A NOVEL SYSTEM FOR CONTROL OF A ROBOTIC WHEELCHAIR BASED ON SSVEP-BCI FOR PEOPLE WITH LOCKED-IN SYNDROME

Richard M. G. Tello*, Sandra Müller†, André Ferreira*, Teodiano Bastos-Filho*

*Post-Graduate Program in Electrical Engineering, Federal University of Espirito Santo (UFES) Vitoria-ES, Brazil
†Electrical Engineering Department, Federal Institute of Espirito Santo (IFES) Vitoria-ES, Brazil

Emails: richard@ele.ufes.br, sandra.muller@ifes.edu.br, andrefer@ele.ufes.br, teodiano.bastos@ufes.br

Abstract—In this work, we present the development of a novel approach for control of a robotic wheelchair commanded by a SSVEP-BCI. Thus, it was developed a visual stimulator with aim of helping people with serious physical disabilities, as is the case of patients with locked-in syndrome (LIS). In this system here developed, the subject can modulate the attention in flickering frequencies without requiring head neuromuscular control or eye movements to control the navigation of a robotic wheelchair. Multivariate Synchronization Index (MSI) was used as method to recognize the visual evoked potentials. Three subjects participated of the experiments and EEG signals were captured through a commercial wireless device named Emotiv Epoc Headset. Four frequencies were used as stimuli and each target represents a specific action or class: 8.0 Hz (forward), 11.0 Hz (turn right), 13.0 Hz (stop) and 15.0 Hz (turn left). The results were quite promising achieving high accuracy values with an average of 76.97% using window length of 2s. Furthermore, a real path and a desired path were compared for the wheelchair navigation. Finally, our hypothesis about the visual selectivity, perception and power of the attention for stimuli in reduced space vision were confirmed obtaining promising results.

Keywords—Independent SSVEP-BCI, Robotic Wheelchair, attentional modulation, MSI.

Resumo—Neste trabalho, foi apresentado o desenvolvimento de um novo enfoque para o controle de uma cadeira de rodas robótica comandada através de uma SSVEP-ICC. Com esse intuito, foi desenvolvido um estimulador visual com o objetivo de ajudar pessoas com deficiências severas motoras, como é o caso de pessoas com síndrome de bloqueio ou LIS. Neste sistema, o sujeito tem a capacidade de modular a atenção em frequências piscantes sem precisar de movimentos dos globos oculares ou neuromusculares para o controle da navegação de uma cadeira de rodas robótica. O Índice de Sincronização Multivariável (MSI) foi utilizado como exator de características. Três sujeitos participaram dos experimentos e os sinais cerebrais foram coletados através de um dispositivo comercial sem fio denominado Emotiv Epoc. Quatro frequências foram utilizadas como estímulos e cada alvo representa uma ação específica ou classe: 8.0 Hz (avante), 11.0 Hz (virar para a direita), 13.0 Hz (parar) e 15.0 Hz (virar à esquerda). Nossos resultados foram bastante promissórios, com altos valores de precisão e uma média de 76.97% analisando janelas de tempo de 2s. Por outro lado, uma rota percorrida pela cadeira (percurso real) e um percurso desejado foram comparados. Finalmente, nossa hipótese relacionada à seletividade visual, a percepção e o poder da atenção em espaços de visão reduzida foram confirmadas e resultados promissórios foram obtidos.

Palavras-chave—SSVEP-BCI Independente, cadeira de rodas robótica, modulação atencional, MSI.

1 Introduction

During the last years, several studies have attempted to construct communication techniques independent of peripheral neuromuscular activities. A technology that promises to be a potential alternative as well as an augmentative communication (AAC) and control solution for people with severe motor disabilities (Kelly et al., 2005a) are the Brain Computer Interfaces (BCIs).

