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Application and Prospects of Non-Invasive Brain-Computer Interface (BCI) Technologies

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Abstract:
The BCI technology has long been known as a technology that could transform our modern world entirely. Despite most of the BCI today being invasive, non-invasive BCI are also developing toward its real world implementation. Compared with the traditional ones, non-invasive BCI has provided us with different approaches, making BCI practical and accessible to a broader range of customers. It could empower the individual with disabilities like strokes or neurodegenerative diseases to interact with their environment without doing open-brain surgery. These BCIs could also be customized and provide a treatment that focuses the attention of the patient. Nevertheless, BCI is still faced with several challenges, such as improvement in its accuracy and efficiency. Yet the future is prosperous, Combined with higher levels of computing analysis via artificial intelligence, BCI can achieve furthermore or human could also integrate this technology within their daily life. However, preceding its application, The importance of its infinite potential regarding the danger that could undermine its benefit should be noticed. Despite its drawback concerning ethnic issues, BCI still holds unlimited potential and will continue to reshape the world today, and beyond.

Keywords: Brain-computer interface; non-invasive technology; artificial intelligence.

1. Introduction

Brain-computer interface (BCI) technologies represent a groundbreaking frontier in human-computer interaction. These systems allow its users to operate machines, communicate, or manipulate digital environments through thought alone. BCIs are classified into three main types: invasive, partially invasive, and non-invasive. Invasive BCIs involve implanting electrodes into the user‘s brain to achieve a direct interface, producing high precision but with significant medical risks. Partially Invasive BCIs, including Electrocorticography (ECoG) and Endovascular procedures, would have a lower risk than invasive BCIs and a higher resolution signal than Non-invasive BCIs. Non-invasive BCIs, on the other hand, rely on external sensors like electroencephalography (EEG), magnetoencephalography (MEG), and functional near-infrared spectroscopy (fNIRS) to measure brain activity without the need for surgical intervention.

The development of non-invasive BCI technologies has gained great traction due to their accessibility and relatively low risk. While these systems could yet reach the accuracy of invasive methods, continuous advancements in sensor technology and machine learning are improving their functionality. Today, non-invasive BCIs are already applied in multiple fields, from healthcare and rehabilitation to entertainment, communication, and even military use.

One of the most world-changing applications of non-invasive BCIs is in healthcare. These technologies could benefit individuals with motor impairments, such as those caused by stroke, spinal cord injury, or neurodegenerative diseases. Some examples of the current non-invasive treatment include using brain-controlled prosthetics, wheelchairs, or exoskeletons to restore the mobility of patients. BCIs can also facilitate communication for individuals with conditions like locked-in syndrome through thought-driven typing or speech devices. Furthermore, BCIs are increasingly being used for neurofeedback therapies to treat mental health conditions like anxiety, depression, and attention disorders.

Besides healthcare, the integration of non-invasive BCIs in entertainment is another transforming area of interest. Brain-controlled video games, where players navigate or interact with virtual environments using their cognitive focus, are shown to improve the gamer's ability to focus. The gaming industry would propel along the advancement of Augmented and Virtual reality (AR/VR) to explore more ways to make these systems more responsive and engaging. Whereas in defense and military sectors, BCIs could potentially enhance decision-making, and improve performance for soldiers under high-stress conditions.

While the current implementation of non-invasive BCIs is promising, their future prospects are even more exciting. Innovations in signal processing, miniaturization of sensors, and the integration of BCIs with wearable technology will soon become the present. The development of BCI technology could transform humanity's imagination into reality, such as the machines protracted within science fiction like Cyberpunk 2077. As the technology advances, however, important ethical and privacy concerns must also be addressed. Since BCIs could provide access to brain activity, they also raise questions about the potential misuse of neural data and the need for stringent regulatory frameworks to protect users' cognitive privacy.

This paper will discuss the current application and the future potential of non-invasive BCI technologies. As these technologies continue to evolve, their impact across industries will only grow, revolutionize solutions from healthcare, communication, to military, and our day to day life.

2. Applications of Non-Invasive BCI Technologies

2.1 Healthcare and Rehabilitation

Non-invasive brain-computer interface (BCI) technologies are making significant impacts in healthcare, particularly in rehabilitation for individuals with neurological disorders or motor impairments. These BCIs translate brain activity into commands for external devices, providing ways help the individuals who have lost mobility due to injury or illness. This is typically useful in the rehabilitation of patients suffering from strokes, spinal cord injuries, or neurodegenerative diseases like amyotrophic lateral sclerosis (ALS) and Parkinson's disease [1-3].

One of the current applications of BCIs in healthcare is motor function restoration. After a stroke or spinal cord injury, patients often face challenges in regaining the ability to walk. While traditional physical therapy is usually insufficient for full recovery, BCI technologies offer a better solution. BCIs could enable patients to engage in motor imagery tasks, which activate brain regions responsible for movement. These systems detect brain activity through electroencephalography (EEG) and translate it into commands that control robotic limbs, exoskeletons, or virtual environments. Many studies already show that non-invasive BCI based robotic rehabilitation is practical with a sample of paralyzed stroke patients, recovering their motor functions [4].

In addition to motor recovery, BCIs are being used to improve the quality of life for patients with chronic neurological conditions. For instance, BCIs are being added to assistive devices like brain-controlled wheelchairs, enabling severely disabled patient to navigate and travel around [5]. Furthermore, BCIs could potentially diagnose brain conditions such as epilepsy by monitoring brain activity and possibly predicting seizures [6]. This provides a complementary solution to managing neurological diseases, allowing for early intervention.

