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Control of Cursor Movement Based on EEG Motor Cortex Rhythm Using Autoregressive Spectral Analysis**

1. Introduction

Electroencephalography (EEG) is a study of the electrical activity of neurons from the cerebral cortex which can be used to direct communication between man and computer. Systems using the signal generated by the brain are called brain computer/machine interfaces (BCI/BMI) [7, 9, 13]. In recent years, research on brain-computer interfaces which use EEG signal became an important part of biomedical engineering. In contrast to the traditional interfaces, they do not need the connection with the muscle or nerve circuits, what allows to control devices without verbal or physical interaction. Therefore, the main application of BCI interfaces is the communication with the outside world for patients who suffer from severe diseases, which limited or precluded any movement [11, 16]. Subcortical cerebral stroke, spinal cord injuries, multiple sclerosis may lead to the so-called 'locked-in' syndrome. In this state the direct translation of signals from the brain is the only possibility of contact with the paralyzed patient. In the present paper, the BCI interface is presented, based on motor cortex EEG rhythms which is used to control the cursor movement in two directions.

2. BCI paradigm

Investigation of the electroencephalography signal for the control application requires a specific way to carry out the experiment in which the repeatable and expected signal response of the brain should be obtained. Such methods are called paradigms. There are

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several paradigms which are used in the EEG-based BCI design. For example it can be used the P300 speller [2] or the mental task paradigm [6]. In the interface described in this paper the ERD/ERS (event-related desynchronization/synchronization) paradigm is used [3, 5, 10]. It is based on changes (increase or decrease) in power of the signal in the specified frequency band which is related to voluntary movement or movement imagination. Usually the imagination of hand, leg or tongue movement is used, due to the fact that these parts of the body are most strongly represented in the sensorimotor cortex of the brain. The advantage of this paradigm is that it is the most natural and close to the voluntary way of thinking method. The drawback is low signal to noise ratio. Thus, for amplify of the signal, multiple repetition of experiments is required.

3. Methods

3.1. Autoregressive Spectral Analysis

Autoregressive Spectral Analysis (AR) [12, 14] is one of the method which gives information about the frequency content (power spectrum) and sources of variation in a time series. In contrast to the Discrete Fourier Transform (DFT), it provides a smoother and more easily interpretable power spectrum. The AR analysis of the time series $\{x_i\}$ assumes that the information about the current value $x[n]$ is included in the past values in the time series. Thus the current value $x[n]$ can be expressed as the weighted sum of the preceding values in time series

$$x[n] = \sum_{i=1}^{M} a_i x[n-i] + \varepsilon[n] \tag{1}$$

where $x[n]$ is the current value of the time series, a_1, a_2 ,…, a_M are predictor (weighting) coefficients, M is the model order, indicating the number of the past values used to predict the current value, and $\varepsilon[n]$ represents an prediction error, i.e. the difference between the predicted value and the current value at this point.

The AR method consists in the determination of the a_i coefficients so that the errors vector $\varepsilon[n]$ reaches the minimal value. This provides to the Yule-Walker equation [15, 17] given by

$$\begin{bmatrix} R_{xx}(0) & R_{xx}(-1) & R_{xx}(-2) & \dots & R_{xx}(1-M) \\ R_{xx}(1) & R_{xx}(0) & R_{xx}(-1) & \dots & R_{xx}(2-M) \\ R_{xx}(2) & R_{xx}(1) & R_{xx}(0) & \dots & R_{xx}(3-M) \\ \dots & \dots & \dots & \dots & \dots \\ R_{xx}(M-1) & R_{xx}(M-2) & R_{xx}(M-3) & \dots & R_{xx}(0) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ \dots \\ a_M \end{bmatrix} = \begin{bmatrix} R_{xx}(1) \\ R_{xx}(2) \\ R_{xx}(3) \\ \dots \\ R_{xx}(M) \end{bmatrix} \tag{2}$$

where $R_{xx}[k]$ is the autocorrelation defined as follows

$$R_{xx}[k] = \frac{1}{N} \sum_{n=1}^{N-k} x[n]x[n+k] \tag{3}$$

where N is the number of data points.

