The Frontier of Brain-Machine Interface (BMI)
ブレイン - マシンインターフェースの最前線

Qi Zhang

Abstract: A brain-machine interface (BMI) makes it possible to control the machines or computers using the signals directly from the brain. It is also called brain-computer interface (BCI). The development of a BMI system involves the studies from many fields such as brain science, information science, medical science, and engineering science. In this paper, the mechanism of BMI is reviewed and different types of BMI systems based on the invasive/non-invasive brain activity measuring methods are introduced, as well as several advanced BMI researches where the brain activities of human beings were involved. In addition, the social impact of BMI for improving the quality of lives for both patients and healthy persons is discussed. The development of BMI is also expected to bring forward the further understanding of the brain from the academic viewpoints. Finally, the prospects of BMI are surveyed.
Keywords: BMI, BCI, brain activity, fMRI, EEG

要約 : ブレイン - マシンインターフェースは直接脳からの信号を利用しマシンやコンピュータを制御することを可能にした。BMI の開発には脳科学、情報科学、医学、工学等の多分野の関与が必要である。本論文は、BMI の仕組みを説明する上、侵襲・非侵襲の脳活動計測法に基づいた異なるタイプの BMI システムを紹介する。特に、各タイプにおいて人間を対象にした先端的な研究を幾つ取り上げる。また、BMI の社会的なインパクトとして、運動機能喪失の患者さんや健常者に対して、クオリティ・オブ・ライフを向上できることを考察すると同時に、学術上では脳の更なる理解につながることも論ずる。最後に BMI の将来を展望する。
キーワード: ブレイン - マシンインターフェース、ブレイン - コンピュータインターフェース、脳活動、機能的磁気共鳴イメージング、脳波

1. Introduction

A brain-machine interface (BMI) is a system which includes a means for measuring neural signals from the brain, a method/algorithm for decoding these signals and a methodology for mapping this decoding to a behavior or action. Sometimes it is also called brain-computer interface (BCI). Nowadays, because machines are usually controlled by computers, while a computer can be regarded as a machine, BMI and BCI essentially have the same meaning. Both of them are widely used by the scientists, and in this paper, the notation of BMI is used.

BMI is a new technology which involves the brain science, information science and engineering science. In the field of brain science, the brain activities have been studied for a long time. The specific brain activities were able to be observed when certain tasks were conducted. For the healthy persons, these brain activities are transferred to other body nerve systems for further behavior or action. For example, the motor systems will move the hands, arms to finish the motor tasks, such as moving a mouse and clicking the button, typing on a keyboard, or grasping a cup to drink the water. But it might be extremely difficult for the patients (e.g. tetraplegia patients) who have lost the abilities to move their body parts due to certain diseases or damage from an accident to finish even a simple task. Though their brains work normally and generate the same brain activities as that of a healthy person, the patients cannot do anything. They need to ask for others' helps for everything in their daily lives. In the extreme cases, they even cannot move their tongues to say a word.

The invention of BMI changed the situation. BMI made it possible for those patients to control machines or computers by themselves. So far, in engineering field, the controls of machines or computers have been studied by the engineering scientists, and already brought about countless practical applications. The control commands are generated by machine embedded microcomputers or ordinary computer programs. On the other hand, in BMI systems, the brain activity signals are detected somehow and used as the control signals to the machines or computers. The signals of brain activities which are measured when the patients think of certain tasks, are used to operate the machines or computers. For example, the patients can feed themselves with water by controlling a robot arm to grasp the cup and fetch the water to their mouths (Hochberg, et al, 2012). They also can display their messages on the computer screen to communicate with others only by thinking in their brains (Hochberg, et al, 2006). In this way, the quality of life for the patients can be improved dramatically.

Similarly, the healthy persons can also benefit from BMI to conduct the task by only thinking. In extreme cases, machines or computers can be operated automatically from the brain activities even before the feeling activities reach the conscious level. By connecting the studies in the brain science and engineering science together, BMI paved a new way to improve the quality of our lives.

In this paper, how the brain activity signals are measured are explained, and different types of BMI based on different brain activity measuring methods are introduced, as well as several advanced researches in each type. The social and academic impacts of BMI and its prospects are surveyed.

