EEG-based Computer Control Interface for Brain-Machine Interaction

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Abstract—**Recently more and more research methods are available to observe brain activity; for instance, Functional Magnetic Resonance Imaging (fMRI), Positron Emission Tomography (PET), Transcranial Magnetic Stimulation (TMS), Near Infrared Spectroscopy (NIRS), Electroenceph-alograph (EEG) or Magnetoencephalography (MEG), which provide new research opportunities for several applications. For example, control methods based on the evaluation of measurable signals of human brain activity. In the past few years, more mobile EEG (electroencephalogram) based brain activity biosensor and signal processing devices have become available not only for medical examinations, but also to be used in different scopes; for instance, in control applications. These methods provide completely new possibilities in human-machine interactions by digital signal processing of brain signals. In this study, the program model, the establishment, the implementation and the test results of the quantitative EEG-based computer control interface, protocol and digital signal processing application are demonstrated. The user-friendly visualization of the evaluated brain wave signals is implemented in visual C# object-oriented language. This EEG-based control unit and interface provides an adequate basis for further research in different fields of brain-machine control methods regarding the examination of possible machine control applications.**

I. INTRODUCTION

To observe brain activity, a number of devices primarily designed for medical applications can be used. Much research is in progress to observe brain signals in different stages, which can be used in the development of brain-controlled devices among others. To observe brain activity, the following devices are mostly used:

A. Functional Magnetic Resonance Imaging (fMRI)

From the brain mapping technologies listed in the abstract, the most modern is the so-called functional magnetic resonance imaging examination, which can also be used to observe brain activity. This device detects the change of oxygen supply of the blood, which is also called the hemodynamic answer of the brain [1-3].

Nerve activities occurring in the brain can be observed during the bloodstream. When one brain field becomes more active, it takes more oxygen delivered by the haemoglobin in the erythrocyte and it causes larger bloodstream, which occurs after brain activity 1-5 seconds later. The bloodstream reaches its peak in 4-5 seconds, then it falls down to its basic level [12, 13].

By using the fMRI activity map, brain parts participating in certain mental processes as well as the long-term memory or learning processes can be examined [1-4].

B. Positron Emission Tomography (PET)

The positron emission tomography (PET) and fMRI technology are non-invasive techniques to view brain activity. The PET device combined with the Computed [Axial] Tomography (CT) is one of the most modern imaging diagnostic technologies. The basis of the operation of the positron emission tomography is ensured by the molecules signed with isotopes beaming positrons, which makes it possible to visualize the biochemical reactions of the human body [5, 6].

In contrast with the fMRI technology, PET technology uses molecules containing radioactive isotopes that dissolve due to positron emission during its operation and has to be taken into the human system. This means that the examination involves radiotherapy [6].

During the examination, images showing primarily the slices perpendicular to the longitudinal axis of the body can be taken. After the process, three dimensional images can be reconstructed in any direction from the slices [7].

C. Transcranial Magnetic Stimulation (TMS)

The transcranial magnetic stimulation is an electrophysiological process that ensures the possibility to explore bone-covered or deep-laying nerve structures in a non-invasive way [8, 9].

During the TMS process, a copper ring is placed above the skull, the alternation of the magnetic field created by electric current in the ring can penetrate the skull and this creates current in the involved area [9]. The magnetic impulse generated by TMS can usually alternate between 1.5 and 4 Tesla, which causes electric current in the nerve tissues and can cause depolarization of the neural membrane at adequate intensity [10].

D. Functional near-infrared spectroscopy (fNIRS)

fNIR is a non-invasive imaging method to measure the chromophore concentration by near infrared (NIR) light attenuation, temporal or phasic changes. Using fNIR, brain activity can be measured through hemodynamic responses of neurons. fNIR relies on the principle of neuro-vascular coupling, the Hemodynamic or BOLD (Blood-Oxygenation-Level-Dependent) response. This principle is similar to fMRI techniques, so fNIR and fMRI are sensitive to similar physiologic changes and highly correlated results in cognitive tasks [18].

fNIR is much cheaper than fMRI and it is a portable device, but cannot be used to measure cortical activity more than 4 cm deep.

E. *Electroencephalograph (EEG)*

To examine continuous nerve activity of the brain, electrophysiological methods can be used, primarily electroencephalograph (EEG) or rarely magnetoencephalography (MEG). Electroencephalograph is an electrophysiological measuring device and it can record the electric activity of neurons in real time. The signal that can be led by EEG, is called the electroencephalogram, which is a complex, multi-component, periodic curve.

