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BRAIN COMPUTER INTERFACES FOR MEDICAL APPLICATIONS

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Abstract: *Developing neuroprostheses and advanced communication systems for patients with disabilities has involved considerable scientific and technological efforts. Many recent projects developed software and hardware based on BCIs for such patients. Principles of Brain Computer Interfaces (BCI), technologies used for this type of interfaces and the latest research activities in the field of BCIs are presented in this paper. The concluding chapter synthesize the capabilities of the current BCI systems and formulates some directions for future research needed to understand how BCIs could be used in medical rehabilitation applications.*

Key words: *BCI, human rehabilitation, communication system, recording method, EEG.*

1. Introduction

A Brain Computer Interface (BCI - also called Brain Machine Interface) represents a non-muscular channel for sending messages, "mental commands", to an automated system such as a robot, prosthesis or a cursor on a computer screen [24]. Research made on BCIs at the University of California Los Angeles in the 1970s revealed a new method of communication between humans and machines [26]. After this research activity, most of the developed projects related to BCIs are neuroprosthetics applications aiming at restoring damaged hearing, sight and movement. The major difference between neuroprostheses and BCIs lies in the purpose of the application. Neuroprosthetics connects the nervous system to a device, whereas BCI connects the brain with a computer system.

BCI introduces a direct communication channel between the brain and the external world, providing a special communication and control channel for people with disabilities, but also a new control channel for those without disabilities. The system does actually not use normal output pathways of the central nervous system, as nerves or muscles do, but relies only on the identification and interpretation of the physiological activity patterns in different areas of the brain. Correlations of these areas with the subject's intentions are nowadays well known and could be used for human-machine interaction purposes. Thus, the various applications developed require different areas for signal recording and different signal quality is needed; hence several recording methods are suitable for use: EEG (electroencephalography), FMRI (functional magnetic resonance imaging),

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MEG (magnetoencephalography), PET (positron emission tomography), optical imaging and ECoG (electrocorticography).

Considering the recording method (signals recorded from inside or outside the brain) BCIs systems are divided in two categories: invasive (intracortical) BCIs and non-invasive BCIs. BCI technology could offer new possibilities for impaired people to communicate within an intelligent ambient. In the following chapters previous work on methodologies and applications for both types of BCIs will be reviewed with the aim of investigating the extent to which BCIs could be used as a reliable man-machine interaction for mechatronics and robotics applications in general and in particular for medical purposes.

2. Brain Computer Interfaces

2.1. BCI System

BCI systems offer a new way to communicate between the human brain and a computer. A BCI system analyses the brain physiological activity recorded by electrodes in order to understand the user's intention. A typical BCI system is composed by the following blocks: a data acquisition system, a signal processing system and commands sent to an application (Figure 1).

For the acquisition system, the most frequently used recording method is EEG. This method uses electrodes applied on the scalp; the main advantage of this method is the portability of the recording system. Other methods are invasive, require bulky instrumentation or are very expensive.

The signal processing block processes all the recorded data and transforms the signals in commands for the application. The system must process all the data very fast in order to provide a real-time operation. In order to produce a command, the user must execute a specific activity. Thus the system can associate the produced signals with the generated command. First, the block performs a pre-processing in order to reject artefacts and increase the signal to noise ratio (SNR). It is also used to ensure that the extracted features are not contaminated by EMG (electromyography - electrical activity produced by skeletal muscles), EOG (electrooculography - measurement of eye movements) or some other non-CNS (central nervous system) artefacts.

The features extraction block identifies the parameters from the pre-processed signals allowing thus discriminating between different classes of commands. Some typical features used in developed applications are the root mean square amplitude and power density in certain area of the spectrum. The system can associate the recorded signal with a feature by using a special classifier. After the class feature is identified, the system can associate it with a command for

