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Brain–computer interface for electric wheelchair based on alpha waves of EEG signal

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Abstract

Objectives: Helping patients suffering from serious neurological diseases that lead to hindering the independent movement is of high social importance and an interdisciplinary challenge for engineers. Brain–computer interface (BCI) interfaces based on the electroencephalography (EEG) signal are not easy to use as they require time consuming multiple electrodes montage. We aimed to contribute in bringing BCI systems outside the laboratories so that it could be more accessible to patients, by designing a wheelchair fully controlled by an algorithm using alpha waves and only a few electrodes.

Methods: The set of eight binary words are designed, that allow to move forward, backward, turn right and left, rotate 45° as well as to increase and decrease the speed of the wheelchair. Our project includes: development of a mobile application which is used as a graphical user interface, real-time signal processing of the EEG signal, development of electric wheelchair engines control system and mechanical construction.

Results: The average sensitivity, without training, was 79.58% and specificity 97.08%, on persons who had no previous contact with BCI.

Conclusions: The proposed system can be helpful for people suffering from incurable diseases that make them closed in their bodies and for whom communication with the surrounding world is almost impossible.

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Keywords: alpha waves; brain–computer interface (BCI); electroencephalography (EEG); wheelchair.

Introduction

Brain–computer interface (BCI) is a direct communication path between the brain and the external device [1–3], designed to analyze real-time brain data to control a computer, neuroprosthesis, or wheelchairs. Unlike conventional interfaces including the signal associated with eye movement (electrooculography, EOG) [4, 5] or the facial muscle contractions (electromyography, EMG) [6], BCI does not need the connection to muscles or peripheral nerves, which allows to control devices without verbal or physical interaction [7–9]. This enables patients in severe stages of illness that prevent any movement, such as subcortical cerebral stroke, amyotrophic lateral sclerosis, cerebral palsy to communicate with the outside world. Commonly, BCI systems are based on properties of electromagnetic waves of the brain, recorded using electroencephalographic techniques [10–12]. In this context, the most important issue is to record and analyze the human emitted electroencephalographic signals and then translate it into the machine control sequence. The possibility of using BCI to control a wheelchair is desired by patients, which resulted in the design of many prototypes of such BCI-based systems [13]. The simplest one controls the wheelchair that moves only in one direction [14]. In that study, the spinal cord injured subject was able to generate bursts of beta oscillations in the EEG signal by imagination of movements of his paralyzed feet. The beta oscillations were used for a self-paced brain–computer interface control based on a single bipolar recording. The subject was placed in a virtual street to simulate driving of wheelchair before using BCI in a real situation. The BCI control system to drive a smart wheelchair which permits the user to select one of four commands is proposed in Ref. [15]. Once a command is selected, the control system executes the selected command and, at the same time, monitors the emotional state of the user. While the user is satisfied, the command is executed; otherwise, the control system stops the wheelchair. The brain-controlled wheelchair prototype developed by B. Rebsamen et al. [16] uses a P300 EEG signal and a motion guidance strategy to navigate in a building. Another solution is the Espirito Santo University wheelchair [17], which uses the desynchronization of the alpha rhythms in the visual cortex that occurs when the eyes are open or closed. Many of the currently developed systems use the hybrid brain–computer interfaces [18–22]. As an example, Wang et al. [18] combine motor imagery, P300 potentials and eye blinking to implement forward, backward and stop control of a wheelchair, while Cao et al. [21] combine motor imagery (MI)-based bio-signals and steady state visual evoked potentials (SSVEPs) to control the speed and direction of a wheelchair synchronously. BCI interfaces willingly use the EEG signal due to its good time resolution and low operating costs. However, from the point of view of a single user, these costs are still high, and the installation of many electrodes cumbersome and inconvenient. A more friendly form of EEG signal registration are EEG headbands that have recently appeared on sale. They are easy to assemble, but have a limited number of measuring electrodes and the recorded signal is worse quality compared to professional recorders. We aimed to contribute to bringing BCI systems outside the laboratory so that it could be more accessible to patients, by designing an algorithm which can work based on the signal from small number of electrodes and with a low signal-to-noise ratio. Our paper describes a brain waves actuated wheelchair concept which is based on two mental states of the subject – state of relaxation and state of focus. Our solution is based on the analysis of the EEG signal for the occurrence of the alpha waves. The state when the alpha waves are present is treated as a binary state and the subject selects the movement direction using the dictionary of binary sequences. The proposed interface is characterized by considerable simplicity, it does not require a training session or several repetitions necessary to complete even a simple movement (needed for systems based on P300 potential [23]) and it requires smaller number of electrodes than most BCI systems. The proposed strategy relies on the brain–computer interface which is slow but safe and comfortable for the user. The paper is organized as follows: Section 2 presents the real-time signal processing, a description of mobile applications and the way in which electric motors of wheelchair are controlled; Section 3 presents results of the experiment with the developed BCI system while the conclusions are contained in Section 4.