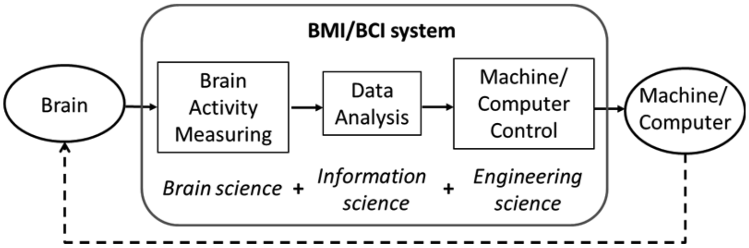

Fig. 1 Schematic diagram of a BMI system

2. Mechanisms of BMI

As mentioned in the last session, the BMI is a bridge between the brain and the machine/computer (as shown in Fig. 1). It includes three processing steps. The first step is to measure the signals of brain activity. The measured signals cannot be used to control the machines or computers directly. They need to be analyzed by information processing technology as the second step. The analysis algorithms and methods developed by the information scientists make it possible to extract the useful signals from the huge amount of measured data. Only these useful signals revealing the relations between the brain activity patterns and the tasks can be used to control the machines and computers. Then these signals are processed again at the machine/computer control step to perform the real control actions.

As the brain measuring technology growing, the number of electrodes or sensors to detect the brain activities became larger and larger. At the same time, more effective and accurate data processing methods are proposed to fit the needs to extract the useful signals. In addition, the machine/computer control units become more advanced to conduct the more and more complicate control tasks. In the following of this paper, the introduction of BMIs is emphasized from the viewpoint of the brain science field at the first step.

3. Different types of BMI

Currently, the brain activity measuring methods can be divided into two types: invasive type and non-invasive type. For the invasive type, surgery operations are necessary to open the skull bones to implant the arrays of electrodes near the neurons in the specific brain areas. In contrast, the non-invasive type needs not to insert anything in the skull.

Corresponding to these measuring methods, the BMI systems can also be divided into invasive and non-invasive systems. In this session, several advanced BMI systems in both invasive and non-invasive types are introduced. Only the BMI using the brain activities from human beings are focused, though there are many other BMIs researches using the brain activities from primates or mammals, such as monkeys, rats or mice.

3.1 Invasive BMI systems

In general, invasive BMI systems relying on implanted arrays of electrodes, are common in experiments involving rodents (Ethier, et al, 2012, Koralek, et al, 2012), nonhuman primates (Velliste, et al, 2008), and the patients (Hochberg, et al, 2006, 2012).

The first invasive BMI placed inside a human brain was the trial with Matthew Nagle in 2004 (Hochberg, et al, 2006). Matthew Nagle was paralyzed from the neck down. Surgeons implanted a tiny array into his motor cortex, which was the first electrode array implanted in the human brain from the company, Cyberkinetics, Inc., of Foxborough, Massachusetts. The array was in the size of about 4x4 millimeters, and with 100 electrodes, each narrower than a human hair. These electrodes acted like 100 tiny microphones suspended in the brain tissue, each able to hear up to a few neurons. They collected the brain activity signals and sent them to a computer.

This system needed a calibration before the actual use. To calibrate the system, Nagle was told to think about moving his hand left or right, as a computer associated the brain pattern with direction. Once calibrated, the computer read signals out of Nagle's brain and moved the cursor accordingly. He could move a cursor on a computer screen with only the power of his thoughts. Soon, Nagle moved the cursor without thinking about his arm. He could check a mock email program, play a simple video game, and even draw a crude circle. This first trial for human being is a milestone of the invasive BMI systems for human beings.

After that, in 2012, the same research group succeeded making two patients with tetraplegia use a neural device to control a robotic arm for reaching and grasping objects (Hochberg, et al, 2012). One patient even could conduct the bottle-grasping and drinking task. This research demonstrated that a BMI system can perform actions that are useful in daily life. Such BMI systems are also called neuroprosthesis devices.

3.2 Non-invasive BMI systems

In contrast to the invasive systems, non-invasive BMI systems use brain activity signals from outside the cortex. The major non-invasive measuring methods are functional magnetic resonance imaging (fMRI), electroencephalography (EEG) and near-infrared spectroscopy (NIRS) methods.

3.2.1 Non-invasive BMI systems based on fMRI

The fMRI measuring methods have been applied in recent years to generate brain images that are sensitive to local changes in blood flow. By acquiring a rapid succession of images that reflect localized changes in cerebral blood flow and oxygenation, fMRI can provide detailed images of localized brain activity induced by sensory, motor, or cognitive tasks with a spatial accuracy of millimeters and a temporal resolution of seconds. Since this technique is non-invasive and poses no known health risks, it is possible to obtain numerous high resolution images from a healthy person. Fig. 2 shows the apparatus of an fMRI scanner.