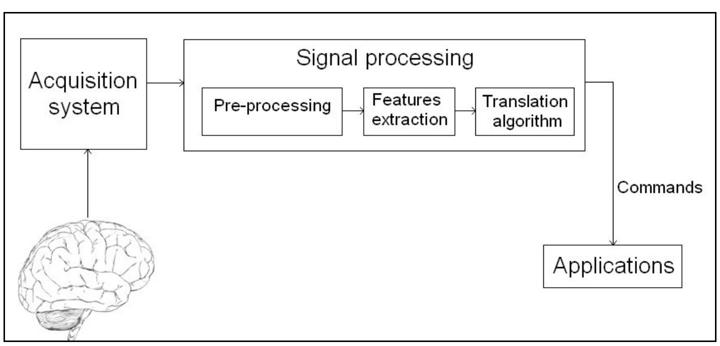

Fig. 1. *Structure of a typical BCI system*

the application. Typical classifiers for BCI applications are: Linear Support Vector Machine (LSVM), Gaussian Support Vector Machine (GSVM), Neural Network (NN), Fisher Linear Discriminant (FLD) and Kernel Fisher Discriminant (KFD).

2.2. Protocols for Invasive BCIs

For invasive BCIs, an array of electrodes is implanted in the grey matter of the patient's brain during a surgery. Electrodes are connected directly to neurons; thus every electrode records the electrical signals directly from the brain. Recognition of different patterns of signals recorded from motor cortex neurons is the key in controlling robotic arms or neuroprostheses [7], [14]. Actual or imagined movements generate neuron spikes at different locations on the recording sites and with systematic training for a specific task neurons will fire in the same locations for different trials.

2.3. Protocols for Non-Invasive BCIs

Non-invasive BCI systems can be characterized based on what kind of imagery or mental tasks the user must perform in order to drive or evoke the command-related EEG response [1]. Thus we can have the next categorization of the typical BCI paradigms [24]:

- P300: represents a positive peak at about 300 ms which is generated in the parietal cortex after an auditory, visual or somatosensory stimulus was presented to the subject [10], [22], [18];
- mu rhythm control: it can be detected over the somatosensory or motor cortex in the 8-13 Hz frequency band. The amplitude of this signal can be controlled by the user in relation to the actual and imagined limb movements or by performing intense mental tasks [1];
- Event Related Synchronization/ Desynchronization (ERS/ERD): these signals are increments (ERS) or decrements (ERD) in specific frequency bands for user imagined or real movements. They are localized over the sensorymotor cortex. Imagined movements represent a preliminary stage of the real movements, but the real movement is blocked in a cortical level;
- Slow Cortical Potential (SCP) [24]: represents slow voltage changes generated in cortex consisting in potential shifts. The changes occur over 300 ms to many seconds [2], [11], [15];
- Short latency Visual Evoked Potential (VEP): these potentials are recorded over the visual cortex in the occipital lobe of the scalp and represent response of the brain to short and fast stimuli.

3. BCI Applications

3.1. Applications with Invasive BCIs

The invasive systems (intracortical) are directly implanted into the grey matter of the brain during neurosurgery. In this way, invasive devices offer a high quality for recorded signals of BCI devices, but the problem is that the body may react to the foreign objects in the brain, creating the possibility of scar-tissue build-up over the implanted device.

Direct brain implants were used to treat blindness (non-congenital, acquired during life). Scientist William Dobelle designed a working brain interface prototype in 1978. The prototype was implanted into the visual cortex of a man blinded in adulthood. The single-array BCI contained 68 electrodes and the prototype succeeded in producing phonophenes, the sensation of seeing light without light actually entering the eye [32].

Another area of BCIs is focusing on motor neuroprosthetics. The aim of these BCIs is to either restore movement of individuals with paralysis or provide some special devices to assist them. Special devices can be different types of interfaces with computers or even robot arms for control. Notable results were first achieved by Philip Kennedy and Roy Bakay. They installed a brain implant in a patient suffering of brainstem stroke and after the patient started to work with the implant, he was able to control the neural signals in an on/off manner [8].

Current research activities aim to create prosthesis for patients with locked-in syndrome. Several approaches were tested in order to find a suitable algorithm/method for a real prosthesis device. Recent studies made on monkeys (Macaca mulatta) proved that invasive methods are suitable for creating a prosthetic robot-arm for control [21]. This study was made by a team from MotorLab at the University of Pittsburgh [31]. Natural arm movements can be recorded in populations of neurons from motor cortex [6], [9], [13], [17], [23]. The results of this research activity proved that recorded cortical signals from motor cortex can be used to control a multi-jointed prosthetic device. The cortical prosthetic device was used for real-time interaction with the physical environment. In addition, the monkey was also able to control the gripper attached at the end of the robotic arm. Microelectrode arrays were implanted in monkey's primary motor cortex. Signals recorded from the electrodes were used to control the robotic arm, thus the monkey was able to feed itself. Food was presented at different locations and the monkey was able to control the position of the robotic arm in order to grasp the food from that location. Monkey's arms were restrained in order for the monkey to pay much more attention in controlling the robotic arm.