The electroencephalogram can be recorded by two methods: in an invasive and a non-invasive way. In case of the first method, some micron diameter micro electrodes are placed in the brain tissue by drilling a hole through the skull. This method is primarily used in animal experiments, while in case of humans, the non-invasive method is used, by placing low resistance metal macro electrodes on the scalp.

During EEG examinations, the potential difference is always observed between two electrodes. These measurements can be both bipolar, when the curve recorded on two different points of the skull is evaluated by correlation to each other, and unipolar, when potential alternation is compared to a curve recorded by an indifferent or inactive electrode. Leads that do not convey neural activity (a point far from the skull, e. g. the earlobe) are called inactive, reference electrode, while those that detect voltage change as a result of neural activity, are called active electrodes [19-21].

The EEG device measures bioelectric brain signals by electrodes placed on the scalp and visualizes them graphically. The electrodes detect the EEG signals that are generated by voltage pulses of a certain field of the brain and the device examines their alternation and spectrum [14, 22]. The recorded EEG signals above the examined brain field, can provide significant information regarding the activity of a certain brain field [19, 22].

F. *Comparison and application possibilities of brain activity measuring devices*

The fMRI and PET-CT are very expensive and not portable equipment, though they are high resolution brain mapping devices. Therefore, they are used in medical applications only. Furthermore, they have inadequate time resolution. TMS also has some disadvantages; for example, the details of its effect mechanism is not known [11], and it can have unpleasant side effects [9, 10].

The time resolution of fNIRS and EEG-based devices are better; in addition, the newly developed devices are portable. As a result of recent developments, EEG-based mobile devices have become relatively cheap and available; therefore, apart from medical applications, they can be used in other research as well. In the last few years, many research projects have started in the field of human brain controlled machines that apply EEG-based devices.

For instance, EEG technology is used in case of ASIMO (Advanced Step in Innovative Mobility), a device that is a robot similar to a humanoid boy and can be controlled by brain waves [23].

Furthermore, at the German Technical University of Berlin, an EEG signal processing-based system have been developed that can detect the braking intent of the driver 130 milliseconds earlier compared to the braking by pressing the brake pedal. Due to this time difference, the stopping distance of a 100 km/h fast vehicle could be reduced even by 3.7 meters [24].

At the University of Minnesota, a brain-wave controlled helicopter that is able to pass through an obstacle course have been developed. The EEG signals were measured by a cap with 64 electrodes and the helicopter was controlled the processing of the brain waves that occurred by the imagination of different movements (left or right fist grips) [25].

In this study, I present a universal EEG-based computer control interface to implement brain-machine interactions using an open source control protocol.

II. HUMAN BRAIN ACTIVITY

The flow of electrons and ions in the cell induces electric current, which generate voltage on the resistance of this area [1]. Synaptic transmission and the contact places between the cells, through which the stimulus covers from cell to cell, is called synapse (Fig. 1). It is mainly evoked by the cell body of a neuron (axon) and the nerve-ending of another neuron (dendrite). The stimulus transmitter is called presynaptic and the carrier is postsynaptic. During the transmission, the two neurons do not abut totally, the stimulus is transmitted by the so-called neuron transmitters. Once the stimulus is transmitted, the presynaptic nerve excretes chemicals that stimulate the postsynaptic nerve [19, 21].

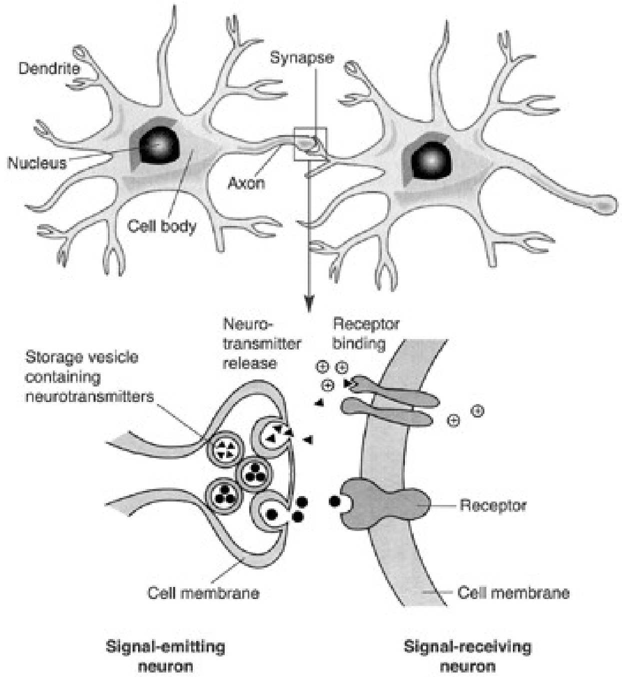

Figure 1. Synapse, the moment of stimulus transmission.

