

Speed control of Festo Robotino mobile robot using NeuroSky MindWave EEG headset based Brain-Computer Interface

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Abstract— This article presents the development, implementation and testing of a brain-computer interface (BCI) system, which enables the speed control of the mobile robot called Robotino, manufactured by Festo Didactic. The BCI system was implemented, and the results of the BCI system were evaluated during a students' project, based on the project-based learning methodology. Speed control has been achieved by utilization of NeuroSky MindWave EEG headset-based electroencephalogram (EEG) method, by processing brain bioelectric signals measured on the frontal lobe. Tests of the system evolved by using the brain-computer interface have been performed and evaluated, both regarding implementing speed control and user's experiences, which have been finished with positive results.

Keywords— *Brain-Computer Interface (BCI); Electroencephalogram (EEG); Human-Robot Interaction*

I. INTRODUCTION

Brain-Computer Interface (BCI) is an emergent technology to build a direct communication channel between human brain and the computer. [1] BCI reads the waves produced by the brain and translates these signals into actions and commands, which can control the computer. [2, 3] The BCI can be used in many applications for example playing games [4, 5], social interactions by detecting emotions [6, 7], or to help disabled persons [8-11]. EEG system has been widely used in the field of BCI. [33, 34]

Toyota Motor Corporation developed a Thought-Controlled Wheelchair based on BCI technology in 2009, which is an electric wheelchair controlled by brain waves. The developed BCI system facilitates a relatively accurate and rapid control. Detection and evaluation of encephalic frequencies are performed by an EEG helmet worn by the user using the electric wheelchair, on which several EEG sensors can be found. Evaluation and processing of received signals are performed by a notebook, which can transmit the right-left-forward commands to the wheelchair. For performing 'stop' procedure, a complementary detector was used, which was not based on detecting brain waves. [12,13].

An other research field of BCI based technology is enhancing security, an asleep detector [14,15] or systems helping braking [16] are being developed in order to reach this goal. At the german Technical University of Berlin, such a system based on EEG signal processing has been developed,

which the braking intention of the driver can be detected with, 130 milliseconds earlier than pushing the brake pedal. This time difference can decrease stopping distance of a vehicle travelling at nearly 100 km/h, by almost 3.7 meters [16]. On the other hand, there are also new possibilities on those fields, where beside operating human limbs, new control features should be performed. [17,18]. The Asimo (Advanced Step in Innovative Mobility) robot is a humanoid (similar to humans), which looks like a boy, and can be controlled by brain waves, this device also uses EEG technology [19]. It may take role in several military applications, in the future even brain wave based control of a recon plane may be possible [20-22]. At the University of Minnesota, such brain wave guided helicopter has been developed, which is capable of passing through an obstacle course. EEG signals have been measured by a EEG helmet with 64 electrodes, and the move of the helicopter was guided by processing brain waves emerging by the imagination of different moves (movement of left or right arm) [23].

The goal of the research is to develop such a brain-computer interface based IT system, which can control the speed of a mobile robot through processing bioelectric signals provided by the Neurosky EEG headset. By using the developed brain-computer interface, speed control based positioning has been examined by our test subjects. The development and test of the BCI system was implemented during a one year students' project.

II. THEORETICAL BACKGROUND OF BCI SYSTEMS

The brain-computer interface is a direct communication channel between a biosensor based brain signal processing unit and an external device. BCI systems can be divided into two major groups according to the measurement of bioelectrical signals. In case of EEG, where biosensors are directly placed into the brain, we are talking about invasive BCI, otherwise, if the electrodes are placed somewhere on the head, for example on the forehead, we are talking about non-invasive BCI [24-26]. Due to the dangers of invasive process, non-invasive BCI systems are preferred.

A. Components of BCI systems

Information process flow of BCI systems are built up by four main components. Figure I. shows a typical BCI system process flow.