An example of the BMI system based on fMRI brain activity measuring was developed by Advanced Telecommunications Research Institute International (ATR) and Honda Research Institute Japan Co., Ltd. for manipulating robots using human brain activities (Honda News Releases, 2006). In this BMI system, the untrained healthy person lying in an MRI scanner made a finger gesture, “paper,” “rock” or “scissors,” (Jyan Ken game) while the changes in his/her hemodynamic responses associated with brain activity were monitored every second. Specific signals generating paper-rock-scissors movements were extracted and decoded by a computer program, and the decoded information is transferred to a hand-shaped robot to simulate the

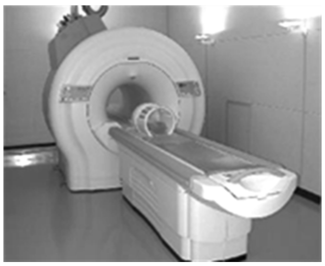

Fig. 2: Apparatus of an fMRI scanner

original movement performed by the subject. This new BMI technology enabled the decoding of natural brain activity of fMRI-based signals and the use of the extracted data for the near real-time operation of a robot without an invasive incision of the head and brain.

3.2.2 Non-invasive BMI systems based on EEG and NIRS

Though fMRI is a major brain activity measuring method, which has high spatial resolution, its temporal resolution is low. In addition, the constraints of the apparatus are very strict. The fMRI system needs to be operated in a shielded room, and the coils should be kept in super-conductive states. The large size and powerful magnetic field generated by the fMRI scanner limit the locations and conditions where it can be used. In contrast, the apparatus of EEG and NIRS are much smaller and are portable. In an EEG measuring, the electrical signals from the brain are measured by hooking up electrodes to the subject's scalp (as shown in Fig. 3). EEGs allow researchers to follow electrical impulses across the surface of the brain and observe changes over split seconds of time. One important advantage of EEG is its high temporal resolution.

On the other hand, NIRS is also a non-invasive, safe, portable brain activity measuring method. It is an affordable optical technique with which to monitor hemodynamic changes in the brain's cerebral cortex. Because of its portability and ease of use, NIRS is amenable to deployment in ecologically valid natural working environments.

In 2009, Honda, ATR and Shimadzu jointly developed a BMI system enabling the control of a robot by human thought alone, based on both EEG and NIRS brain activity measuring (Honda News Releases, 2009). In this BMI system, EEG and NIRS sensors were placed on the head of the user. Then, one of four pre-determined body part options

Fig. 3: The appearances of the experiments for EEG measuring

was provided to the user. The user imagined moving that body part without making any physical movement. Changes in both brain waves and cerebral blood flow triggered by the brain activity were measured simultaneously. The data obtained were analyzed on a real-time basis to distinguish what the user imagined. Upon receiving the result, Honda's ASIMO humanoid robot made corresponding movements such as raising its arm or leg. The world's highest level accuracy rate of more than 90% was achieved in the tests. The brain activity measuring in combination of EEG and NIRS made it possible to distinguish the brain activities with high precision just from human thought alone.

Similar to this research, most of the BMI systems aim the motor systems. Motor imagery of the body or cursor movement for motor prosthesis has been the hottest topic (Blankertz, et al, 2007, Pfurtscheller & Neuper, 2001). However, the majority of people have normal or correctable visual ability, to whom visual perception is the most useful sensation obtaining information from the outside world. By detecting human feeling based on the brain activity, the environment can be adjusted automatically to make the people more comfortable and enjoyable bypassing any consciously involvement. Such BMI systems can be used by healthy people as a further communication path to improve the quality of their lives.

The author conducted a research where a classifier that could distinguish EEG signals responding to visual stimuli was developed (Zhang, 2008). Brightness difference was used as a preliminary case study. In the case of watching on the screen of a TV or a display, the brightness of the TV or the display will give the audience a pleasant feeling if they are watching the contents at proper brightness dynamics. In contrast, when the brightness is too high, people will feel dazzled and easy to get tired. Some image details in the highlight part even get lost. On the contrary, when the brightness is too dark, the details of the images are hard to be represented, and the audience needs to pay extra effort to get the same information as that in the suitable brightness, so that enjoyment of the contents is impaired. All these will give the audience an unpleasant feeling. To distinguish the differences of the brightness, this research developed an EEG-based classifier which could decode the different brightness perceptions based on the non-invasive EEG brain activity measuring. It was aiming people who have normal visual ability to interact with daily electronic device.

4. Discussions

The BMIs introduced as the above mostly take signals from the brain to control machines or computers. These types are called output-type BMIs. On the other hand, there are also BMIs pass signals into the brain to restore lost senses such as hearing, touch, or vision. These are called input-type BMIs. These developments are drawing from and inspiring advances in neuroscience, computer science, and engineering.

