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Multimodal human-machine interface based on a Brain-Computer Interface and an electrooculography interface

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***Abstract*— This paper describes a multimodal interface that combines a Brain-Computer Interface (BCI) with an electrooculography (EOG) interface. The non-invasive spontaneous BCI registers the electrical brain activity through surface electrodes. The EOG interface detects the eye movements through electrodes placed on the face around the eyes. Both kind of signals are registered together and processed to obtain the mental task that the user is thinking and the eye movement performed by the user. Both commands (mental task and eye movement) are combined in order to move a dot in a graphic user interface (GUI). Several experimental tests have been made where the users perform a trajectory to get closer to some targets. To perform the trajectory the user moves the dot in a plane with the EOG interface and using the BCI the dot changes its height.**

I. INTRODUCTION

Nowadays, there are numerous assistive technologies for physically impaired users. In this sense, there are a great number of interfaces that enhance the quality of life of disabled people, increasing their independence and granting greater social inclusion. One kind of interfaces for disabled people are the ones based on electrooculography (EOG) that detect the eye motion by measuring the difference of potential between the cornea and the retina [1]. They have been used in several applications, e.g. to control robots [2].

Other interfaces for disabled people are Brain-Computer Interfaces (BCIs) that allow the users to generate control commands with the only help of their thoughts. There are different kinds of BCIs [3], but in this paper a non-invasive spontaneous BCI has been used. It registers the electroencephalographic (EEG) signals using surface electrodes. This kind of BCIs have been used in several applications, like controlling robot arms [4]. However, current spontaneous BCIs are still far from being used to perform complex tasks which require generating more than three mental commands.

Multimodal interfaces can be used to solve the limitations of using only one interface as a BCI. Several multimodal interfaces have been developed combining a BCI with other techniques, like electromyography [5] or eye-tracking [6].

The objective of this paper is to design a multimodal interface that combines a BCI with an EOG interface. The BCI developed in [7] has been improved reducing the number of electrodes to seven and including a processing of the EEG signals that combines two frequency algorithms based on the Fast Fourier Transform and the Wavelet Transform. The EOG interface also improves a previous algorithm developed in [8] making it more robust, efficient and reducing the time to obtain the gaze direction. The combination of both interfaces allows increasing the number of commands that can be used to interact with a device. This would be impossible using only one of the interfaces. A graphic user interface (GUI) has been designed to perform several tests where a dot is moved by the EOG interface in a plane while the BCI changes its height.

The remainder of this paper is organized as follows. In Section II the system architecture of the multimodal interface is presented describing the BCI and the EOG interface as well as the combination of the commands of both interfaces. In Section III, the experimental results obtained using the GUI are shown. Finally, the main conclusions are summarized in Section IV.

II. SYSTEM ARCHITECTURE

Fig. 1 shows the general diagram of the multimodal interface. The data are registered each 0.5 seconds and the channels corresponding to the EEG and EOG signals are processed independently to obtain a command for each one. Once the mental task that the user is thinking and/or the eye command peformed by the user is obtained, they are combined to generate only one command. In Fig. 2 a real image of the local environment is shown.

First of all, the EOG and EEG signals are registered using the gUSBamp device from g.tec. The device has 16 channels. To register the EEG signals, seven passive electrodes have been placed on the surface of the scalp. On the other hand, to register the EOG signals four dry flat electrodes have been placed on the face around the eyes. In next sections, the location of the electrodes for each interface will be explained. The sample frequency used is 1200 Hz. The g.tec device provides some internal filters to use on the signal. A bandpass filter between 0 and 100 Hz, and a Notch filter of 50 Hz to eliminate the network noise have been applied. The software used to register and process the signals, and to develop the GUI has been programed in Matlab using the API (Application Programming Interface) provided by the device (gUSBamp MATLAB API).

A. EOG Interface

EOG is based on the fact that the eye acts as an electrical dipole between the cornea (positive potential) and the retina

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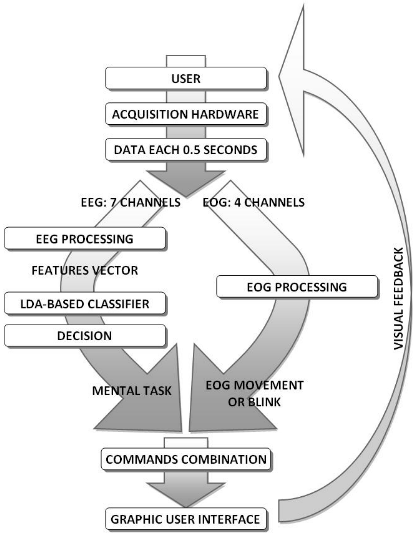

Fig. 1. General diagram of the multimodal interface.