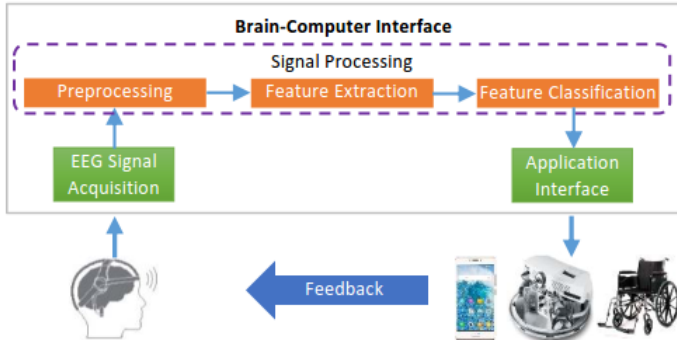


Fig. 1. The BCI's information process flow

The Signal Acquisition component realizes the signal acquisition, filtering, amplification and digitalization functions. The electric signals could be recorded from the electrodes. Because the amplitude of captured signals are low, they need to be amplified, then digitalized to process by computer algorithms. The digitalized EEG signals are pre-processed (i.e. digital filtering) and main features are extracted and classified by complex signal processing algorithms (i.e. Fourier method). These features can be used to control in external devices or computer.

B. Quantitative EEG and mathematical approach

Brain activity can be monitored through examination of electric and magnetic phenomenons of neurological operation, one of the widespread methods is EEG. [27] Process of EEG signals are performed by QEEG methods in most cases, when the spectrum of bioelectric signals is defined and evaluated [28-30]. Definition of brain bioelectric signals is performed by Fourier method. The Fourier Series of $x(t)$ $0 \leq t \leq T$ can be written as the following mathematical form (1):

$$x(t) = \sum_{-\infty}^{\infty} (X[k] \cdot e^{jk\omega_0 t}) \quad (1)$$

where

$$\omega_0 = \frac{2\pi}{T}, k = \dots, -2, -1, 0, 1, -1, 2, \dots \quad (2)$$

The Fourier Series can be also presented as in trigonometric form (3):

$$x(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} (a_k \cos(k\omega_0 t) + b_k \sin(k\omega_0 t)) \quad (3)$$

where $x(t)$ is a periodic function, whose periodic time is T , and can be integrated in $[0, T]$ integrational range. The a_0, a_k, b_k constants presented in the Fourier Series can be calculated according to the following formulas in exponential and trigonometric forms (4-9):

$$X[k] = \frac{1}{T} \int_{t=0}^T x(t) e^{-jk\omega_0 t} dt \quad (4)$$

$$a_k = X[k] + X[-k] \quad (5)$$

$$b_k = j(X[k] - X[-k]) \quad (6)$$

$$a_0 = \frac{1}{T} \int_0^T x(t) dt \quad (7)$$

$$a_k = \frac{2}{T} \int_0^T x(t) \cos(k\omega_0 t) dt, k = 0, 1, 2, 3, \dots, N \quad (8)$$

$$b_k = \frac{2}{T} \int_0^T x(t) \sin(k\omega_0 t) dt, k = 0, 1, 2, 3, \dots, N \quad (9)$$

In case of non-periodic signals, Fourier transformation can be applied, whose exponential form is (10):

$$X(\omega) = \int_{-\infty}^{\infty} x(t) e^{-j\omega t} dt \quad (10)$$

While during the sampling, the signal continuous in time is transformed into discrete period signal series, the frequency spectrum related to the sampled data $x_0, x_1, x_2, \dots, x_{N-1}$ can be calculated according to the DFT (11):

$$X[k] = \sum_{n=0}^{N-1} x[n] e^{-jk\omega_0 n} \quad (11)$$

The continuous Fourier transform could be evaluated over a finite interval rather than from $-\infty$ to $+\infty$ if the wave form is periodic. Similarly, if there are only a finite number of sampled data the DFT handle the data as if it is periodic. (samples 0 to $N-1$ is the same as N to $2N-1$). Therefore, DFT is evaluated for the fundamental frequency $\frac{1}{NT}$ Hz, $\frac{2\pi}{NT}$ rad/s.

Performing DFT needs a lot of calculation, but this can be decreased by optimizing calculational algorithm. In case of DFT, calculation demand is $O(N^2)$, while performing the so-called Fast Fourier Transform (FFT) process, it could be decreased to the $O(N \cdot \log N)$ value (where N is the data size). By FFT algorithm, brain bioelectric spectrum can be calculated, where the strength of particular brain waves specific to the encephalic operation can be defined [31, 32].