The parameter M which defined the AR model is determined by fitting the model to the data, and checking the prediction error variance. The most common criterion for the selection of M is Akaike's Information Criterion (AIC) [1], which can be presented in the following form:

$$AIC(M) = N \ln(\sigma_p^2) + 2M \tag{4}$$

where σ_p^2 is the prediction error variance associated with M. The selected M minimizes the value of the criterion.

The power spectral density function for this model can be calculated using the formula

$$P_{AR}(f) = \frac{1}{\left|1 + \sum_{k=1}^{M} a_k \exp(-2\pi i f k \Delta t)\right|^2} \tag{5}$$

where $\Delta t = 1/f_s$, f_s – sampling frequency.

3.2. Off-line experiment

The interface presented in the present paper is based on the idea of imagination of right and left hand movement. Since human somatotopic organization indicates that human limbs are controlled by contralateral brain hemispheres, we expect that the most important changes in brain activity occur mainly at electrodes C3 or CP3 which lie over left hemisphere of motor cortex in case of right hand movement imagination and contrary, at electrodes C4 or CP4 which lie over right hemisphere of motor cortex in case of left hand movement imagination.

In order to distinguish the differences in the signal related to right and left hand movement imagination a series of off-line experiments were carried out. During the off-line experiments the user sat in front of the computer screen in a comfortable seat. The experiment consisted of fifty repetitions of right and left hand movement imaginations. The duration time of single trial was eleven seconds and consisted of three periods. First period from 0 to 5 s was the relaxation time, second period from 5 to 6 s indicated the imagination of hand movement by sound signal, and the third one from 6 to 11 s was relaxation time again. Subjects were requested to relax muscles and suppressed eye blinking to avoid EMG and EOG activity artifacts. The trials with evident artifacts were excluded from further analysis.

One 50-trials experiment took about 9 minutes. The configuration of the electrodes used for data acquisition is shown in Figure 1. EEG activity was recorded from 16 of the standard electrode locations (international extended 10/20 electrode system) distributed meanly over sensorimotor cortex. All 16 channels were referenced to the average of the right and left ear's signals (electrode A1 and A2). The sampling frequency was 500 Hz. The EEG signal obtained from the experiment was prepared for further analysis in three steps. First, all evident artefacts were excluded from the signal, secondly the data were filtered with band-pass Butterworth filter so that the range of frequencies was about 5–45 Hz. Finally, the signal was averaged over all trials.

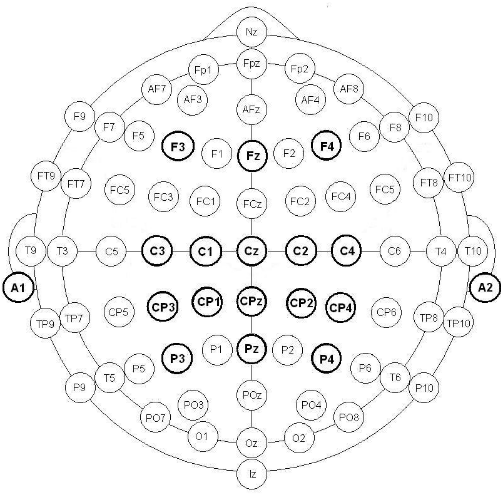

Fig. 1. The international extended 10/20 electrode system. The electrodes used for data acquisition are marked in bold circle. The ear's electrodes are the referencing ones

The differences in the power changes of both signals were calculated and then visualized using maps of the event-related desynchronization (ERD) and event-related synchronization (ERS). ERD/ERS maps inform about the power decrease/increase, averaged over trials in relation to power in a reference time interval. The estimation of the time-frequency distribution of energy density was performed using the method of Continuous Wavelet Transform [4, 8, 18]. In Figure 2 the ERD/ERS maps calculated for the averaged signal from electrodes C3 and C4 are shown. The time interval of sound signal which indicates the imagination of hand movement is marked by dashed line. The reference period is from 0 to 1 s. We have found that in the experiment with hand movement imagination, ERD appears bilaterally in both alpha (8–13 Hz) and beta (18–30 Hz) bands when the imagination of movement is performed, while ERS appears contralateraly in the beta band as post-movement beta synchronization (β-rebound) after the end of movement (imagination of movement). That differences in the power spectrum between left and right movement imagination is used to control the cursor movement.