Recent work of the same research team has been focused on using the robotic arm in order to control some objects in the environment. They replaced the gripper at the end of the robotic arm with a three fingers control system. This system was controlled using the recorded signals in the same manner as in the first test, but now the monkey was trained to control another object presented in the workable area of the robotic arm by means of this new attached system. The test proved that, by means of signals recorded from intracortical electrodes, a robotic arm can be controlled in the same manner as a natural arm is controlled only by thoughts.

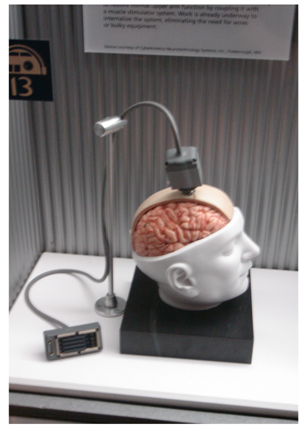

Fig. 2. *Dummy image of BrainGate presented at an exhibition* [27]

Another similar device with the one developed at MotorLab is BrainGate (Figure 2). The system is developed by the bio-tech company Cyberkinetics in conjunction with the Department of Neuroscience at Brown University. Neuroscientist John Donoghue is leading the research project.

The system is a brain implant and is designed to help patients who have lost control of bodily functions, such as patients with spinal cord injury, brainstem stroke or amyotrophic lateral sclerosis (ALS) [28], [30].

The computer chip is implanted into the brain. The chip uses an array of 96 hair-thin electrodes (Figure 3) that convert the electro-magnetic activity of the neurons into electrically signals [5], [20]. Size of the electrodes array is of only 4x4 mm. Signals are decoded by a computer program and used in controlling robotic arms, a computer cursor or a wheelchair. Cathy Hutchinson is

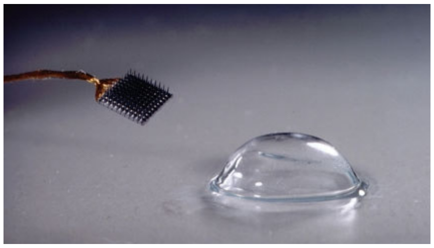

Fig. 3. *Image of electrodes array* [28]

among the patients who volunteered for using the BrainGate system. She is paralyzed and unable to speak, but her brain is sharp. She succeeded to control a cursor on a screen and she is able to operate a computer program for writing, checking emails, navigating on internet and she can even control her wheelchair.

Recent studies, as the projects presented above, aim to offer real-time systems for patients for controlling or for rehabilitation. Some other research activities were also performed on monkeys [7], [16] or even on rats [3], [4], [19]. Moreover, these studies proved that continued training over a specific task can increase the accuracy of the executed task. In addition, these studies revealed the possibility to develop real-time controlling systems such as robot arm controlling systems.

Projects like BrainGate already started using human patients in order to validate the results for practical applications. According to [30], three patients already have been implanted with the BrainGate sytem. In this study individuals with limited or no ability to use both hands due to cervical spinal cord injury, brainstem stroke, muscular dystrophy or amyotrophic lateral sclerosis (ALS) are being recruited.

3.2. Applications with Non-Invasive BCIs

Non-invasive BCIs represent a good alternative for the above method. The common method used for signal recording is the EEG (Figure 4 presents a possible configuration for recording tested at *Transilvania* University of Braşov). The EEG method uses electrodes attached to the scalp using a conductive gel. Signals recorded in this way are used in many experiments with the aim of restoring the movement of patients, controlling different devices, writing just by thoughts. Signal resolution is poor compared with the invasive method. Nevertheless, recent research activities have proved that it is a very good alternative and it is possible by means of different special algorithms developed to achieve similar result as for the invasive method.