Regarding human brain, it can be claimed that its specific functions during operation are well known. The interpretation of brain waves would not be possible without understanding the operation of the brain, through which the brain waves produced by brain activity are aimed to retrieve and investigate. Such activity can be observed by examining the electrical and magnetic phenomenon of neural functions by the widespread method called electrophysiology.

Brain activity, brain waves and the neural functions of the brain are mostly observed by electroencephalogram (EEG). The processing of EEG signals is usually executed by quantitative EEG (QEEG), by which the frequency spectrum of EEG signals can be investigated [15, 22].

The EEG signal is a complex multi-component periodical wave, which is rich in relatively larger amplitude (8-12 Hz) waves in calm state. The exact source of the EEG signals has not been discovered in details so far. Probably these signals occur as a consequence of aggregated electric activity of several, thousands of neurons located on the surface of the cerebral cortex. Bioelectric signals generated in the brain, or the electric activity of neurons induce some electromagnetic fields. This means that voltage alternations occur by cortex activity.

III. BRAIN WAVES

Brain activity is shown in the spectrum of measurable EEG signals. When our brain becomes „excited" its „talk" becomes faster, just like in case of humans. What our brain wants to „tell" us, can mainly be seen in low frequency waves, between approximately 1 and 12-14 Hz. The occurrence of frequency components is determined by alertness level: in case of increased alertness, generally, high frequency components are experienced, whereas in deep sleep stages delta waves occur.

The detected brain signals given by the EEG device are mostly investigated by Fourier analysis, which separates the signals into frequency components resulting the spectrum of the detected brain wave [22]. Each brain wave frequency component has a specific functional significance as shown in Table I.

TABLE I.
FREQUENCY COMPONENTS OF BRAIN WAVES

Brain wave Type	Frequency range	Mental states and conditions
Delta	0.1Hz to 4Hz	Deep, non-REM sleep, unconscious
Theta	4Hz to 8Hz	Intuitive, creative, recall, fantasy, imaginary, dream
Alpha	8Hz to 13Hz	Relaxed, but not drowsy, tranquil, conscious
Low Beta	13Hz to 16Hz	Formerly SMR, relaxed yet focused, integrated
Midrange Beta	16Hz to 20Hz	Thinking, aware of self and surroundings
High Beta	20Hz to 30Hz	Alertness, agitation
Gamma	40Hz to 80Hz	Motor functions, higher mental activity

IV. THE MOBILE EEG DEVICE

The MindFlex is an innovative control device based on ThinkGear technology developed by NeuroSky and it was introduced in 2009. The device controls the levitating of a ball based on the evaluation of brain wave types that occur during the processing of electric biosignals of the brain received by the EEG headset. The measured real–time brain wave intensity is evaluated by the algorithm running in the micro controller in the EEG headset or in the control computer similarly to other real-time computer systems used in engineering practice [5, 6].

The headset has three sensors; one of them measures the frontal lobe and the other two should be placed on the lower parts of the ear (reference points). Thanks to ThinkGear technology, the digital signal processor in the EEG headset can determine the magnitude of concentration. [16]

The EEG headset forwards the processed signals to the controlled unit (Fig. 2) in a wireless but non-standard Wi-Fi connection [3]. As a result of this, wired serial connection is used to evaluate the EEG data. On this serial line, the read of the processed data sent by the EEG headset was done by an USB-UART decoder [4].