Methods

EEG data acquisition

The alpha waves, used in our project, are neural oscillations in the frequency range of 8–13 Hz and an amplitude of 20–100 μV generated by the human brain. They are mainly generated by the closure of the eyes, as an effect of synchronous electrical activity of thalamic pacemaker cells [24], and measured over the region of the visual cortex – the occipital lobe. Alpha rhythms may be recorded in approximately 95% of healthy adults with closed eyes. Posterior alpha amplitude in most normal adults is in the range 15–50 μV, however, alpha amplitudes recorded from frontal electrodes are lower [25]. It is usually sinusoidal in configuration, may wax and wane spontaneously in amplitude, and sometimes has a spiky appearance – a spindle configuration denotes a beating phenomenon that results from the presence of two (or more) dominant frequencies [26]. Alpha waves were discovered (by Hans Berger 1929) as the first of all known EEG rhythms because they are the highest amplitude waves occurring during wakefulness in a healthy adult. The other rhythms that occur during wakefulness are beta and gamma waves. Beta waves are associated with the concentration and information processing and occur in the frequency range from 12 to 30 Hz with an amplitude up to about 20 μV. Gamma waves are characterized by a frequency range from 30 to 80 Hz and due to their low amplitude, they are rarely detected in the EEG signal. Gamma rhythm is associated with motor functions and activity. It also appears in higher cognitive processes and is related to the perception of stimuli and memory. In addition, we distinguish also sleep rhythms, i.e., theta and delta waves.

In our project, for the EEG measurements of alpha waves, the cup electrodes connected by wires to the BRAINTRONICS ISO-1032CE amplifier and AsTEK 200 adapter were used. In our study, four electrodes were placed according to the 10–20 system: one grounding electrode (*Fp*1), one frontal lobe electrode (*Fp*2), two reference electrodes (*A*1, *A*2). The location of the electrodes in the experiment is shown in Figure 1. Because that the electroencephalographic signal has a very small amplitude compared to the electrical signal coming from the muscles, a reference measurement has to be made. In some studies, electrical potential is measured as the difference between two points, one of which is placed on the scalp and the other does not record the brain's electrical activity. In our study, two reference electrodes placed on the earlobe were used. In this case, the electrical potential is calculated as the difference between the signal recorded by the selected channel and the arithmetic mean of two signals from the reference channels according to formula:

$$V_{Fp2} = Fp2 - \frac{A1 + A2}{2}, \tag{1}$$

where V_{Fp2} is electric potential of $Fp2$ point, $Fp2$ is signal from active channel $Fp2$, and $A1$ is signal from reference channel $A1$, $A2$ is signal from reference channel $A2$.

Real-time signal processing

The EEG signal was preprocessed by eliminating interference from the power supply with the use of band-stop filter (cutoff frequency = 50 Hz), low-pass filtration with purpose of eliminating artefacts from the muscles (cutoff frequency = 30 Hz) and high-pass filtration with the purpose of eliminating interference caused by electrode-skin contact (cutoff frequency = 3 Hz). The spectrum of the recorded signal before and after preprocessing is shown in Figure 2.