III. STUDENTS' PROJECT

The development, implementation and testing of a brain-computer interface (BCI) system was organized during a students' based project. The project was elaborated taking into account the Project Based Learning (PBL) methodology. The main challenge of the project was to motivate students in the field of EEG technology and BCIs and give more knowledge in the topic of signals, systems, measurement and control theory. The project was organized in one semester according to the project schedule showing Table I.

TABLE I.
STUDENTS' PROJECT SCHEDULE

Topics	Weeks
Introduction to BCI systems	1
Introduction to EEG	2
EEG devices	3
Special hardware and software training (serial communication)	4
Design and building of BCI System	5-12
System testing, bug fixes, fine tuning	12-13
Human tests, evaluate results	14
Discussion and presentation, project, discussion	15

IV. BCI SYSTEM OVERVIEW

Creating the brain-computer interface, procession of encephalic bioelectric signals has been performed by a notebook, with an application written on a high-level program language. Controlling the robot was achieved by using an other computer, on which the application made in Robotino View development environment developed by Festo company was running.

A. BCI speed controller

The purpose of this research is to investigate and explore the possibilities of the brain-computer interface, to learn how efficient mobile robot speed controller system can be built. For performing speed control based on performing encephalic bioelectric signals, an EEG headset, a processor and evaluator system, and a guided robot are necessary. Structure of the system can be seen on Figure 2.

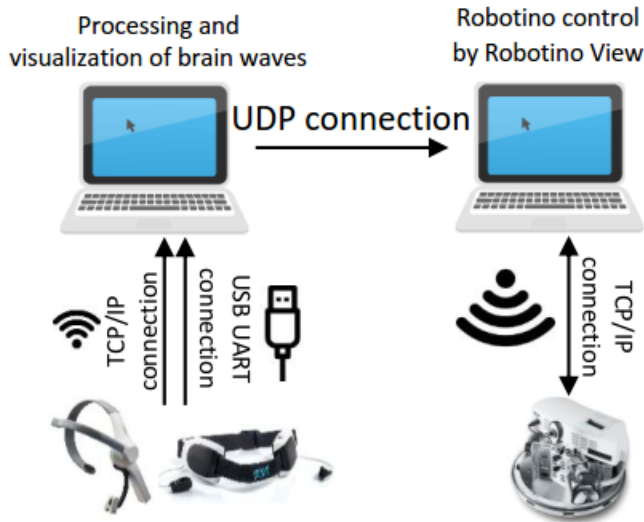


Fig. 2. BCI Speed Control System

B. EEG headsets

For performing our research task, we needed an EEG headset, which the brain waves can be defined with. In BCI systems, wearing systems of more electrodes are less comfortable. During performing the system, we have chosen MindFlex and MindWave EEG headset devices manufactured by NeuroSky Inc.

The MindFlex and MindWave EEG headsets are using single sensor on frontal lobe and neutral points on ears by ear clips. Figure 3 shows the headsets and their main parts.

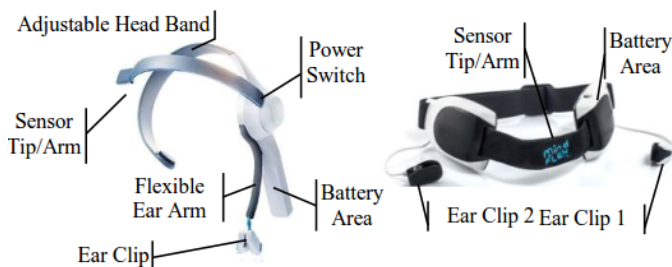


Fig. 3. MindWave (left side) and MindFlex (right side) EEG headset

The Neurosky uses the ThinkGear Technology to process and classify the EEG signal based on quantitative approach. The device can calculate the eSense Attention and Mediation values between 0 and 100. The eSense Attention value was used to change the speed of the mobile robot.

C. Festo Robotino, Robotino View and Robotino Sim Software

Festo Robotino mobile robot is used to test speed control realization. (Fig. 4). Robotino uses omnidirectional drive to move, has a bumper sensor around, infrared distance sensors, a color camera and it is controlled by an industry-standard PC system.