A common protocol used for non-invasive BCIs is related to P300 evoked potentials. Most applications based on P300 use a paradigm in which the user faces a screen that may contain letters, numbers or different commands. Each symbol flashes for a number of times chosen before. The user makes a selection by counting each time the symbol flashes. In order to decide which symbol was chosen by the user, different algorithms are used. Usually, P300 applications do not require initial training for the user. The typical communication rate is of about one word (i.e. 5-6 letters) per minute, but the improvement in the ability to select letters faster triggers an increase in the communication rate. Many ALS suffering patients are using this new spelling machine. One remarkable case is

Fig. 4. *EEG configuration for recording*

of the patient Scott A. Mackler, who uses this spelling machine in order to communicate with others and also to continue his research work at a laboratory [29].

Several studies on animals and humans using microelectrodes arrays implanted within the brain have shown the possibility of using recorded electrical activity within the brain to control movements of robotic arms or cursor on a computer screen [6], [21], [23]. One study presents a non-invasive method for controlling a cursor on a computer screen [25]. Previous research activities sustained that only invasive BCIs can offer a multi-dimensional ability for controlling robotic arms or neuroprostheses. In this study, the subject was facing a video screen and, in one trial, one target was appearing on the screen. The subject was asked in each trial to move the cursor, using only mind control, from the centre of the screen to the target. The time allocated for one trial was 10 seconds. The accuracy of the trials was of about 82%, considering the four subjects used for this study.

P300 evoked potentials can also be used for different applications for controlling robot arms [12]. A researcher from Ghent University, Dieter Devlaminck, succeeded in controlling a robotic toy arm by using P300 paradigm for spelling. This test also showed that the non-invasive method is a good alternative in controlling a robotic device. However, the problem for this alternative is the response time: the robotic arm was controlled, but the response of the user's choice was after a few seconds, the time spent by the program to detect user's choice.

One research team from Berlin Institute of Technology succeeded in demonstrating that a non-invasive BCI can be used for controlling a complex real device. The subject was supposed to control a pinball machine only by thoughts. Using complex predictive algorithms, the subject was able to control paddles by imaging movements of left and right hands. In this study, three subjects gained good control, but there were also two subjects that could not establish reliable control.

4. Conclusions and Future Work

From the above literature summary, comparing invasive and non-invasive BCIs, we can draw up some very important conclusions, as follows:

(*i*) Invasive BCIs are currently much more suitable for real-time applications. Recent tests on monkeys proved that, by means of invasive BCIs, robotic arms and prostheses can be controlled in real-time.

Also invasive BCIs on humans are a success, one patient can control a cursor on a monitor, thus the subject can operate a computer only by his thoughts. Still, the biggest problem with invasive BCIs is the high cost of the required special electrodes array. Another problem is that electrodes array must be implanted in the patient's brain; thus, a special expensive surgery is required. Although the patient's brain is not affected, the durability of the electrodes array could decrease. Scar-tissue might grow near the electrodes, thus the quality of recorded signals can be altered or it can even happen for electrodes to stop record signals.

(*ii*) Non-invasive systems are much cheaper than invasive ones, but the main problems raised are related to the computational response time from the system. While real-time applications are required for locked-in patients, the non-invasive methods cannot yet meet such a requirement. Also, these systems offer a very good communication channel for locked-in patients and can be used on a larger scale because of the reduced price. Although the patient cannot generate a message very fast, the BCI still allows communication with other people, which is very important for patients who cannot even move their eyes for answering questions (a typical method used before of BCIs).

Future work for invasive BCIs can be directed in using these systems on a larger scale for human patients as, so far, most available studies were made on monkeys. Further studies on humans are needed to advance towards offering disabled patients a possibility to be independent persons. Nevertheless these systems raise problems as the reliability of the electrodes array the special requirements that can be met only in special institutes and with expensive costs.

For non-invasive BCIs the future studies must be directed towards real-time solution systems. By means of different prediction and pattern recognition algorithms, applications using non-invasive BCI systems can offer real-time solutions. New paradigms for the spelling application could be explored. For example, we can increase the speed of writing a word simply by evaluating the first written letters and then the user can select from a list of possible words without the need of choosing every single letter. Another direction of investigation would be the integration of BCI systems with different platforms like eye-tracking that can enhance the communication for locked-in subjects who can still move their eyes, but every possible alternative has particular problems.

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