Signal Acquisition in Brain-Computer Interface

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ABSTRACT
Brain-Computer Interface (BCI) is a system that allows direct communication between brain and computer based on neural activity of the brain. It is radically different from existing interfaces, such as keyboard or eye-tracker, in which that it does not require any part of the body, but allows the user to use only their intent to control computer system.

BCI holds a lot of potential because it is an interface that only relies on brain activity and does not require any muscle control from the patient. BCI could be used to create limb prosthesis that the patient can control only with their thoughts, or restore communication to patients who are completely paralyzed or 'locked in'.

In order to create a successful BCI, it is essential to capture signals of the brain activity in a form that can be interpreted by the computer. However, the current state of signal-acquisition in BCI still leaves much to be desired. The signal acquisition has to be accurate, efficient, in real-time and won't put the patient in too much of health risk. There are two approaches to achieving this. Invasive BCI, which implants electrodes within the scull and acquire signals directly

Author Keywords
Brain-Computer Interface, Invasive BCI, Non-invasive BCI

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
BCI is a system that measures the brain's neuronal activities and transfers them into computer signals, which in turn can be used to manipulate computer system or devices.

BCI opens up many different possibilities. A major driving motivation behind researches on BCI is helping patients who are totally paralyzed (or 'locked in') by amyotrophic lateral sclerosis (ALS), spinal cord injuries, stroke or other neuromuscular diseases. Locked-in or otherwise severely disabled patients cannot use conventional augmentative technologies such as eye-tracker or keyboard, because such technologies require some measure of muscle control. In contrast to this, BCI does not depend on any peripheral nerves and muscles. Therefore, BCI could allow locked-in patients to communicate and interact with their environment. [8, 9] BCI could also be used to help amputees. BCI systems can be employed to create limb prosthesis that the patient can control with their willpower just like they are controlling real arms or legs. [2]

A fundamental step in creating a useful BCI is recording the signals of brain's neuronal activity. However, this is no easy task. Brain rests within the skull and layers of tissues and other biomass, so collecting the data from such enclosed source can be very difficult. [1] Also, the signal acquisition process must fulfill several performance requirements in order for it to be suitable for BCI. The acquired signal must be accurate for BCI to faithfully reconstruct the user's intent; it won't do if the user intended for the cursor to move left, and instead the cursor moved to right. The acquired signal must have high temporal resolution, i.e. high sampling rate; the system should function in real-time and provide user online feedback.

Also, the approachability of signal acquisition as well as its performance must be considered. No matter how well a BCI performs perfectly theoretically, if the system is unusable or dangerous for people, that BCI will be eccentrically meaningless. Many existing BCI-approaches require extensive surgical process that puts the patient in significant health risk. Therefore, there is still extensive research on improving the performance and approachability current BCI signal acquisition methods.

BCIs systems are often categorized based on the method the brain activity are recorded. [1,2,3] One approach, invasive BCI, involves implanting electrodes within the skull and sampling signals directly from to brain. In another approach, known as non-invasive BCI, signal acquisition is made from surface of the head and no surgery or invasive implants are required. Both approaches have advantages and disadvantages. This report will look on both invasive and noninvasive approaches of BCI and address the current challenges that the literature faces; this report will also summarize some of the frontier researches in the area and propose future works that may improve performance and usability of signal acquisition methods even further in the future.

CHALLENGES

Temporal resolution
For an interactive BCI, real-time feedback is essential. When a user intends to move a cursor, the monitor should display these movements accurately. This means that BCI system should be able to sample brain activity in reasonably high speed. Also, as review in [10] explains, in order to allow real-time feedback, acquired signal should be processed as fast as or faster than signal acquisition.

Spatial resolution
Human rain is not a simple single-channel signal generator. Rather, brain is a complex structure which emits numerous signals from multiple regions at a time. According to [9] different regions of brain are associated with different types of neural activities; for example, a region of brain could be responsible for motor control, while another region of brain could be responsible for speech control. In order to create an accurate BCI, the system should first be able to differentiate between signals acquired from one region of brain to another.

Health issues & Long-term stability
Some existing BCI-approaches provide recordings of high spatial and temporal resolution, but at the trade-off of the patient's well-being. As discussed in the material in [1], [2] and [3], many

existing BCIs plant electrodes within the skull and place electrodes embedded into or upon the surface of the brain, which puts the patient in surgical risks, not to mention the great discomfort the patient must go through. Also, even after the surgery, there is a risk of infection as invasive electrodes leave a pathway for infection to enter from external surroundings to the brain.