After proper preprocessing, the signal is analyzed by the algorithms detecting alpha waves. The developed algorithm for controlling an electric wheelchair uses the spectra power density analysis to determine which waves are dominating. The state of relaxation

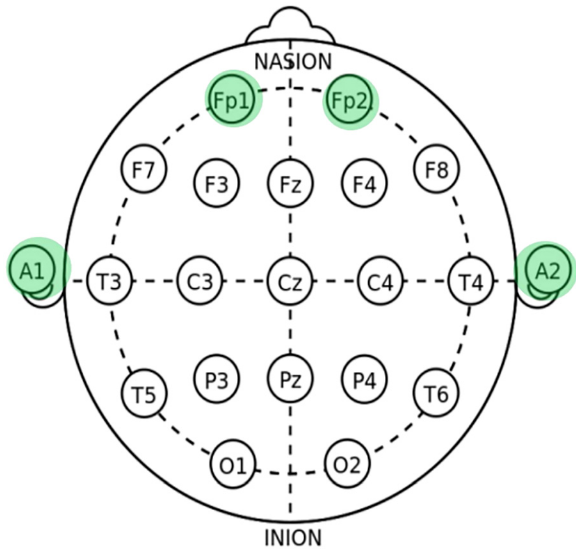

Figure 1: Placement of the electrodes used for the data acquisition (marked by the green circles). The ear's electrodes A1 and A2 are the referencing ones.

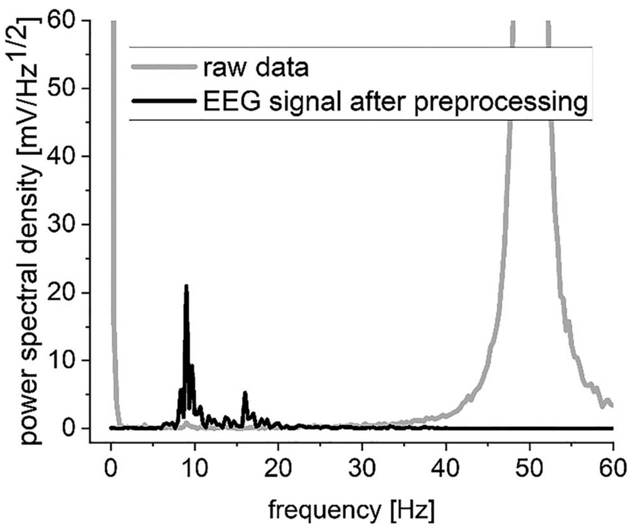

Figure 2: Spectral power density as a function of the frequency of a raw data (gray) and after signal preprocessing (black).

achieved by the subject, i.e., the high level of alpha waves, is equivalent to a high binary state. The state opposite to relaxation, i.e., the state of concentration, corresponds to a low binary state. By the analysis of the alpha wave in electroencephalographic signal, we are able to obtain a certain binary decision 0 or 1 from the subject. However, the communication based only on the selection of one of two possible states is considerably limiting. Therefore, a dictionary of binary sequences corresponding to particular movement directions was developed. A set of binary words related to the individual commands that the subject can use to control the electric wheelchair is presented in Table 1.

Table 1: Set of binary words corresponding to the individual commands used for the wheelchair controlling.

Binary sequence	Command
000	Forward
111	Backward
100	Left
110	Left
011	Right
101	Speed increase
010	Speed decrease

In order to move an electric wheelchair forward, the subject has to achieve concentration state in three consecutive sequences. The fourth sequence is intended for engine motion and in that time interval the EEG signal is not recorded. In order to move the wheelchair to the left, the subject has to reach the state of relaxation in the first sequence and the state of concentration in the next two sequences. By analogy to those two described cases, subject can choose other symbols presented on the graphical user interface, to send the appropriate command to the wheelchair. The way in which a single binary sequence corresponding to particular directions of movement is formed, is presented in Figure 3.

In the developed algorithm, sections of the signal with the length of $N = 1500$ samples are analyzed which corresponds to 3 s of a time interval. The selected fragment is processed with a Discrete Fourier Transform (DFT), using the Fast Fourier Transform (FFT) algorithm [27] and then, the spectral power density is calculated. To distinguish the state of relaxation from the state of concentration, the alpha recognition factor is determined. It is calculated as the ratio of the maximum amplitude for the frequency within alpha frequency range (8–13 Hz) to the mean value of amplitude in the frequency range neighboring with the alpha wave (3–8 Hz and 13–18 Hz) according to the formula [28]

$$w = \frac{2(N_1 + N_2)A_\alpha^{\max}(f)}{\sum_{3Hz}^{8Hz} A(f) + \sum_{13Hz}^{18Hz} A(f)} \quad (2)$$

where N_1 is the number of Fourier transform points in the frequency range from 3 to 8 Hz determined by the size of the data array being transformed (Fourier transform resolution), N_2 is the number of Fourier transform points in the frequency range from 13 to 18 Hz, $A_\alpha^{\max}(f)$ is the maximum amplitude of spectral power density within