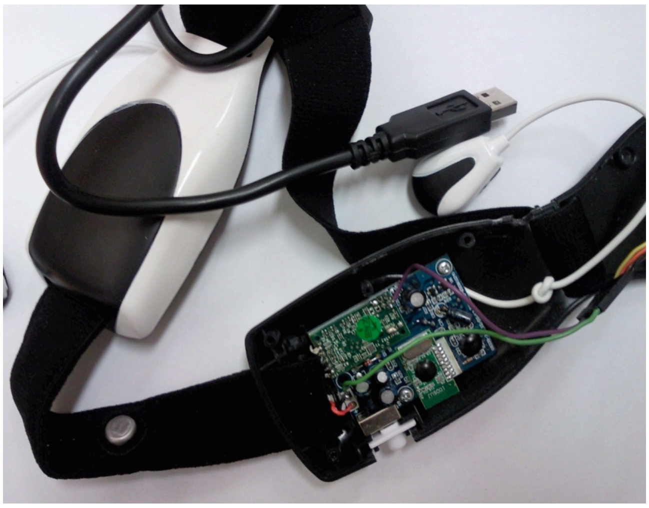

Figure 2. The MindFlex EEG headset.

V. ATTENTION LEVEL AND BRAINWAVES

The connection between attention and brain waves was already observed in the 1970s and an EEG-based attention analyzer was patented (US Patent Number: 3877466, 1975). The method of measuring attention is based on the examination of the spectrum strength determined by the FFT algorithm of brain waves (Cooley, 1965). As a result of the observations, they found that the strength of the alpha brain waves in high attention state is rather low. However, the amplitude of alpha brain waves in low attention state is large. The observed difference between the changes of the brain waves is the base of the patented attention analyzer. The parameters of brain waves can be determined by digital signal processing algorithms, its spectrum can be calculated with discrete Fourier transformation (DTF) algorithm and the results can be evaluated based on the received brain waves strengths. With this method, the strength of brain waves from the spectrum and the level of attention can be defined.

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-i \cdot 2\pi k \cdot \frac{n}{N}} \quad k = 0, \ldots, N-1 \tag{1}$$

VI. VERY SIMPLE CONTROL PROTOCOL (VSCP)

VSCP is a free to use package with open software and firmware tools, highly scalable application level protocol for machine to machine automation tasks. This protocol does not assume anything about the lower level system and can be used for TCP/IP, Ethernet, CAN, USB, RS-232 etc. The complete VSCP has two levels of communication, Level I is designed to CAN but Level II version of the protocol is intended for Ethernet or Wi-Fi. All share the same common message fields and framework. The main advantages of this protocol are its autonomous, distributed device functionality, uniform device configuration, uniform device discovery and identification. [28] In a VSCP network, a common physical layer connects the individual nodes/devices to form the control network. This network is a distributed system with all nodes working autonomously.

VSCP and friends is a collected software package, a complete solution for measurement and control. VSCP uses a well specified message format and the protocol supports global unique identifiers for nodes. It automatically assigns a unique ID to a newly installed node and inform other nodes and possible hosts that a new node is available and ready. It has a register model to give a common interface to node configuration and a model for controlling node functionality. [28]

VSCP is an event-based system. Nodes generate events and nodes react on events. Normally events are not addressed but instead are broadcast on the bus. Each node on the network will receive the event and will decide if this event needs to be handled or not. The example shows a button being pressed Node 1 sending an event message onto the bus informing all others and Node 3 receives the message and decides this button should trigger Lamp 2 to turn on (Fig. 3).

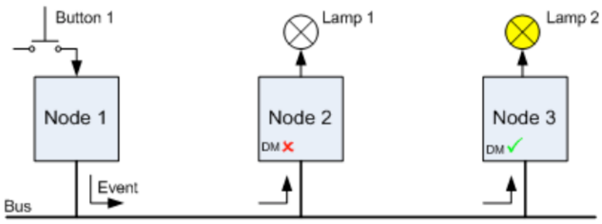

Figure 3. Communication between Nodes

All nodes can optionally implement a decision matrix. This matrix is used to define one or a group of events that should trigger a predefined functionality at the module. Events are defined into classes and types; for example, measurements, information and control. If an event is received, it should be handled by the decision matrix (DM) of the node. All events have an originating address, a GUID - consisting of 16 bytes but a shorter, typically, one byte nickname ID is used on most systems - for the node they are sent from. It is always possible to deduce the full GUID from the nickname. Events are divided into groups. First, there is Level I and Level II events. Level I events are limited to a maximum of eight bytes of data, while Level II events can have up to 488 bytes of data. [29]

A software package called VSCP & Friends is available to support VSCP users and it contains the VSCP daemon. The server makes it possible to control several VSCP segments over the Internet. The server has secure Internet interface and makes it possible to add drivers for segments of nodes or special equipment. A driver can communicate with the server using the CANAL interface for a Level I driver and the TCP/IP interface for a Level II driver. VSCP Works is a client application which can be used to send/receive VSCP events to/from every segment/device that export a CANAL interface and remote VSCP daemon. VSCP is an easy and cost effective way to build systems with distributed intelligence. The protocol is open source, so it is free for anyone to use and modify to their own needs.