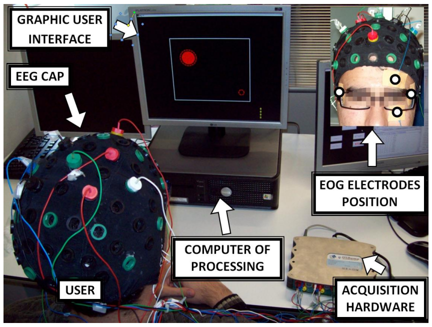

Fig. 2. Local environment with the user, the acquisition hardware and the computer to process and perform the tests.

(negative potential) [9]. To obtain the EOG biosignals from the user, the four dry flat electrodes have been distributed as it can be seen in Fig. 2. The electrodes used are the model E273 from Easycap, which are flat Ag/AgCl electrodes of 12 mm diameter with a light-duty cable and 1.5mm-touchproof safety sockets. The advantage of this type of electrodes is that they do not require conductive gel to operate, so there is only need of some cleaning abrasive gel on the skin before contact, what makes easier and faster the placing of the electrodes on the user.

EOG signals are usually between 50 and 3500 μV with a frequency range of about 0-100 Hz between the Bruch membrane and the cornea [9]. They have a practically linear behaviour for gaze angles between $\pm 50^\circ$ for horizontal movement and $\pm 30^\circ$ for vertical movement [1].

To detect the eyes movement a new algorithm has been developed improving the characteristics of a previous work [8]. The new algorithm is able to detect the gaze direction of the eyes (right, left, up and down) as well as the blink of the users. The users must perform a fast movement of the eyes on the desired direction returning next to the center position. The algorithm works using time windows of 1, 0.5 or 0.25 seconds. In this paper, the window has been chosen to synchronize the output with the BCI, which has been designed to return a mental task each 0.5 seconds. The algorithm is even able to detect when an eye movement is performed between two windows of processing.

To obtain the output, i.e. the direction of the gaze or the blink of the user, each window is analized. First, a moving average filter is applied to get a clearer signal. Next, the derivative is done to detect the abrupt changes of the signal when the user performs a fast movement of his/her eyes. The maximums and minimums of the window are searched as well as the time when they are produced. The values lower than the noise threshold are removed and the rest of maximums and minimums values are added to a vector including the time when they were produced. Finally, this vector is evaluated in order to obtain the gaze direction and the blink.

To detect a blink it is checked if the value of the vector is higher than the blink threshold. Otherwise, if a sequence of two values of the vector (maximum-minimum or minimum-maximum) was produced with a difference lower than 0.6 seconds, a right/up or left/down movement has been produced. If the value of the vector does not fulfill any condition it is removed from the vector unless it is the last value of the vector, that in this case is kept for the next time the algorithm is called, allowing detecting movements that were performed between two windows of processing.

B. Brain-Computer Interface

The non-invasive spontaneous BCI has been already designed in [7] and allows differentiating between three mental tasks. Some improvements have been added to the algorithm to increase its eficiency. The mental tasks chosen are related to motor imagery. The users were asked to imagine the repetitive small circular movement of their right and left arm. As rest state, a simple counting operation was chosen. It consists of counting backwards from 20. The BCI registers the bioelectrical activity of the brain (EEG signals) through 7 surface electrodes placed on the scalp (before, 16 electrodes were used). The electrodes have been placed in the following positions of the motor cortex of the brain: FC1, FC2, C3, Cz, C4, CP1 and CP2, according to the International System 10/20 [10].