Fig. 4. Festo Robotino

Via Wireless LAN, the robot can be control by the external PC and can send all sensor readings to it. This way, the control programs can run on the external PC or on Robotino directly.

The robot can be controlled via Wifi connection, from the so-called Robotino View graphic development environment. The Robotino View is an environment for interactive 'native' graphical programming. In the functional block development environment controller, image processor, logic, vectoralgebral etc. objects are available, and complex control can be achieved with them. The development environment ensures establishment of data connection from external softwares via TCP/IP and UDP connections. The robot control program can be programmed by the Robotino View development environment.

The Robotino Sim is a robot simulation software, which models the movement of the robot in virtual 3D environment realistically (Fig. 5). The simulation model contains all features like the real robot.

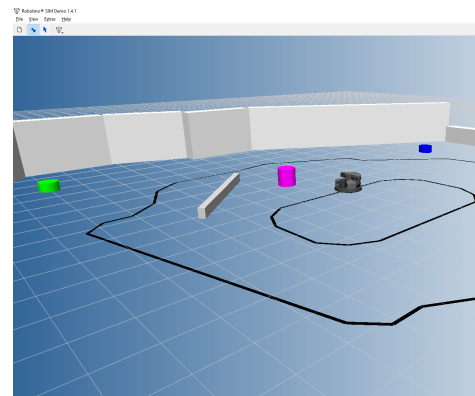


Fig. 5. Robotino Simulation Software

V. IMPLEMENTATION OF BCI SYSTEM

During software performance of the brain-computer interface, the system development life cycle (SDLC) terminology has been applied, where particular software development cycles can be separated and defined well, making tracking the development process easier. During performing the software, we were about to create the clear code, in order to make an easy-to-overview and easy-to-maintain application.

A. Defining Requirements

Main requirements about BCI system can be summarized in the following points:

- is able to establish data connection to control hardware;
- is able to receive data sent by both EEG headsets, and is capable of checking if there were any kind of failures due to signal disturbance during data transmission;
- is able to determine the extent of attention values from MindFlex and MindWave EEG device;
- is able to change the speed of the Robotino mobile robot;

The next phase of development is creation of system plan, according to the requirements defined in the specification.

B. Systems design

For accurate planning of data structures to be implemented and algorithms, Unified Modelling Language (UML) has been used in most cases. As the first step of the process, sub-systems building up the system, and the connections between them have been defined (Fig. 2).

In the next step, the logic structure of the application has been defined (Fig. 6).

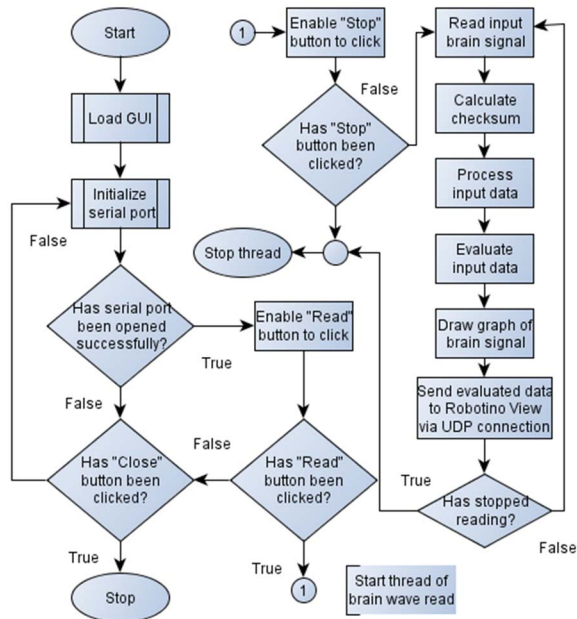


Fig. 6. Logical desing

During the planning process, several other charts have been made, such as static and dynamic UML diagrams, which gave huge help in creation of models static and dynamic in time.

The application to be implemented has been built up by four classes. The so-called FormOfBrainWaveRead partial class, whose object copy handles events happening during the application, and can be considered as the extention of the Form base class. Our second class according to models, is the FormGraphics, which describes the summary of data visualization, and depends on the FormOfBrainWaveRead class.