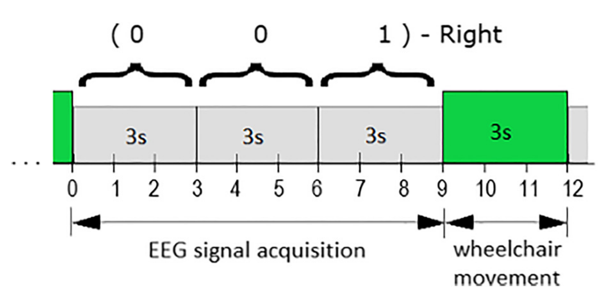

Figure 3: The formation scheme of a single binary sequence corresponding to particular directions of movement.

alpha frequency range, $\sum_{3Hz}^{8Hz} A(f)$ is the sum of the spectral power density amplitudes for frequencies from 3 to 8 Hz and $\sum_{13Hz}^{18Hz} A(f)$ is the sum of the spectral power density amplitudes for frequencies from 13 to 18 Hz. Specific threshold values for detection of alpha waves are selected experimentally and can be modified depending on individual differences. In order to achieve a state of relaxation, which in the developed BCI system corresponds to a binary value *1*, the determined alpha recognition factor must be between two thresholds: lower (no alpha wave) and upper (muscle artifacts). Figure 4 presents the graph of spectral power density for a 3 s window in which the subject achieved the relaxation state (*a*) and when a strong alpha wave representation is absent (*b*).

Mobile applications

In order to implement the electric wheelchair control system using alpha waves, a mobile application was designed. The application was developed in *Java* programming language in *Android Studio* environment as an animation presenting the subsequent 3 s stages in which the EEG signal is recorded. In each stage, the subject has to achieve a state of relaxation or concentration.

The execution of a specific sequence by the subject results in the movement of the electric wheelchair in the desirable direction. The main application window and the window showing a part of the animation in the 3-s stages are presented in Figure 5(a). An important aspect in the context of correct functioning of the brain computer interface is the synchronization of EEG data recording with the graphic presentation. A delay of a few milliseconds may have an adverse effect on the signal analysis and the efficiency of classification which finally can lead to the incorrect behavior of the entire system. Synchronization was carried out using the server–client architecture which allows for division of the tasks. In the implemented BCI system the communication between the client (mobile device) and the server (computer) takes place wirelessly via the WIFI network, using the TCP/IP communication protocol. The safety of the person using the brain–computer interface is another important issue. Because that the control of an electric wheelchair is carried out by brain waves, there is a risk of erroneous recognition of the direction in which the subject wants to move. To protect the person using such a system against, i.e., hitting the obstacle, a mobile application provides the possibility of wireless monitoring and correction of the subject track. The interface for such an external control is presented in Figure 5(b). In the upper right corner of the application, there is an icon for connecting to the server via WIFI. Just after the connection between the mobile device and the server is correctly created, the supervisor of paralyzed person can start wirelessly controlling the wheelchair by five buttons: upper arrow, bottom arrow, right arrow, left arrow, and stop sign. Stop sign serves to emergency stop the entire BCI system and reset the logic of the microcontroller.

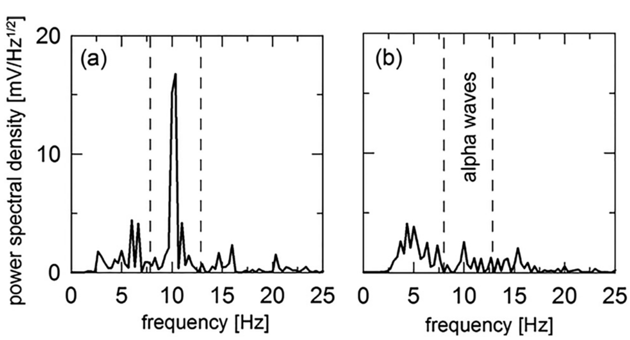

Figure 4: Spectral power density as a function of the frequency with a strong representation of alpha waves (a) and when the strong representation of alpha waves is absent (b). The dashed vertical lines denote the boundary of the alpha frequency range.