BCI is a technology which provides to human a direct communication between the user’s brain signals and a computer, generating an alternative channel of communication that does not involve the traditional way as muscles and nerves (Wolpaw J.R., 2000). Therefore, a BCI records brain signals and extracts Electroencephalography (EEG) signal features and these features are then translated into artificial outputs or commands that act in a real world. A subcategory of BCI using Visual Evoked Potentials (VEPs) has drawn attention for its high Information Transfer Rate (ITR), high accuracy and no previous training to the subject.

When the eye retina is excited by a stimulus at a certain frequency, the brain generates an electrical activity of the same frequency with its multiples or harmonics. This stimulus produces a stable VEP of small amplitude termed as “Steady-State” Visually Evoked Potentials (SSVEPs) of the human visual system.

In a typical SSVEP-BCI system, several stimuli flickering at different frequencies are presented to its user. The subject overtly directs attention to one of the stimuli by changing his/her gaze attention (Zhang et al., 2010). This kind of SSVEP-BCI is commonly called as “dependent” since muscle activities, such as gaze shifting, are necessary. Patients with stroke trauma, poliomyelitis, amyotrophic lateral sclerosis (ALS), botulism, spinal cord injury (SCI), multiple sclerosis, and Guillain-Barré syndrome suffer from motor dis-
abilities, which can disrupt their communication with the external environment, resulting in the so-called locked-in syndrome (LIS). Therefore, “dependent” SSVEP-BCIs might not be applicable for patients with traumatic brain injuries, prevented head movement or ocular motor impairments. Nonetheless, “independent” SSVEP-BCIs could be an alternative solution for these patients.

An Independent-SSVEP-BCI is controlled by subject’s attentions without requiring head neuromuscular control or eye movements. Also, regarding to Independent-BCI’s applicability in daily life, its approach could be used in a portable system able to select a command on the screen of a smartphone using only of the attentional modulation.

Neurophysiological studies (Fries et al., 2001; McMains and Somers, 2004; Reynolds and Chelazzi., 2004) have demonstrated an increases in neural activity elicited by a visual stimulus when a human directs his/her attention to a region of visual space containing a stimulus. These results have led to suggest the hypothesis that attention improves the representation of a stimulus in the occipital areas of the cortex.

On the other hand, studies from (Hairston et al., 2014; McDowell et al., 2013) reveal that wireless EEG acquisition systems provide important advancements by pushing EEG technology towards alternative approaches to establish connectivity between the electrode and the scalp. Their wireless un-tethered operation makes them more applicable for use in every-day, less restrictive scenario (Hairston et al., 2014). Thus, they are better suited for studies where the goal is to monitor neural activity within naturalistic scenarios (McDowell et al., 2013). However, the presence of motion-and muscle-related signal artifacts still remains a very important factor to take into account for user applications in real-world.

This work presents a novel approach for control a robotic wheelchair based on SSVEP-BCI. Thus, we have conducted an approach of attention modulation based on stimuli of reduced spaces. Four small targets represented in four Light-Emitting Diodes (LEDs) that flicker in four frequencies established (8, 11, 13 and 15 Hz). Three subjects with average age of 28 years old participated in the experiments and a path for navigation was established in order to evaluate the performance of the robotic wheelchair control. A commercial wireless device called Emotiv Epoc headset was used for the acquisition of EEG signals. Multivariate Synchronization Index (MSI) was used as feature extractor in the recognition of SSVEP components and the response time for each commands was established in 2 seconds.

2 Methods

2.1 Wireless EEG Acquisition

Emotiv Epoc Headset is a wireless device used for acquiring signal. EEG signals from occipital O1 and O2 channels with 128 samples per second of sampling rate ($f_s$) were collected. The sensors used for reference are: (i) Common-Mode Sensing (CMS) and, (ii) Driven Right Leg (DRL) that are fixed for default and in parallel to P3/P4 channels (the two mastoids), respectively.