The third class is the RobotinoDataSend, which object is responsible for sending proper data according to the communication protocol to Robotino View. The fourth class is called SerialPortManager, which precisely describes management of serial port needed for the task.

C. Implementation

The data processor and viewer module performs via the serial port, reading, converting, processing data coming from the headset, and the visualization of received EEG signals for users. In the program, after opening the serial port, pushing 'Read' button starts data process and visualization. The FormOfBrainWaveRead class describes management of events caused by the program or user. These events invite data processor and visualization functions. Object of SerialPortManager class is responsible for data processing.

The Robotino mobile robot movement control has been performed via UDP connection, which is supported by the Robotino View development environment. Movement control of the robot has been performed based on the extent of Attention. The speed of the robot was controlled by the average of attention strength value. Average attention levels have been sent via UDP connection to Robotino View UDP server at port 9180 in every second.

In the Robotino View, creation and run of the UDP server can be performed by Data Exchange UDP functional block available in the development environment. Program performed in the Robotino View, calculates the speed of robot by functional blocks seen on Fig. 7.

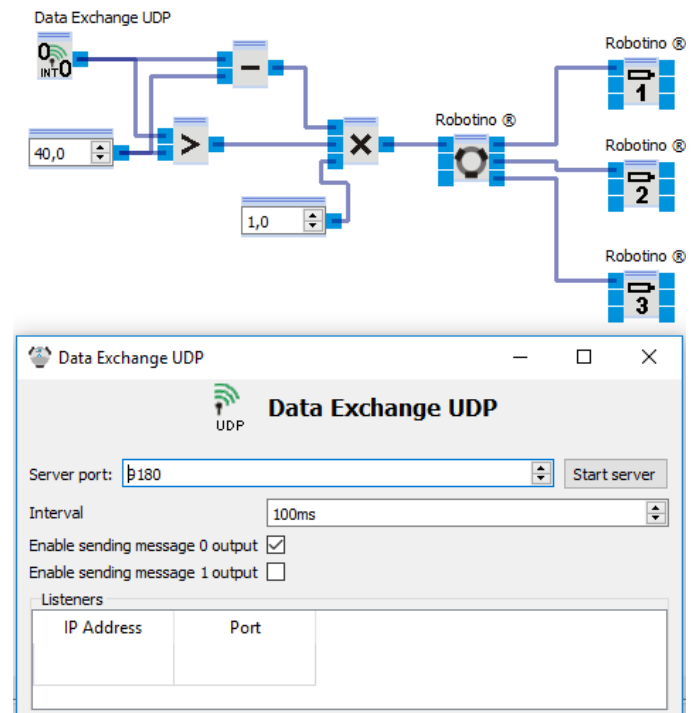


Fig. 7. Data Exchange UDP and functional block

Until attention level reaches 40, value of series calculating speed is 0, when it exceeds it, speed of moving forward, so its x-direction speed V_x – which is the highest input of Omnidrive

block – will be in proportion to attention level. Robotino View performs control of Robotino via WiFi connection with TCP/IP protocol, by providing IP address of the robot. Movement of Robotino can be watched in Robotino Sim simulation environment running on the computer via the UDP port 8080.

VI. TESTS AND DISCUSSION

By the help of data processor and control unit performed by BCI device, several case studies have been performed regarding movement control of the robot. Checking usability and controllability of the BCI device was realized involving seven test subjects (five men 1-5, and two women 6-7, age: 20-35). Testing subjects had to move the robot into desired positions by controlling the speed of the mobile robot. The robot started from a starting position (START), stopping in two intermediate positions (STEP1 és STEP2) and reaching the final point, 3 m far from the start position, (FINISH) was the control goal for five times. (Fig. 8.)