Electric motors control

The core of the wheelchair drive was an *Arduino Mega 2560* microcontroller. The purpose of such a choice was the high versatility of this platform. The quantity of I/O pins provided by the microcontroller was enough to communicate with all the devices used in the wheelchair drive. The scheme of the drive is shown on Figure 6.

It consists of two DC motors, each providing 180 W of power. Both motors are driven by *Pololu Simple High Power Motor Controllers* that work on maximum voltage of 40 V and maximum current of 12 A. Each driver is connected to the *Arduino* through UART. Two separate 12 V batteries are the sources of power, one per one motor. To prevent crashes with objects in the environment, two IR proximity sensors are connected to the microcontroller. One is located at the back and one at the front of the wheelchair. Its sensing range is approximately 60 cm, which is enough to stop the wheelchair after detecting an obstacle. To monitor the speed and the acceleration two encoders with Hall sensors and a 3-axes accelerometer were used. All the sensors are powered by *Arduino* 5 V pins. The *Arduino* microcontroller continuously monitors the USB serial connection. After receiving and recognizing the command, it runs one of the algorithms to move the wheelchair. It sets the speed of the motors by sending command to the motor controllers through UART. After 2 s it stops both motors. When the wheelchair is turning right or left, the motors rotate in opposite directions. Setting the speed is done using the functions provided by the motor controller manufacturer that are dedicated for *Arduino*. They also allow the user to limit the acceleration of the motors. It is possible to adjust the acceleration to the level which is comfortable for the user, therefore different speeds and accelerations of wheelchair mobility have been tested. In Table 2 the boundary values of measured acceleration and speed of the wheelchair are shown. Note that the optimal values allow the wheelchair to stop safely after detecting the obstacle. They provide speed that is comparable to slow walk and are comfortable for the user.

Results and discussion

The simplified diagram of the developed brain–computer interface is presented in Figure 7. The electroencephalographic signal recorded with four gold electrodes from the surface of the head, is transmitted to the EEG amplifier. After conversion to digital form, the signal is sent to the computer through the Ethernet cable. The mobile application, which serves as a graphical interface, is fully synchronized with the data recording by dint of server–client architecture.

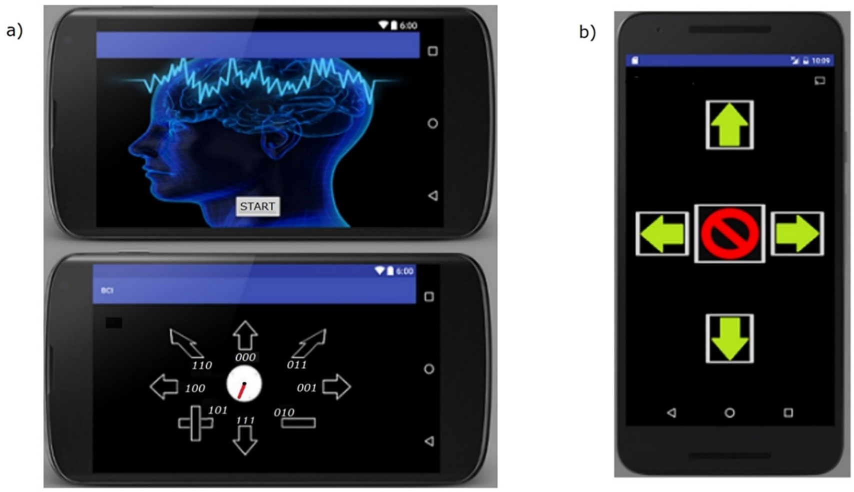

Figure 5: (a) Mobile application for recording of alpha waves, (b) mobile application for controlling electric wheelchair.