VII. THE IMPLEMENTATION OF THE BRAIN VISUALIZATION AND EVALUATION SOFTWARE

The magnitude of brain wave signal is determined with an EEG (electroencephalogram) measuring and processing unit, produced by NeuroSky. The read, the conversion and the various visualization of the measured and processed signals are implemented in the developed software.

A Windows Forms Application has been developed to evaluate and visualize the brain wave data of the MindFlex EEG headset, described in the previous chapter [17]. This program can run on a PC and was implemented in C#. The following requirements have been considered regarding the visualization and evaluation software:

- it should be able to receive data sent through serial communication by the EEG headset;
- it can check if any data transfer errors have emerged during transmission;
- it stores data in adequate format and structure for further procession;
- it illustrates processed data in a column chart for evaluation;
- it can execute data evaluation faster than the data sending speed of the headset;
- in case of the PC software, the investigation of signals and display of the measured and processed data alternation has also been achieved to be able to observe changes in the brain wave signals.

For the software development Microsoft Visual Studio was applied. This development environment supports modern object-oriented programming on Windows operating system.

The developed program can be divided into four main functions: the EEG device data communication, the data processing and analysis, the visualization; furthermore, the control communication with nodes. The EEG device data communication function reads, converts the data received from the headset through serial connection. The data processing and analysis function realize the FFT spectrum analysis, the visualization part displays the spectrum by a column chart and the time function of the brain signal by a line chart. The control communication part realizes the control interactions with other nodes using VSCP protocol. The user interface can be seen in Figure 4.

The source code contains three classes: one of them is the so-called *BrainWaveReaderForm*, which deals with events and derives from the Form class which derives from the source of all classes named Object. *BrainWaveReaderForm* is responsible for data processing and control communication between other nodes. The second class is called the *FormGraphics* class and is responsible for data visualization and is in connection with the *BrainWaveReaderForm* class. The third class is the *SerialPortManager*, which manages the EEG serial port communication. In Figure 5, you can see the flowchart illustrating the main functions of the program.