BMIs can be applied not only in the fields of medical rehabilitation to unlock the patients from the diseases or injury, but also in the fields of entertainment such as playing games or watching the TV in the more comfortable environment for the healthy persons. Both of them can improve the quality of life (QOL) of human beings.

On the other hand, BMIs are also giving scientists a new way to study the inner workings of the brain as human beings move, feel, remember, and think. Because the development of BMI is based on the studies of the brain activities, the better understanding of the brain mechanism will result in the higher efficiency and precision for the BMI systems. On the contrary, the brain activity generated by the neurons will be adapted to the BMI via the interactions between the brain and the machine/computers, and then make the BMI work more effectively (Koralek, et al, 2012).

Currently, the BMI is one of the hottest interdisciplinary research topics. Many BMIs have been developed. However, the precision of the control is still not enough for the practical applications. There is still a long way to go for the BMI to reach the practical product level.

For the invasive BMI systems, it is generally thought that electrode arrays positioned inside the brain convey more information from the brain activities than non-invasive sensors. However, as well as the risks associated with surgery, a disadvantage of such implants is the potential for scar tissue to form around the electrodes, which can result in a deterioration of signal quality over time. Hochberg and colleagues' work (Hochberg, et al, 2012) is notable in that one patient had had the implanted electrodes for more than five years. But in many cases, the patients will be alive for decades. This issue needs further studies to improve.

On the other hand, the non-invasive BMI developed by ATR and Honda (Honda News Releases, 2006) revealed that fMRI-based neural decoding could allow a robot hand to mimic the subject's finger movements ("paper-rock-scissors") by tracking the hemodynamic responses in the brain. Because the fMRI measuring has the low temporal resolution, there is an approximate 7-second time lag between the subject's movement and the robot's mimicking movement. Though the researchers succeeded in gaining a decoding accuracy of 85%, which is a high accuracy for the current BMIs, it is not enough for a practical use. The accuracy is also the problems for the systems based on EEG and NIRS.

In addition, the ethics issues are necessary to be considered when the BMI researches are conducted. Regulations, rules and guidelines need to be established.

5. Conclusions

In this paper, the BMI which is one of the hottest interdisciplinary research topics was reviewed. Its mechanism was explained and several advanced invasive/non-invasive BMI researches which were based on the brain activity measuring methods of electrode array, fMRI, EEG and NIRS for human beings were introduced. In addition, it was discussed that BMI technology could improve the quality of lives for both patients and healthy persons. The developments of BMI still need and will also bring forward the further understanding of the brain.

References

1. Blankertz, B., Dornhege, G., Krauledat, M., Müller, K., Curio, G. (2007) The non-invasive Berlin Brain-Computer Interface: Fast acquisition of effective performance in untrained subjects. NeuroImage, 37, 539-550.
2. Ethier, C., Oby, E. R., Bauman, M. J., & Miller, L. E. (2012) Restoration of grasp following paralysis through brain-controlled stimulation of muscles, 485, 368-371.
3. Hochberg, L. R. et al (2006) Neuronal ensemble control of prosthetic devices by a human with tetraplegia, Nature, 442, 164-171.
4. Hochberg, L. R. et al (2012) Reach and grasp by people with tetraplegia using a neurally controlled robotic arm, Nature, 485, 372-377.
5. Honda News Releases (2006) ATR and Honda Successfully Develop New Brain-Machine Interface Creating Technology for Manipulating Robots Using Human Brain Activity, Honda Worldwide, May 24, 2006.
6. Honda News Releases (2009) Honda, ATR and Shimadzu Jointly Develop Brain-Machine Interface Technology Enabling Control of a Robot by Human Thought Alone, Honda Worldwide, March 31, 2009.
7. Koralek, A. C. et al (2012) Corticostriatal plasticity is necessary for learning intentional neuroprosthetic skills, Nature, 483, 331-335.
8. Pfurtscheller, G., Neuper, C. (2001) Motor imagery and direct brain-computer communications. Proc. IEEE, vol. 89, 1123-1134.

9. Velliste, M., Perel, S., Spalding, M. C., Whitford, A. S. & Schwartz, A. B. (2008) Cortical control of a prosthetic arm for self-feeding, Nature 453, 1098–1101.
10. Zhang, Q. (2008) EEG-Based Classification of Brain Activity for Brightness Stimuli, Australian Journal of Intelligent Information Processing Systems, 10, 18-27.

Received on Januray 6, 2014.