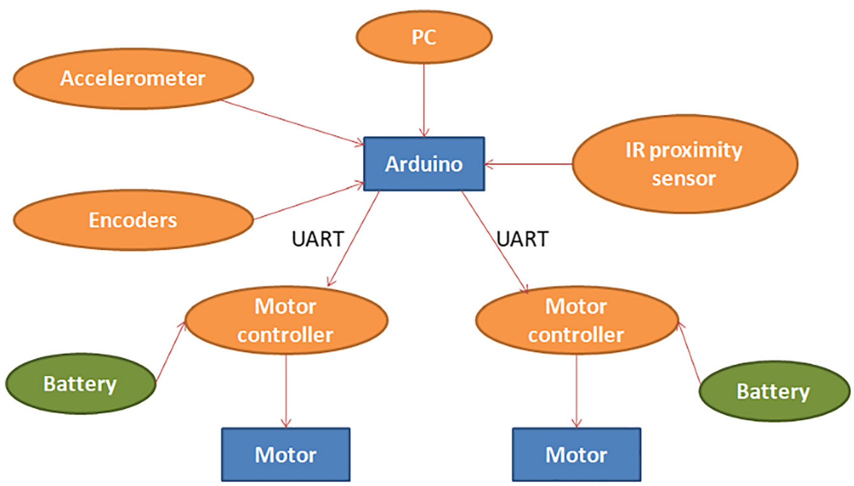

Figure 6: Diagram of the motors control system in the electric wheelchair.

Communication between mobile application and computer, on which the server is located, is carried out wirelessly via WIFI network. EEG signal is processed and digitally filtered using MATLAB tools. Then, on the basis of spectral analysis of the EEG signal, a control command is obtained. This command is read by the microcontroller, which sends appropriate signal to DC controllers and sets the motors of the electric wheelchair in motion. The images showing developed electric wheelchair when used by the subject are presented in Figure 8.

Table 2: Boundary and optimal values as a result of an acceleration tests. The right column presents a distance passed between sending the stop command stopping the wheelchair and its stop.

	Acceleration [m/s^2]	Speed [m/s]	Distance [m]
Max.	1.02	0.7	0.72
Min.	0.25	0.3	0.06
Opt.	0.56	0.7	0.43

In Figure 9 the spectral power density as a function of the frequency is presented for experimental data for three exemplary cases. First column shows the relaxation state in three consecutive time intervals which leads to the backward movement of the wheelchair. The second column, corresponding to the forward movement, shows the concentration state in three consecutive time intervals, while the third column presents two concentration and one relaxation state which results in turning right.

In order to test the developed algorithm, 10 series of tests were carried out. In each of them the subject had to choose one of the symbols presented on the graphical user interface and make the appropriate sequence consistent with the dictionary of binary values. The results are summarized in Table 3. The average sensitivity was obtained at the level of 79.58% confirming the possibility of effective wheelchair control. Note that the tests were carried out on persons who had no previous contact with BCI and without any training. The mean value of the specificity,

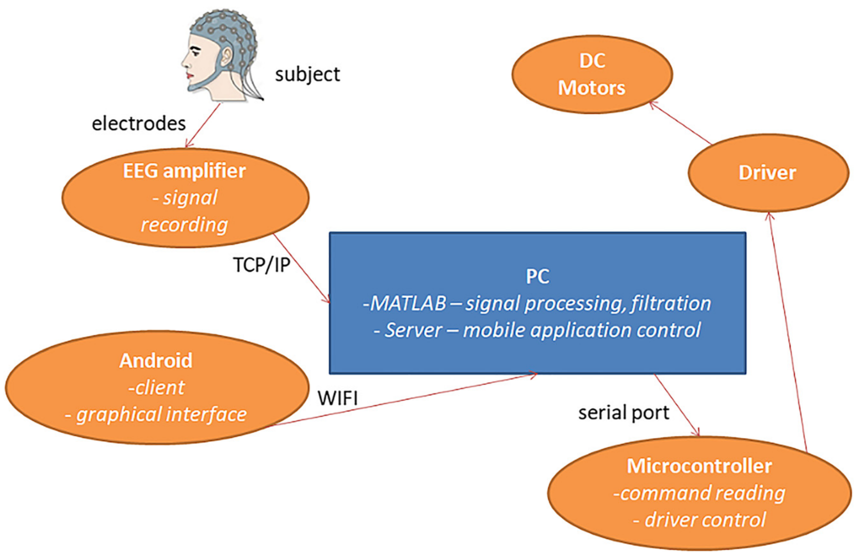

Figure 7: Diagram of the developed brain–computer interface.