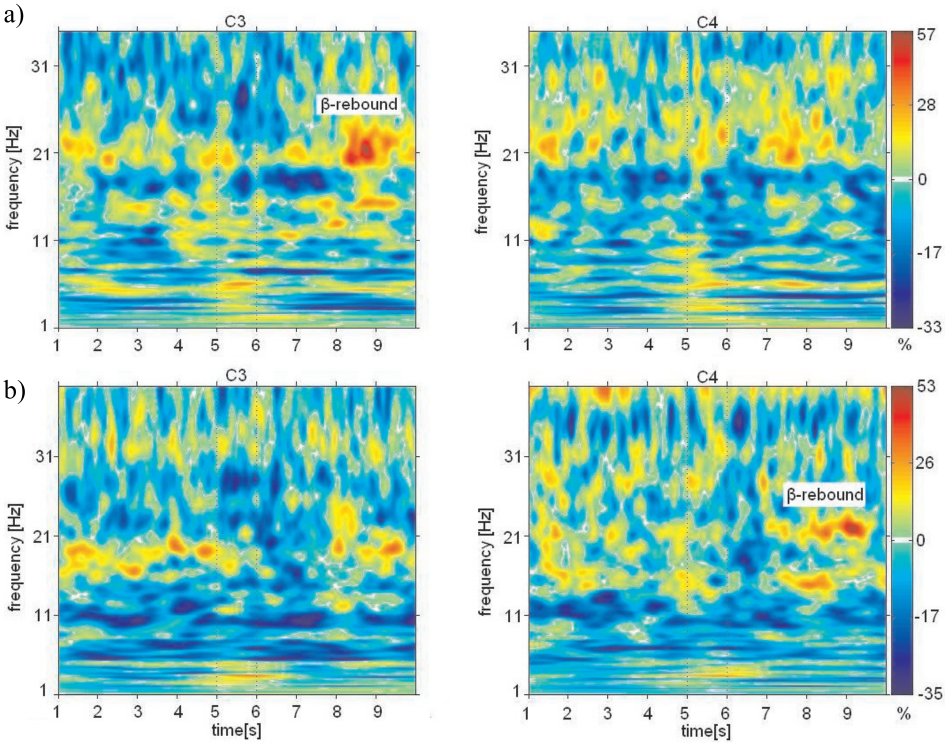

Fig. 2. Time-frequency maps of ERD/ERS related to right hand movement imagination (a) for electrode C3 (left) and electrode C4 (right) and left hand movement imagination (b) for electrode C3 (left) and electrode C4 (right). The estimation of the time-frequency distribution of energy density is scalogram (Continuous Wavelet Transform). The reference period is 0–1 s

4. Control of Cursor Movement

4.1. Cursor movement in real time

Based on results of the off-line experiment presented in section 3, two locations of electrodes over motor cortex were chosen: one electrode over left motor cortex (C3 or CP3) and one electrode over right motor cortex (C4 or CP4). The signal is preprocessing in real time in the following steps: firstly, the signal from both electrodes is referenced to the mean value of the signal from ear's electrodes, secondly, the signal is filtered using time filters and optionally spatial filters and finally, the signals go under AR algorithm with given parameters to determine the power spectrum. Figure 3 shows the power spectrum of the signal from two electrodes C3 and C4 in the time interval corresponding to the beta-rebound after right movement imagination (Fig. 3a) and left movement imagination (Fig.3b). To compare, the power spectrum for relaxation time is plotted by dotted line in Figure 3a.