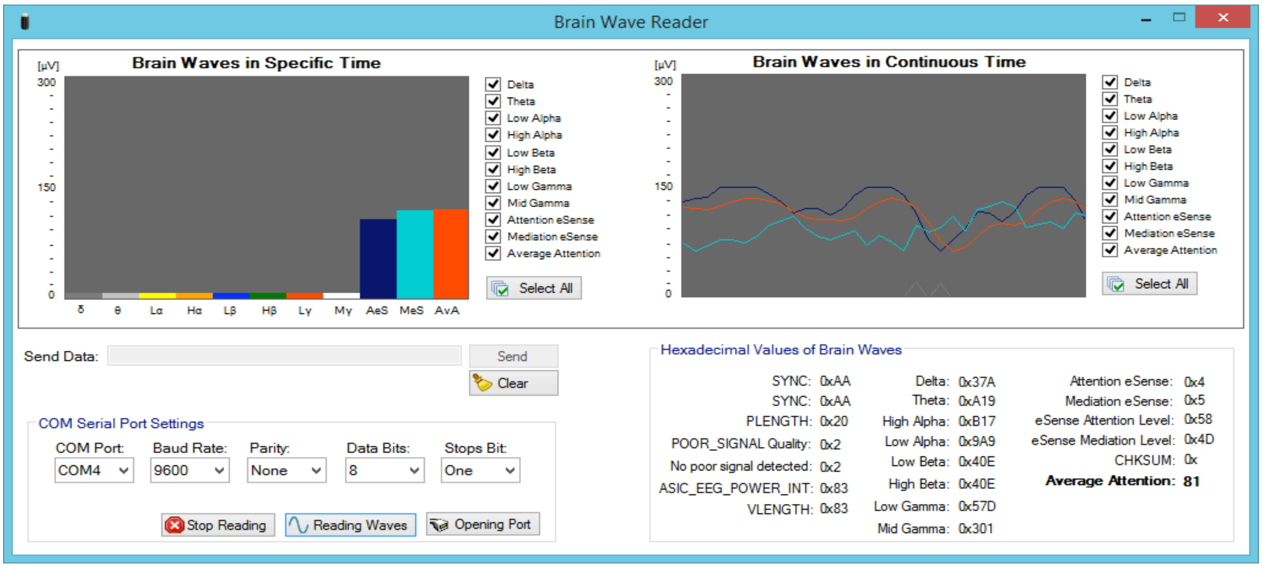

Figure 4. User Interface of BCI data process and visualization software

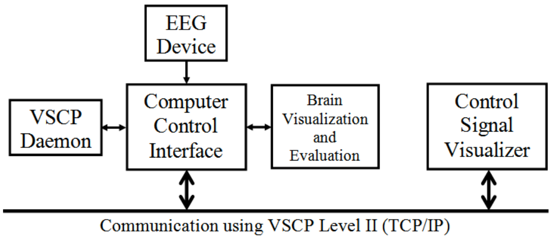

Figure 5. Test environment for control interface

VIII. EVALUATION

The Computer Control Interface system was realized by the own developed Brain Visualization and Evaluation Software and VSCP daemon running on the same computer. The Brain Visualization and Evaluation Software acquired and processed the data coming from the EEG device. The attention signal of the EEG device was applied and sent to the controlled node, which was a Control Signal Visualizer test application. It was a simple data comparator and was run on a different computer. The computers were connected to TCP/IP network. If the attention value was higher than the comparator's level, the red light turned on, otherwise it remained turned off. The comparator level can be adjusted by a track bar.

The control application was tested with continuously measured and processed EEG signal. Users can switch on the light if they concentrate strongly according to the level of the comparator adjusted by the track bar. The test environment and test application is shown in Figure 5 and 6.

The effectiveness of the human brain-controlled system operation, which was described above, was examined by Chi-Square Independence Test statistical analysis. The effectiveness of the control was tested at 50% concentration comparator level while ten test subjects had to switch on the lamp according to a given sequence by varying the concentration intensity during a five minutes test. When the concentration was low the lamp was switched off, and when the concentration was high the lamp was switched on.

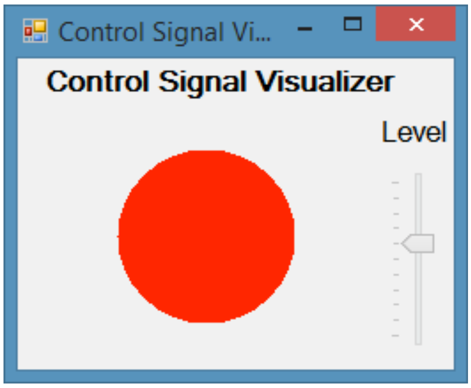

Figure 6. Control Signal Visualizer test application

Data analyses were performed using SPSS statistical software® version 20.0 (SPSS, Inc., Chicago, IL).

TABLE II.
CONTINGENCY TABLE

	brain-controlled lamp off	brain-controlled lamp on	**Total**
desired lamp off	**12**	**6**	**18**
desired lamp on	**7**	**15**	**22**
Total	**19**	**21**	**40**

Chi square = 4.82
Asymp. Sig. = 0.028

Since the P-value is less than the significance level (0.05), we cannot accept the null hypothesis. Thus, we conclude that there is a relationship between desired and brain-controlled lamp status. Regarding the significance test, we report the Pearson Chi-Square value, (degree of freedom = 2) and p-value as in we observed a good association between the current and the preferred brands, $\chi 2(2) = 4.82$, $p = 0.05$.

IX. CONCLUSION

The program described above enable users to investigate how brain wave signals - measured by the EEG headset - alternate in time and how they depend on the changes of concentration. On the basis of the results, the information received from the processing of brain waves can be used in several research areas; for instance, control, multimedia applications or games etc. The program can easily be further developed and added new functions due to its modular build, which can be the basis of future application developments.

It can be established that good relationship is observable between the sequence of control command series and the commands issued according to concentration level. According to the statistical results the technology does not give perfect results, but it can be assumed on the basis of strong correlation value that the technology will be further developed in the future and even the measurement of brain bioelectric activity become applicable for certain human control tasks.

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