG interface has comparable rankings with the mouse interface regarding the number of commands used, but in the same time it occupies the last position by the completion time parameter. A lower rank for the completion time is assigned for the mouse interface, although it is the first for the number of commands.

Comparisons were made also between the two tests of each interface and differences were found for each pair as the following: keyboardNC1 (number of commands for Test1) – keyboardNC2 (number of commands for Test2) $t(13) = 15.280$, p-value < 0.001, mouseNC1 – mouseNC2 $t(13) = 5.360$, p-value < 0.001, joystickNC1 – joystickNC2 $t(13) = 4.950$, p-value < 0.001, EOGNC1 – EOGNC2 $t(13) = 6.174$, p-value < 0.001, keyboardT1 (completion time for Test1) – keyboardT2 (completion time for Test2) $t(13) = 4.639$, p-value < 0.001, mouseT1 – mouseT2 $t(13) = 5.590$, p-value < 0.001, joystickT1 – joystickT2 $t(13) = 6.121$, p-value < 0.001 and EOGT1 – EOGT2 $t(13) = 7.866$, p-value < 0.001. We conclude that for each interface were found significant differences for the two tests in terms of completion time and number of commands used. Less commands and lower completion times were revealed for each interface under the second test. Although the EOG had higher completion times for both tests, by comparing the mean differences obtained for each interface we can see that the EOG interface had the highest variation (see Table 4). The EOG completion time had significantly lower values, with a mean difference of 20.715 s between the two tests, being the highest improvement for an interface (see Table 4).

No significant differences were determined by using the EOG interface for the number of commands $F(3,24) = 0.230$, p-value = 0.636 or for the completion time $F(3,24) = 0.087$, p-value = 0.771 by considering the gender factor. As it was expected the joystick interface has the higher performance for the completion time parameter for both tests.

Similar pathways were obtained for the control interfaces and all the users were able to navigate through all the gates without colliding with them. The different pathways followed by a user during navigation inside the VE are shown in Fig. 9. As it was proved by the completion time and number of commands used parameters, a better control of the application was achieved for the second test, since the users were familiarized with the VE and control interfaces.

4.5. Subjective questionnaire

At the end of the experiment the participants were asked to rate the EOG interface on a 7-point Likert scale with measures ranging from 1 (strongly disagree) to 7 (strongly agree). Post-task scenario subjective measures included the following statements:

- It is easy to interact with the application using the EOG interface (interaction).
- The system is accurate (accuracy).
- The interface has all the functions and capabilities I would expect it to have for a navigation task (functionality).
- Overall, I am satisfied with the EOG interaction interface (overall).

Fig. 10 shows the results concerning the grades (Likert-scale) obtained by the EOG interface for each of the subjective criteria. Participants suggested that some other commands should be inserted in the proposed interface, such as strafing (sidestepping). A few users suggested that widgets should be transparent and, interactive environments such as video-games should be developed.

4.6. Discussion

This study intended to develop an EOG interface based on visual widgets for navigation inside a VE. The target category of this interface is represented by the disabled people, and further tests will be conducted with this category of persons. To accomplish this task, eye movements are used in order to generate commands, but a good classification algorithm is required in order to achieve this. Eye movements are represented by blink, winks, fixations or eye saccades. The eye saccades represent the control signals for the present study, while other eye movements are considered artifacts. A calibration is required when the application starts because EOG signals are not deterministic, vary for different persons, recordings and even for the same acquisition conditions (Barea et al., 2012).

In the present study a comparison with typical control interfaces was proposed in order to determine the EOG interface performances. It was determined that the EOG interface has comparable performances with the classical desktop interfaces in terms of number of commands used, being rated as the second interface in this study, but has the lowest performance by considering the completion time parameter. Overall the EOG interface is not a superior interface but, represents a valuable control channel for disabled people that cannot use the traditional interfaces. Training of subjects is automatically done when the application starts and after only 5 min of use important improvements were achieved by all the users, in terms of number of commands used and lower completion times.

The performance of the classification algorithm was determined by computing the true positive (TP), true negative (TN), false positive (FP) and false negative (FN) statistical measures (Deng et al., 2010). The expert system has an accuracy of 95.63%, with sensitivity and specificity of 97.31% and 93.65%. Values are comparable with those related for earlier studies (Deng et al., 2010; Gandhi et al., 2010; Yamagishi et al.., 2006). In Barea et al. (2012) recognition accuracy of 100% is achieved for saccadic movements, but there were performed only saccades with over 10° and only for the horizontal EOG channel, while in the present study small saccadic movements with values around 6–12° were used. Most false positives (incorrect saccades classified as correct) were detected in the EOG-v signal. A few blinks (see Fig. 6d) were misclassified as correct forward commands because their corresponding amplitude was in the range accepted for a forward command and the second slope of the blink wasn't detected (it had a small amplitude in the range corresponding to noise). As a solution, it will be used the low-pass EOG-vertical channel (see Fig. 4c) mixed with the EOG-v band-pass filtered (see Fig. 4d) signal for a higher detection accuracy.

5. Conclusions and future work

In this paper, an expert visual navigation interface based on EOG signals was developed and evaluated in a VE. The system recognizes six commands by using band-pass filtering, a set of fuzzy logic rules and a finite state machine. The system accurately detects the control signals defined by eye saccades and rejects the user's blinks and winks. The conducted experiment proved that all users could accurately navigate through the VE without previous knowledge about the EOG systems. Comparable results with a mouse interface were obtained for the EOG interface in terms of number of commands used. Although, compared with different tested control interfaces, a higher completion time was required for the proposed interface it represents a valuable solution for disabled people that cannot use the normal pathways for control a computer application or a device. The novel part of the present EOG-based system is the hybrid classification algorithm, the navigation in a VE using widgets and its accuracy.

The implemented system may be used to control any navigation application through EOG signals such as virtual museums exploration, video games etc. As future work the system may be adapted to include extra commands in order to facilitate the communication speed. Also, the accuracy of the classification algorithm can be increased by using the low-pass filtered signals.

Acknowledgements

This paper is supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), financed from the European Social Fund and by the Romanian Government under the contract number POSDRU/88/1.5/S/59321 for author (1) and by the Sectoral Operational Programme Human Resources Development (SOP HRD), financed from the European Social Fund and by the Romanian Government under the contract number POSDRU89/1.5/S/59323 for author (2).

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