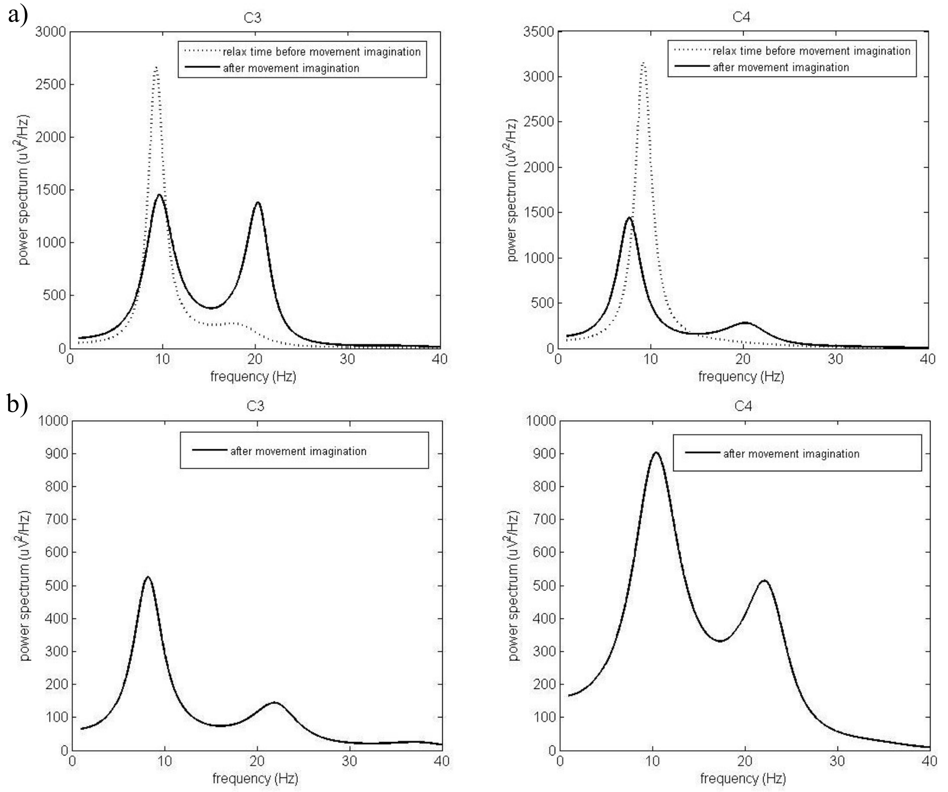

Fig. 3. AR power spectrum in the time interval corresponding to the beta-rebound after the imagination of right hand movement (a) and left hand movement (b) from two electrodes laying over motor cortex. The differences in the amplitude in beta bound can be seen. To compare, the spectrum during relaxation time is shown with dotted line

It can be seen that in the case of right hand movement imagination the amplitude of the beta rhythm in the electrode C3 is higher than in the electrode C4 while in the case of left hand movement imagination the higher amplitude of the beta rhythm appears in the C4 electrode. In the interface presented in the paper, the cursor movement is controlled by the difference between amplitudes in a chosen frequency band ν (beta rhythm) over the right (A_R) and left (A_L) motor cortex (the electrode C4 and C3, respectively)

$$M_\nu = A_L - A_R \tag{6}$$

Value of M_ν determines a vertical cursor movement. If M_ν reaches value from the range specified in calibration process for right (left) hand movement imagination, the cursor shifts 10 pixels up (down). The calibration process takes place as follows: the user imagines the right hand movement for the calibration time (about 60 s) and then the mean value μ_R and standard deviation σ_R of M_v are calculated. The range for up cursor movement is defined as $\mu_R \pm \sigma_R$. After that the calibration process for left hand movement imagination is carried out which specified the range for down cursor movement $\mu_L \pm \sigma_L$. The block diagram of algorithm for cursor movement control is presented in Figure 4.