Figure 8: Mechatronic design of our electric wheelchair when used by the subject.

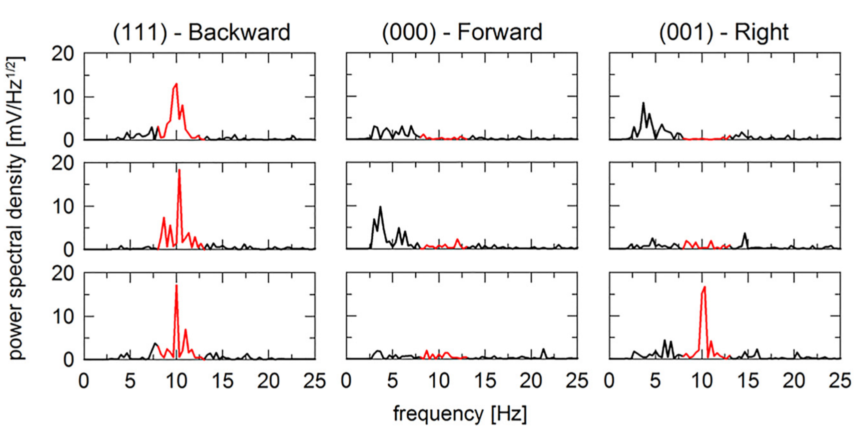

Figure 9: Spectral power density as a function of the frequency for a single binary sequence corresponding to exemplary directions of movement: (111) – backward, (000) – forward, (001) – turning right. The alpha frequency range (8–13 Hz) is marked in red.

false positive rate and precision are respectively: 97.08%, 2.92%, and 80%. The backward command was best recognized by the algorithm, which is easy to explain because it consisted of three relaxation states (111). In turn, the worst recognized command, with the largest number of false negatives, was the 010 command, assigned to the speed decrease. Most often it was confused with 001 (right turn).

Table 3: Evaluation of the algorithm based on alpha waves. Average values for sensitivity, FPR and precision are marked in bold.

	Sensitivity	FPR	Precision
For individual class			
Forward	0.8	0.0047	0.96
Backward	0.96	0.0190	0.87
Left	0.83	0.0285	0.80
Right	0.76	0.0571	0.65
Left 45°	0.8	0.0428	0.72
Right 45°	0.8	0.0238	0.82
Speed ↑	0.76	0.0285	0.79
Speed ↓	0.63	0.0285	0.76
Mean	**0.79**	**0.0292**	**0.80**
For individual subject			
Subject 1	0.78	0.0304	0.82
Subject 2	0.73	0.0375	0.75
Subject 3	0.86	0.0196	0.87

Commands 001 and 110 (right turn and left 45° turn, respectively) were mostly false positive recognition. It is worth considering swapping words so that the most frequently used commands have words assigned with the highest value of sensitivity as well as high level of precision.

Conclusions

We propose a wheelchair controlled by EEG brain–computer interface fully controlled by alpha brain waves, using the phenomenon of relaxation, which is able to operate on a signal with a low signal-to-noise ratio and a few electrodes. It is based on the state of relaxation and a set of eight binary words that allow to move forward, backward, turn right and left, rotate 45° right and left as well as to increase and decrease speed of movement. The mobile application fulfilling the role of a graphical user interface was also implemented. Thanks to the server–client architecture, the application is fully synchronized with the recording of EEG data, which is necessary for the proper functioning of the entire system. The application enables monitoring and controlling of electric wheelchair by the carer of the paralyzed person. It is possible to correct the subject's track or to shut down the entire system in the event of a dangerous situation. Our tests performed on three subjects revealed high sensitivity of the proposed BCI-system with any training stage. Our solution is therefore a simple and effective method to control a wheelchair by people with motor paresi, which does not require the usage of many electrodes limiting the patient's movement or multiple repetitions of image tasks which after a short time make the patient weary.

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Informed consent: Informed consent was obtained from all individuals included in this study.
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