2.2 Visual Stimuli

A coupling structure of four small boxes (5cm x 5cm x 5cm) containing a LED in each one and covered with thin white papers diffuser was mounted in the top of a LCD screen. The volunteers sat aboard of the robotic wheelchair, in front of a stimulator system, 70 cm far from this. The timing of the four LEDs flickers was precisely controlled by a microcontroller (PIC18F4550, Microchip Technology Inc., USA) with 50/50% on-off duties, and frequencies of 8.0 Hz (top), 11.0 Hz (right), 13.0 Hz (bottom) and 15.0 Hz (left). These frequencies represent commands or classes: Class 1 ($f_1=8$ Hz), Class 2 ($f_1=11$ Hz), Class 3 ($f_1=13$ Hz) and Class 4 ($f_1=15$ Hz), more details are shown in Figure 1. These frequencies were chosen due to: i) our previous studies (Tello et al., 2014a; Tello et al., 2014b; Tello et al., 2014d; Tello, Pant, Muller, Krishnan and Filho, 2015) have shown that these generate strongest SSVEP responses; ii) safety recommendations specified in (Fisher et al., 2005) have shown that these; iii) studies conducted by (Pastor et al., 2003) about the relationship between visual stimuli and SSVEP-evoked amplitudes recommend these frequencies; iv) according to (Kelly et al., 2005b) it suggest that frequencies in alpha band improves the recognition of attentional modulation for SSVEP stimuli. The amplitude and phase of the SSVEP are highly sensitive to stimulus parameters, such as color, luminance, repetition rate, contrast or modulation depth, and spatial

Figure 1: Specifications of the visual stimulation unit based on LEDs.
frequency. On the other hand, flicker stimuli can elicit epileptic responses to certain luminance or chromaticity. Higher luminance can induce a higher risk of epilepsy (Vialatte et al., 2010) and the chromaticity of a visual stimulus has a strong impact on the human eye response in case of combination of colors (Drew et al., 2001). Red/blue and green/blue combinations have the strongest effect on pupil constriction and they can seizure attacks (Drew et al., 2001). Regarding frequency dependency, repetitive visual stimuli modulated at certain frequencies can also provoke epileptic seizures. According to (Drew et al., 2001), lower frequency flickers generally produce more powerful constrictions, with color-dependence of flickers most visible between 3 and 6 Hz.

Therefore, taking into account all aforementioned recommendations and according to (Tello et al., 2014c; Tello, Muller, Ferreira and Bastos-Filho, 2015), we used the green and yellow colors for the stimulation with triangular and square shapes where the subject will be able to modulate attention through of the perception in reduced visual spaces. This attentional modulation was performed making a minimum visual angle (horizontal: <4.09° and vertical: <2.05°); these values are insignificant and within of the systems that operate in independent way of neuromuscular function, such as it is shown in Figure 2. Also, studies performed in (Tello et al., 2014c; Tello, Muller, Ferreira and Bastos-Filho, 2015) demonstrated that green and yellow colors obtained high values of performance and comfort for SSVEP stimulation.

2.3 Subjects

Three male subjects were recruited to participate in this study (average age: 28.0; Standard Deviation (STD): 1.0). The research was carried out in compliance with Helsinki declaration, and the experiments were performed according to the rules of the ethics committee of UFES/Brazil, under registration number CEP-048/08. The volunteers were labelled as: s1, s2 and s3. Previous selection of volunteers was performed and topics related to the precaution as visual problems, headaches, family history with epilepsy and problems related to brain damage were taken. All volunteers reported not having any inconvenience for conducting the tests and no one had previous experience in using a BCI.

2.4 Experimental Procedure

A desired path was used to subjects move his/her wheelchair through attentional modulation. The experimental procedure is shown in an explanatory Figure 3. Basically the procedure consists of each forward movement which lasts twenty seconds, and each clockwise rotation or counterclockwise 90 degrees lasts ten seconds. Each experiment lasts 110s (55 classified trials).

Figure 3: The path of the navigation of the robotic wheelchair.