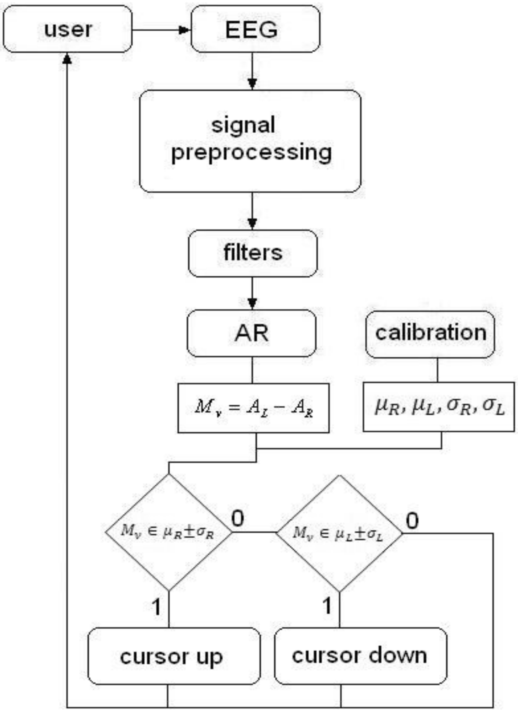

Fig. 4. The block diagram of algorithm for cursor movement control

4.2. Interface design

The online interface consists of two steps. The first one is the 'setting' panel which is used to set up such AR parameters as length of the analyzed sample and the model order *M* for each user individually. In this step individual variation in EEG signal is taken into consideration. This allows one to select the optimal frequency range of beta waves for the most efficient cursor control for each user, separately.

The cursor moving panel is shown in the Figure 5. A trial begin when the cursor appears in the middle of the screen and start to move in two dimensions with its movement controlled by the user's EEG activity as described in section 4.1. There are two targets: one at the top of the screen with the answer 'yes' and one at the bottom of the screen with the answer 'no'. Thus, the user can choose one of two answers what allows him to communicate in a simple way. The target change the color when the cursor reaches it. Then the next trial could begin. The time it takes for the cursor being initially in the middle of the screen to reach either the TAK/NIE area is about 40–60 s. The preliminary research shows that the proposed algorithm interpret correctly the intended cursor movement at about 70 percent.

a) b)

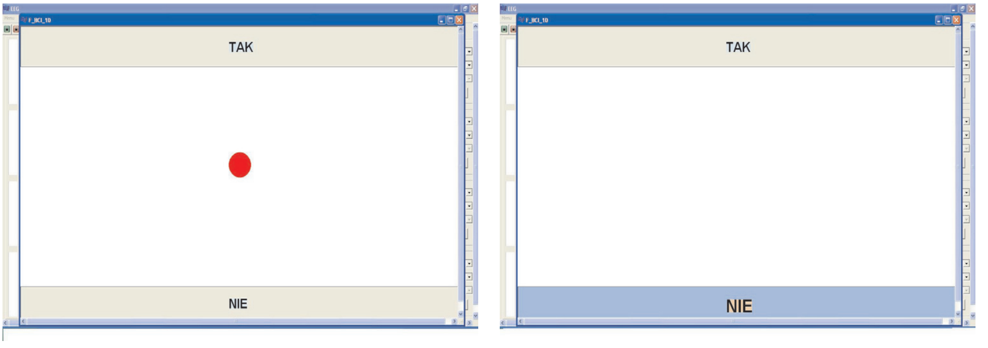

Fig. 5. The cursor moving panel at the beginning of the experiment (a) and after reach the target (b)

5. Conclusions

In the present paper the BCI interface based on EEG motor cortex signals is presented. The differences in power spectrum in beta rhythm for left and right hand movement imaginations is used to control cursor movement in two opposite directions. The potential application of this type of interface is to communicate with paralyzed patients by allow them to answer for "yes/no" question. The preliminary research shows that the proposed algorithm has about 70 percent efficiency.

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