The processing and classification used to obtain the mental tasks that the user is thinking is explained next:

1) Processing: The EEG signals are amplified and filtered each 0.5 seconds in windows of 1 second of duration (overlap of 0.5 seconds with the previous sample). After that, a preprocessing has been made to improve the quality of the signals, that starts filtering the signal between 5 and 21 Hz. Next, a Common Average Reference (CAR) that consists of subtracting the background activity to all the electrodes is applied. Then, the signals are processed to extract their most important features combining the Fast Fourier Transform (FFT) and the Wavelet Transform (WT) algorithms. With the FFT the frequency features between 8 and 16 Hz with a resolution of 2 Hz have been calculated obtaining 5 features for each electrode. To obtain the WT coeficients, the Wavelet Packet Decomposition has been used to generate a tree getting three ranges of frequency (0 to 38 Hz, 19 to 28 Hz, and 9 to 19 Hz) and calculating the energy of the 3 coeficients. Finally, a Surface Laplacian filter (SL) is applied removing on each electrode the average contribution of signal of the other electrodes in order to improve the signal/noise ratio. As the electrodes studied are 7, their features are concatenated in a features vector of 56 elements (5 characteristics of the FFT and 3 of the WT of each electrode) that will be the input for the classifier.

2) Classifier: The classifier based on Linear Discriminant Analysis (LDA) that we developed in [7] has been used to obtain the mental tasks. This classifier combines four different models to classify three mental tasks related to motor imagery. Each model separates a main class (right, left or rest) from a secondary class made up of the two other tasks. Three regions have been created including an uncertainty region will correspond to the central region where the classes cannot be properly separated.

A score-based system has been developed to obtain the output of the BCI: right, rest state, left or uncertainty. According to the regions where the vector has been classified, each mental task has been scored and added in order to select the task corresponding to the higher score. The uncertainty state is returned as output when it is not sure which mental task is doing the user, improving the accuracy of the system by decreasing the error percentage. The final decision is calculated as the mode of the last five outputs provided by the BCI. A detailed explanation can be seen in [7].

C. Combination of the EOG and BCI commands

The BCI and the EOG interface have been combined in order to be able to perform more complex tasks. Once the EEG and EOG signals are processed, the mental task that the user is performing and the gaze direction are obtained each 0.5 seconds. The combination of both commands has been used to interact, in this case with a GUI. The commands of the EOG interface (up, down, right and left) have been used to move a dot in a plane while the commands of the BCI allows controlling the height of the dot.

In this first approach the control has been simplified using a non simultaneous control. When the user performs an eye movement in the desired direction, the dot starts moving in this direction. When the user wants to stop it, he/she must perform an eye movement on the opposite direction. While the dot is moving, it is not allowed to change the direction of movement without stopping the dot first. This has been done to force the user to return to a rest state. When the dot is stopped, the BCI starts working changing the height of the dot. If the user thinks of the mental task corresponding to right, the dot increases its height, and if the user thinks of the left mental task the dot decreases its height. To give time to the user to start thinking in the correct mental task, when the dot stops, the height of the dot does not change until 1.5 seconds later.

III. EXPERIMENTAL RESULTS

Three male healthy volunteers with ages between 25 and 35 participate on the experiments. The volunteers learned to control both interfaces independently. First, the thresholds of the EOG interface were searched for each user and then the users could train performing several eye movements. The success percentage of the EOG algorithm was measured and it will be shown later. After that, the users started their training with the BCI. First, the EEG signals of the users thinking the mental tasks were registered to create an specific LDA-based model for each one. Next, the users trained with several graphic interfaces that shows them a visual feedback of BCI output, so the users knows if they are doing well or not. Once both interfaces are controlled properly, the user starts working with the multimodal interface.

The multimodal interface has been used to control the movement and height of a dot in a graphic user interface (GUI) in a non-simultaneous control. The GUI shows a workspace where a dot can be moved in X, Y and Z. Two targets with a specific position have been placed on the GUI. The objective of the user is to perform several eyes movements using the EOG interface to get closer to them in the X and Y plane, and then, with the assistance of the BCI, to think of the corresponding mental task in order to change the height of the dot to match it with the target. The dot starts in the position X=0, Y=0 and Z=0. First, the user will go to the target 1 (placed in X=-200, Y=120 and Z=150) and next to the target 2 (placed in X=280, Y=-210 and Z=50). Time used to arrive from the starting position to the first target, and to go from the first to the second target are measured. Furthermore, the global error (G) in position as well as the independent error in each dimension (x, y and z) are measured.