3 Feature Extraction and Classification

Brain signals were captured by the Emotiv Epoc and then these signals were transmitted by wireless and processed in an embedded computer by algorithms developed in Matlab. This embedded computer in the wheelchair has the following specifications: Mini ITX motherboard, 3.40 GHz Intel Core i5 processor, and 4GB RAM. The EEG data were segmented and windowed in window lengths (WL) of 2 s without overlapping. Then, a spatial filtering is applied using a Common Average Reference (CAR) filter and a band-pass filter between 3-60 Hz for the twelve channels. A graphical explanation of the complete system is illustrated in Figure 4.

Several studies (Vialatte et al., 2010; Pastor et al., 2003) confirm that visual evoked potentials are generated with greater intensity in the occipital area of the cortex. Based on that fact, we have evaluated the detection of SSVEPs located in the channels O1 and O2, i. e., these two channels were used as input vector for the feature extractor after of filtering process aforementioned. Multivariate Synchronization Index (MSI) was used for feature extraction. A brief description of this technique is explained below.
MSI is a novel method to estimate the synchronization between the actual mixed signals and the reference signals as a potential index for recognizing the stimulus frequency. (Zhang et al., 2014) has proposed the use of a $S$-estimator as index, which is based on the entropy of the normalized eigenvalues of the correlation matrix of multivariate signals. The reference matrix $Y_i$ of size $2H \times N$ is based on sines and cosines that simulates the signal contain the frequency of stimulation. In our case, we have considered the fundamental frequency and one harmonic as the stimulating signals, respectively, and crosscorrelation matrices $C_{11}$ and $C_{22}$ for $X$ and $Y_i$, respectively, and crosscorrelation matrices $C_{12}$ and $C_{21}$ for $X$ and $Y_i$ can be obtained as (Tello et al., 2014a), where $i$ refers to the number of targets.

$$C_{11} = (1/N)XX^T \quad (1)$$
$$C_{22} = (1/N)Y_iY_i^T \quad (2)$$
$$C_{12} = (1/N)XY_i^T \quad (3)$$
$$C_{21} = (1/N)Y_iX^T \quad (4)$$

A correlation matrix $C^{i}$ can be constructed as

$$C^{i} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \quad (5)$$

The internal correlation structure of $X$ and $Y_i$ contained in the matrices $C_{11}$ and $C_{22}$, respectively, is irrelevant for the detection of stimulus frequency (Carmeli et al., 2005). It can be removed by constructing a linear transformation matrix

$$U = \begin{bmatrix} C_{11}^{-1/2} & 0 \\ 0 & C_{22}^{-1/2} \end{bmatrix} \quad (6)$$

So that $C_{11}1/2 = C_{11}$, $C_{22}1/2 = C_{22}$ and by applying the transformation $C^{i} = UCU$ which results in a transformed correlation matrix of size $P \times P$, where $P = M + 2H$ (Carmeli et al., 2005). The eigenvalues $\lambda_1^{i}, \lambda_2^{i}, ..., \lambda_P^{i}$ of $\tilde{C}^{i}$, normalized as $\tilde{\lambda}_m^{i} = \lambda_m^{i}/\sum_{m=1}^{P} \lambda_m^{i}$ for $m = 1,2, ..., P$, can be used to evaluate the synchronization index $S_i$ for matrix $Y_i$ as

$$S_i = 1 + \frac{\sum_{m=1}^{P} \tilde{\lambda}_m^{i} \log(\tilde{\lambda}_m^{i})}{\log(P)} \quad (7)$$

see (Zhang et al., 2014). Using $S_1, S_2, ..., S_K$ computed for the stimulus frequencies $f_1, f_2, ..., f_K$, the MSI can be estimated as

$$S = \max_{1 \leq i \leq K} S_i \quad (8)$$

In this case, the way to assess the performance of the SSVEP-BCI system was the Shannon’s Information Transfer Rate (ITR), see details in (Vialatte et al., 2010).