BCI-Illiteracy

According to [8] and [11] researches show that roughly 10% to 20% of subjects are incapable of successfully operating a BCI system, a phenomenon that has been labeled BCI-illiteracy by the researchers. Because this phenomenon impacts a BCI system's usability regardless of the efficiency of signal acquisition methods, it is a major hurdle that the literature must overcome.

APPROACHES, FINDINGS & METHODOLOGIES

The review will categorize approaches into two different categories - invasive BCI and non-invasive BCI, and go through some of the leading researches in both of these approaches.

Invasive BCI

Invasive BCI is the most obvious and direct solution in measuring brain activity. This approach measures brain activity by using electrodes implanted intracranially [1, 3], thus the title "Invasive".

Invasive BCI was the first form of BCI to be built and tested, and researches on invasive can be traced back as early as 1960s and 1970s. In 1970's, Fetz and colleagues demonstrated through a series of experiments were able to train rhesus monkeys to vonlurteerly control primary motor cortex. [1][3]

The advantage of invasive BCI is the high quality recordings that can be achieved, as recording can be made from individual neurons at very high sampling rates. [1] Invasive BCI-recorded signals could obtain more information and allow quicker responses, which might lead to decreased requirements of training and attention.

However, invasive BCI has many qualities that make it inapplicable to human subjects, as pointed out by different review articles. [1,2,3] Invasive techniques cause significant amount of discomfort to the patient, not to mention the surgical risk involved in opening the skull and embedding electrodes into the brain. [1] Even after the surgery, the patient is still vulnerable to long-term possible health risks; there is a wide range of biocompatibility issues as the body reacts against foreign substance, and also the electrodes leaves pathway for possible infection from external environment to the brain. [3]

Another problem of invasive BCI is that it does not guarantee long-term stability. Recording quality often deteriorates over time, due to scar tissue building up around the electrode, preventing signals being transferred to the system. The user should be able to consistently generate the control signal reliably without the need for frequent retuning. [1,2]

Single-unit recording

Single-units recording BCI takes recording from a single ensemble of brain cells, i.e. a single neuron. [3] In order to record single unit activity, penetrating microelectrodes are implanted a few mm down into the brain, in order to directly sample the brain's neuronal activity. However, as pointed out by review articles such as [1, 3] single-unit recording possesses all the risks of invasive BCI as stated above; therefore, it is rarely ever considered on human subjects in recent days. [1]

Subdural Electrocorticography (ECoG)

ECoG BCI has been a rapidly developing subject in the field of invasive BCI, as it addresses permanency and health issues of invasive BCI mentioned above.

In this approach, subdural electrodes are patched on the surface of the brain, to record ECoG signals of the brain. This way, electrodes are closer to the neuronal activity of the brain compared to non-invasive BCI such as EEG, resulting to higher spatial and temporal resolution and lower signal-to-noise ratio. At the same time, ECoG uses subdural electrodes and does not require electrodes penetrating the brain, and therefore does not possess the high surgical risk and user discomfort the invasive BCI.

Schalk et al. [5] demonstrated that ECoG could be employed to create a BCI system that allows users to perform two-dimensional tasks. In the study, five participants were implanted with subdural electrodes to measure ECoG signals. Then, the participants were trained to manipulate cursors in the computer screen only using their intent, and were asked to perform a series of two-dimensional tasks such as mo

From the results, Schalk et al. validated that ECoG could be used to support two-dimensional tasks. Also, the study claimed that patients participating in ECoG based BCI required only minutes of training to gain achieved two dimensional, control compared to weeks or months or training reported for EEG based BCI. Based on these reasons, the authors argued that ECoG could be a powerful and applicable alternative to existing EEG because ECoG has higher spatial resolution, less susceptibility to noise, wider frequency range and lesser training requirements.

Epidural Electrocorticography (EECoG)

Epidural Electrocorticography (EECog) is a variant of ECoG that addressed some of the health-related problems that ECoG faces.

While ECoG has reduced invasiveness compared to standard single-unit BCI, it still exposes the patient with major health risks. [3] located two main health-related problems regarding ECoG BCI. First, subdural electrodes interfered with the natural buffering system of the brain. Brain is highly soft and plastic organ which moves freely inside the skull, with dura mater separating the brain and the skull. If electrodes are placed on the surface of the brain and routed out through the dura mater it could interfere with brain's normal movements, causing irritation. Second, subdural electrodes can serve as a path for infections to enter from outside environment, through the dura mater, and into the brain.