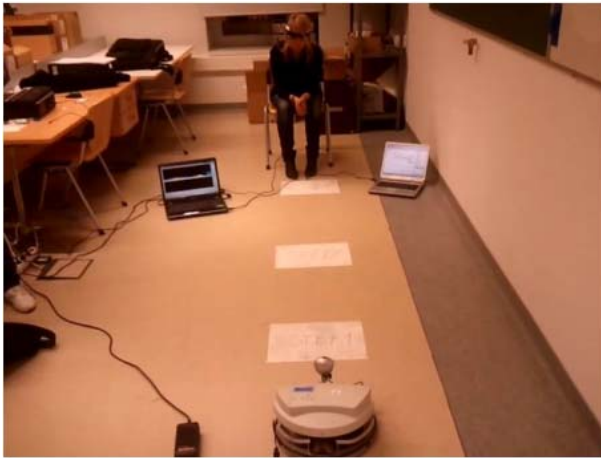


Fig. 8. Test Subject

Initial opinions regarding usability and test results were quite dividing, because the first use of the device was not successful enough, although prior experiments performed on myself had been also the same. During using the device, testing subjects did not know how to control their thoughts, how to reach a calm, relaxed condition in terms of brain activities, and an enhanced level of attention. According to these, their first impressions regarding usability of the device were bad, and the measured results were not appropriate either.

Then providing them our own experiments of using the device, giving them advices, how to attempt to control their attention, their opinion about usability of the device were continuously becoming better and better, by dealing more with it, and the desired movement and telephone control task success rate as well. Feedbacks from the test subjects regarding usability, and the test results of experiments are summarized in Table I. and Table II.

According to the given results, it can be seen, that testing subjects had difficulties in the first steps of using the device. In case of moving the robot, test subjects had difficulties in stopping it, so they could hardly reach the calm condition. Due to that, sometimes it happened, that the robot started on the test course, but did not stop in the intermediate positions, there were

only acceleration and deceleration during moving. Following more than half an hour use of the devices, efficiency of using the device improved a lot, which are also shown by the results in the table. Feedbacks given by the testing subjects about usability of the device became better by more than 1.86 mark and reached the good level, and by controlling mobile robot, the initial very unstable movements became more and more controllable, and the average of positioning failure fell under ± 30 cm. Opinion of test subject was, that in the beginning they had not known how they should have been controlled the device properly with attention, so they had not been able to perform the desired feature well. Thanks to the experiments got by using the device, which were not only some minutes, but sometimes some ten minutes of use, they started to focus their attention to be distinguished by the device, becoming appropriate for controlling. Since they managed to learn this 'way of thinking', usability of the device became much better, they got more sense of achievement and enjoyed using the device more, having better opinion about the usability of the device too.

TABLE II.
USABILITY TEST

Evaluation at the beginning		Evaluation after practice	
Test subjects	Usability ¹	Test subjects	Usability ¹
1.	3	1.	5
2.	2	2.	3
3.	2	3.	4
4.	3	4.	5
5.	2	5.	3
6.	1	6.	3
7.	4	7.	4
Average	2.42	Average	3.86

¹The maximum mark was 5. 1: not usable, 2: poor usability, 3: limited usability, 4: usable, 5: well usable

TABLE III.
POSITIONING TEST

Evaluation at the beginning		Evaluation after practice	
Test subjects	Accuracy [Mean $\pm$ SD ¹ cm]	Test subjects	Accuracy [Mean $\pm$ SD ¹ cm]
1.	62 $\pm$ 14	1.	18 $\pm$ 5
2.	86 $\pm$ 22	2.	32 $\pm$ 9
3.	undefinable	3.	24 $\pm$ 7
4.	51 $\pm$ 11	4.	17 $\pm$ 6
5.	undefinable	5.	33 $\pm$ 11
6.	undefinable	6.	41 $\pm$ 13
7.	42 $\pm$ 8	7.	25 $\pm$ 7
Average	60.25$\pm$13.75	Average	27.14$\pm$8.29

¹SD: Standard Deviation

VII. CONCLUSION

The article presents the development and test of a brain-computer interface (BCI) system, which controls the speed of a mobile robot, Robotino. The development was implemented during a students' project, which motivated them by the PBL methodology. Tests of the BCI system was performed and evaluated, both regarding the user's experiences and control properties. According to the facts written in the phase describing the results, it can be seen, that the device can not be controlled properly without learning into it, but after learning, easy-to-use applications were created, which test subjects enjoyed to experiment with. Summarizing the results the article shows a BCI system, its application and test for human based control by

brain waves. Of course, this method has got some disabilities yet, but by further development of EEG technology, more and more accurate controlling will become available, which may lead to a wider-spread use of such systems.

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