The size of the workspace is: from -360 to 360 pixels in the X-axis, from -300 to 300 pixels in the Y-axis, and from 0 to 200 pixels in the Z-axis. The dot is moved in a grid (in increments of 40 pixels in the X-axis, 30 pixels in the Y-axis and 10 pixels in the Z-axis) each time a command is received (each 0.5 seconds). The error has been calculated using the euclidean distance between the dot and the targets inside the grid. Fig. 3 shows a 3D representation of the trajectory performed by a user in the GUI.

A. Results

The EOG algorithm was tested obtaining satisfactory results. The users obtained a success percentage around 94% (the rest corresponded to no detections). Only some users showed some error during the first tries while performing up and down movements. But these errors are not critical because of the output detected is a blink that does not perform any action on the interface. Furthermore, with the training, these errors completely disappeared. The BCI was tested in [7] where the users obtained a initial good enough results (success rate of around a 60% with a 10% of uncertainty) that improved during the tests.

Table I shows the results of the three users using the multimodal interface. All the users preferred to get closer to

TABLE I

RESULTS OF THE TRAJECTORIES PERFORMED BY THREE USERS GETTING CLOSE TO TWO TARGETS.

		Target 1					Target 2				
		Time	Error (euclidean distance)				Time	Error (euclidean distance)			
	Trial	**(seconds)**	**Global**	**X**	**Y**	**Z**	**(seconds)**	**Global**	**X**	**Y**	**Z**
User#1	1	14.5	2	0	0	2	63.5	1.4	1	1	0
	2	11.5	2	0	0	2	22	2.5	1	1	2
	3	9.5	1	0	0	1	26.5	1	1	0	0
User#2	1	9.5	3.2	0	1	3	17.5	8	0	0	8
	2	12.5	1	0	0	1	91.5	0	0	0	0
	3	8	0	0	0	0	27.5	2	0	0	2
User#3	1	7	6.2	1	1	6	16	1	0	1	0
	2	14	0	0	0	0	19.5	3	0	0	3
	3	34	1	0	0	1	18.5	1	0	1	0
Mean		13.4	1.8	0.1	0.2	1.8	33.6	2.2	0.3	0.4	1.7

the targets first by performing eye movements using the EOG interface, and then, use the BCI thinking the corresponding mental task to adjust the height of the dot. Most time used to arrive to the targets is used by the BCI because it is slower than the EOG interface. The BCI requires thinking constantly in the corresponding mental task to increase or decrease the height of the dot, while with the EOG interface only a movement must be performed to start moving the dot or to stop it. The time used by the users to arrive to the targets is quite low.

Since the distance from the starting position to the target 1 (euclidean distance = 8.1) is lower than the distance from the target 1 to the target 2 (euclidean distance = 19.1), the time used is lower too. In Table I, the global error and the error for X, Y and Z axes are shown. The error obtained in X and Y position is very low in all of the cases because of the accuracy of the EOG interface is better that the BCI. The non-simultaneous control in the tridimensional space using only one of the interfaces would be very complex requiring mens to change between the different dimensions. This will make more difficult the control for the user.

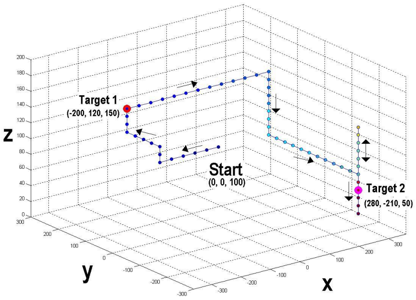

Fig. 3. Trajectory performed by a user.

IV. CONCLUSIONS AND FUTURE WORKS

A multimodal interface composed by a BCI and an EOG interface has been designed. This interface allows increasing the number of commands that can be generated to interact with a device. The multimodal interface is based on an improvement of a BCI previously designed and a new EOG processing algorithm. It has been tested in a graphic user interface where several trajectories have been performed by three users to get closer to some targets. The results have shown that the users are able to use the multimodal interface to control the 3D movement of the dot. This would be impossible using only one of the interfaces.

Our future work will be focused on using this multimodal interface to control a robot arm. In this case, the use of the blink will allow interacting with the environment having one more degree of freedom. A simultaneous control of both interfaces will be evaluated too. The use of a robot arm to interact with daily objects will allow handicaped people increase their independence and quality of life.

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