Gomez-Rodriguez et al [6] concentrated on creating a BCI-based rehabilitation device using epidural ECoG electrodes, which can address both of these problems. By placing electrodes on the surface of the dura rather than the brain, the electrodes can safely anchor to the skull/dura complex and brain/skull motion is left unhindered. Likewise, the outside layer of the dura is part of the peripheral immune system reducing the chances of initiating an infection in the CNS. The only problem was that EECoG is that electrodes will be placed slightly farther from the brain compared to ECoG.

The aim of the research was creating a EECoG-BCI that could be used to create prosthesis that the user could control. In the validation process, it was shown that a patient with paralyzed arm was could generate appropriate EECoG signals with imagined arm movements. It was thought that EECoG could be an appropriate tool to be used in paralysis rehabilitation, with its high performance and minimum invasiveness.

Non-Invasive BCI

Because signal acquisition is made outside the skull, non-i*nv*asive BCI do not have to consider problems such as surgery-related health risks or long-term stability.

Electroencephalography (EEG)

As agreed by review articles [1, 2] and researches [4, 5, 7, 11], the most standard signal acquisition method used for non-invasive BCI systems in recent years must be electroencephy (EEG). In EEG-BCI, electric potential of the brain's activity is measured with multiple devices placed at the scalp of the skull, and the map of brain activity is drawn from theses measurement.

EEG has high temporal resolution, and is able to take measurement every thousandth of a second, making it optimal for real-time BCI which requires fast feedback from the system to the user. However, the biggest advantage of EEG-BCI is its practicality. [4] In EEG, setup takes no more than few hours, and only involves electrodes being fixed on the scalp of the head by applying gel.

A research carried out by Popescu et al. [4] is an example that highlights EEG's such advantages. In this research, the authors created a BCI system that maximized EEG's portability and practicality. Compared to standard EEG systems where up to few dozen electrodes are used, in this research only 6 electrodes were used. Also, to minimize set-up time and user frustration, the authors employed EEG cap; rather than each electrode being placed individually on the participant's scalp, the participant could simply put on a cap that contains all the electrodes arrangements and the set-up would be complete. Finally, the authors deemed standard gel-application time-consuming and frustrating, and developed a dry-EEG cap that does not require any application of gel.

Given such examples, it may seem as if that EEG is the future of signal acquisition. However, EEG does possess certain drawbacks. EEG-based BCIs attempt to analyze the subject's brain activity through measurements of the combined electrical activity of massive neuronal populations. Article in [2] suggested that because of this approach, spatial resolution of EEGs becomes limited as activity generated by different regions of the brain overlap each other. Furthermore, as the signal passes through brain tissue, bone and skin before it reaches the electrodes on patient's scalp, resolution of the signal can decrease significantly. Finally, there is the problem of long training. Training for successful manipulation of EEG system can take days or even weeks, it has been reported. [2]

Functional Magnetic Resonance Imaging (fMRI)

An alternative non-invasive signal acquisition method which addresses the low spatial resolution of EEG is functional magnetic resonance imaging (fMRI). As explained by Sitaram et al. [9], fMRI uses magnetic field to scan blood-oxygen-dependant (BOLD) activity across the entire brain. Many researches show that there is a direct relationship between BOLD and neurotic activity of the brain, allowing BOLD to be used as a reference indicator for BCI measurings. This scan of the BOLD activity is then processed to provide an estimation of the brain's neuronal activity.

Because the 3D scan of the BOLD activity of the entire brain is obtained through magnetic field, fMRI provides measurements that have very high spatial resolution, and show which brain region is going through what kind of neuronal activity. [9]

Sitaram et al.[11], in their review of fMRI BCI, argued that fMRI can be a viable alternative to existing BCI methods such as EEG due to its high spatial resolution. The review article demonstrated that fMRI's high spatial resolution could be employed to measure various brain activities such as emotional processing, control of motor systems and visual perception. The study also discussed how fMRI-BCI could be applied to psychological treatments; if a patient is suffering from a disorder and the region of the brain that causes this disorder is known, fMRI-BCI would be especially suited as it has a higher spatial resolution and could be used target the area of the brain that causes the disorder.

A major downside of fMRI is that, as acquired BOLD data must be evaluated and interpreted into brain activity offline, results become available only after significant delay after data acquisition. This means that fMRI is useful for taking a single recording of the brain's neuronal activity, but not so applicable for creating a real-time BCI for which high sampling rate and real-time feedback for the user is required. To overcome such limitations and achieve real-time fMRI (rtfMRI), researchers are attempting to improve signal acquisition and analysis techniques involved in fMRI.