4 Navigation Control

The kinematic model of our unicycle robotic wheelchair is described by a simple non-linear model (see Figure 5) as in Equation 9:

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} v \cos \theta \\ v \sin \theta \\ \omega \end{pmatrix} \quad (9)$$

where $M = (x,y,\theta)$ is the wheelchair position and orientation in world reference frame, and the pair $(v,\omega)$ is the input control encompassing the linear and angular velocities. In our case, linear $(v = 0.3 \text{ m/s})$ and angular $(\omega = 9\text{ o/s})$ velocities are constant.
Figure 5: Wheelchair’s kinematics.

- If the wheelchair moves forward: \( v = 0.3 \text{ m/s} \) and \( w = 0 \).
- Moves to right (clockwise): \( v = 0 \) and \( w < 0 \).
- Moves to left (counter-clockwise): \( v = 0 \) and \( w > 0 \).
- To stop: \( v = 0 \) and \( w = 0 \).

From these parameters, if the robotic wheelchair moves forward with a constant velocity of 0.3 m/s and a time established of 20s, this will move it forward in 6 m. On the other hand, if the robotic wheelchair turns clockwise with angular velocity of 9° per second and a time established of 10s, this will have rotated 90°.

To calculate the current position of \( x, y \) and \( \theta \) of the robotic wheelchair, odometry is used by calculating the sum of the variations at each instant of time:

\[
\begin{align*}
(x) &= \left( \sum_{t_0}^t \dot{x} \cdot \Delta t \right)\\
(y) &= \left( \sum_{t_0}^t \dot{y} \cdot \Delta t \right)\\
(\theta) &= \left( \sum_{t_0}^t \dot{\theta} \cdot \Delta t \right)
\end{align*}
\]

(10) \[\text{5 Experimental Results} \]

A comparison of performance (accuracy) was tested for 3 subjects using WL = 2s aboard of a robotic wheelchair in an online way. In addition, these results were also compared with the path and class desired. A summary of results is shown in Table 1. Information transfer rate (ITR) parameter was calculated according to (Tello et al., 2014a).

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Accuracy [%]</th>
<th>ITR [bits/min]</th>
<th>Trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>s1</td>
<td>80.00</td>
<td>57.67</td>
<td>55</td>
</tr>
<tr>
<td>s2</td>
<td>78.18</td>
<td>53.85</td>
<td>55</td>
</tr>
<tr>
<td>s3</td>
<td>72.73</td>
<td>43.56</td>
<td>55</td>
</tr>
<tr>
<td>Mean</td>
<td>76.97</td>
<td>51.63</td>
<td>-</td>
</tr>
<tr>
<td>± STD</td>
<td>±3.78</td>
<td>±7.41</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: Accuracy results from navigation of the robotic wheelchair using WL of 2 s.

6 Conclusion and Discussion

According to our results shown in Table 1, high values of accuracy were obtained with an average of 76.97 % and STD of 3.78 %, taking into account that the subjects didn’t perform neuromuscular movements and four frequencies blinking were presented at the same time. In addition, the highest value of ITR (57.67 bits/min) was found in subject 1. Our studies showed good results and quite promising and even could be improved, taking into consideration that was the first time that volunteers had used a BCI, and it is widely known that its continuous use can increase the accuracy. Furthermore, our hypothesis about the visual selectivity, colors perception and the power of the attention to stimuli in spaces reduced vision have been confirmed. On the other hand, a similar path to the desired path between subjects was performed (real path).

Acknowledgement

The authors thank to FAPES and CAPES for supporting this research.

References


Figure 6: (a) Classified trials and (b) executed path for s1; (c) and (d) for s2; and (e) and (f) for s3, respectively.


Tello, R., Muller, S., Bastos-Filho, T. and Ferreira, A. (2014c). Evaluation of the influence of stimuli color for a SSVEP-based BCI, *XXIV (CBEB), Brazil*.

Tello, R., Muller, S., Bastos-Filho, T. and Ferreira, A. (2014d). Towards the portability of an Independent-BCI based on SSVEP, *XXIV (CBEB), Brazil*.