In 2010, Eklund et al. [9] successfully created and validated such an rtfMRI BCI system. In this research, a real-time fMRI was created by employing efficient analysis algorithms and faster processors. Three subjects were involved in testing the system, and were asked to manipulate cursor in the monitor by imagined movements in hands and toes. Using the system, the subjects were able control the cursor to type in the keyboard and successfully answered questions only using their intent.

Nevertheless, the authors of [9] also admitted that the biggest challenge that fMRI faces still is its temporal resolution. The results showed that each command from the patient was delayed for several seconds, due to the delay that takes for BOLD signal of the brain to reflect the neuronal activity of the brain. According to the authors, the BOLD delay is difficult to eliminate since it is a part of the human physiology. It was suggested that predicting the brain's activity a few seconds earlier could be a viable solution for reducing this delay.

BCI-Illiteracy

Until now, we focused on improving the signal acquisition's performance and health considerations. However, performance still varies substantially between subjects and between each session a subject goes through. In fact, Grosse-Wentrup [11] argued that such variation in performance is one of the main obstacles that modern BCI is facing.

Allison et al. (2008) [5] in his research, proposed a possible approach for decreasing the effect of BCI-illiteracy with a new concept; hybrid BCI. The study, focusing on EEG-BCI, was inspired by the fact that each people produce different EEG activity depending on the task being performed. For example, a subjects who could not produce sufficient brain activity patterns to control an event-related desynchronization (ERD) BCI could produce activity that is adequate to control an steady state visual evoked potential (SSVEP) BCI, and vice versa. Therefore

In order to test the performance of such hybrid system, the study asked participants to perform three different types of tasks on EEG-BCI; an ERD-related task, a SSVEP-related task, and a task that stimulated both ERD-EEG and SSVEP-EEG. The result showed that subjects who could not use produce brain activity necessary ERD or SSVEP BCI could use hybrid BCI. This meant that more people could use a BCI system combining multiple types of BCI.

It was Volosyak et al. [7] who took this concept even further. In this research, a concept called "BCI Wizard" was introduced a system which could automatically find "best BCI approach for each user". The research however did not implement the BCI Wizard itself; rather, the research took the first step in creating the BCI Wizard, by exploring the reactions that individual users had for different BCI paradigms and suggested some possible methods that could allow the system to automatically detect the optimal BCI signal acquisition for each user.

FUTURE WORK

It is clear that invasive BCI provides better quality signal and compared to non-invasive BCI, as signals can be acquired close to the brain. Therefore, more work could be done to improve the approachability of invasive BCI. For example, EECoG approach provides signal acquisition with minimum amount of invasiveness, and more research could be done on this area.

Alternatively, more work could be done to improve the performance of non-invasive BCI. As EEG has limited spatial resolution that limits how much its performance can be improved, alternative non-invasive BCI approaches could provide solution. As fRMI BCI provides a full spatial resolution and is only limited by its data acquisition speed and continuing to improve the speed and performance of fRMI BCI could be a viable solution.

It is likely that decreasing or even eliminating BCI illiteracy should be a major goal in future works on BCI. No matter how much the performance and applicability of existing BCI improves, as long as the BCI illiteracy exists usability of any BCI would effectively be crippled. In order to confront the problem of BCI, the line of research taken by [7] and [8] combining multiple BCI could be explored.

A lot of existing BCI-related topics concentrate on creating a BCI for medical reasons. However, as approaches such as EEG are providing cheaper and more convenient BCI, developing BCI for commercial reasons could be an option for researchers to look into. This would mean focusing less on providing the highest possible quality and speed for BCI regardless of cost and complexity; rather, cost and portability of BCI would become more important factors.

SUMMARY

In this report, we have discussed the current standing of the literature, and derived the successes and existing limitations on the field.

The report covered two alternative approaches to signal acquisition for BCI, invasive and non-invasive, and advantages and disadvantages of both these approaches. The trend of recent researches show that invasive BCIs are imitating non-invasive BCIs by working on improving their approvability, while non-invasive BCIs are imitating invasive BCIs by attempting to increase their performance. It may be that in a near future, a BCI that fully incorporates advantages of both approaches will be developed.

As the report has discussed, a fully functioning, efficient BCI that is usable by all people are yet to be achieved. However, the future is more optimistic; as the research on improving BCI signal acquisition continues, improvements on existing BCI systems and solutions for major problems in the field are emerging. It may be that in a near future, science can provide a full-functioning and usable BCI that would bring humankind even closer to computers.

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