Virtual reality (VR)-based rehabilitation is another promising development in this field. Patients can interact with virtual environments through brain signals, creating immersive, engaging experiences that make rehabilitation more enjoyable and effective. Moreover, many research and study reported positive effects of this new treatment

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method. Combining BCIs with VR offers new ways for patients to visualize and practice movements, speeding up recovery while maintaining motivation [7].

2.2 Assistive Communication

For individuals with severe communication impairments due to diseases like ALS, brainstem stroke, or locked-in syndrome, BCIs provide a revolutionary tool for communication. These technologies could allows individuals to express themselves using their brain activity. Non-invasive BCIs, particularly those based on EEG, have demonstrated remarkable progress in enabling assistive communication [8].

These BCIs operate by detecting brain signals generated when the user focuses on certain subject—such as letters or words on a screen—and translating those signals back into what the subject is. Through this method, this technology offers hope for individuals who were previously unable to communicate verbally or in writing. For instance, the P300 speller is a well-known EEG-based BCI system that allows users to select letters from a grid based on their brain's response to visual stimuli [9]. Recent study also shows that spelling with non-invasive BCI is also feasible although with a slightly lower accuracy [10]. Though the communication speed is slower compared to conventional methods or an invasive BCI, non-invasive BCIs do significantly improve the user's life quality with sustainable communicability to some extent.

Moreover, the impact of these systems goes beyond basic communication. They empower individuals with disabilities to reengage in social interactions, express their thoughts, and maintain personal relationships [11]. As non-invasive BCI technology advances, improvements in speed, accuracy, and ease of use are expected, making it more accessible to a greater range of users. Additionally, aligning with the development of artificial intelligence (AI), future BCIs could potentially predict words or phrases based on context, further improving efficiency of communication [12].

2.3 Neurofeedback and Cognitive Enhancement

Neurofeedback, a form of biofeedback that teaches individuals to regulate their brain activity, has gained popularity as a therapeutic tool for the enhancement of mental health. Non-invasive BCIs are playing an important role in this field by providing a connection from the brain to the monitor, showing brainwave activity. Conditions such as anxiety, depression, attention deficit hyperactivity disorder (ADHD) [13], and post-traumatic stress disorder (PTSD) could be improved by using this method [14].

In neurofeedback therapy, individuals learn to modulate their brainwave patterns by receiving immediate feedback from a BCI system. Take a patient with ADHD as an example, this method allows them to train their brains to increase beta wave activity, which is associated with concentration and attention [15]. Meanwhile, theta wave activity are reduced, which is linked to hyperactivity and inattention. Over time, this can lead to sustained improvements in focus and self-regulation, reducing the need for medication.

BCIs also have applications in cognitive enhancement for healthy individuals. Non-invasive BCI could produce a state of calming and relaxing, boosting decision-making abilities and the overall cognitive performance. For instance, BCIs are now being used in peak performance training to help Athletes, eSports players, and professionals [16]. It is also effective in enhancing their endurance of high-stress environments or to improvement upon their reaction times.

2.4 Military and Defense

In military and defense applications, non-invasive BCIs are being used as tools for enhancing soldier performance, decision-making, and situational awareness. The real-time monitoring capability of BCI can be used to optimize training sessions, preparing the soldiers for the demands of combat [17]. By simulating the battlefield condition, soldiers could be train to reduce error in high-stress situations.

Additionally, BCIs are being tested as a means of controlling unmanned vehicles or drones using thought commands [18]. Such technology could even be combined with visual reality, allowing the user to control faster and more precise in the field. These technologies could improve coordination on the battlefield, while minimizing the real-life casualty of any battle.

However, there are concern regarding the use of BCIs for monitoring and potentially manipulating soldiers' mental states. As BCI technologies develop, careful consideration should be required to balance military efficiency with respect for individual rights and ethical boundaries.

3. Prospects of Non-Invasive BCI Technologies

3.1 Advances in Signal Processing and Machine Learning

The future of non-invasive BCIs is closely tied to advances in signal processing and machine learning. One of the current challenges facing all BCIs is the difficulty in accurately interpreting brain signals. These signal are difficult to distinguish from other background activity. Signal processing techniques, which could filter out unwanted information, could improve the quality of brain data collected by non-invasive methods like EEG [19].

Moreover, machine learning plays a critical role in making sense of this data. By training algorithms to identify patterns in brain signals, BCIs can improve their accuracy and responsiveness. These machine learning models can continuously update their information by real-time brainwave. This allows the machine to adapt to the received signal from the brain, enabling it to recognize thoughts [20]. In task like communication assistance, the AI model could generate a more precise message from the user. The classification of different machine learning methods and their usage rates are shown in Figure 1.

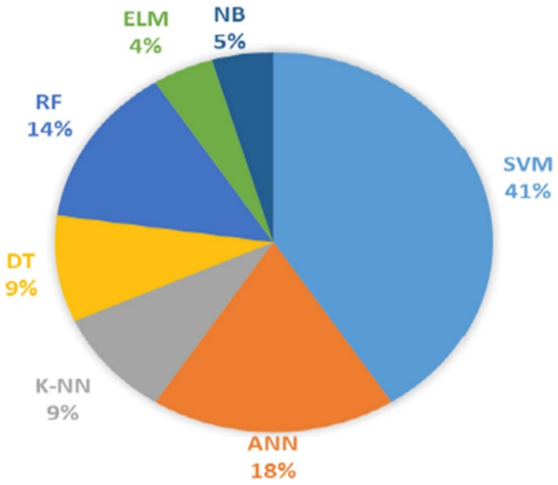

Figure 1 Usage statistics of traditional machine learning methods [21].

Artificial neural network (ANN), Radial basis functions (RBF), Random forest (RF), Decision tree (DT), k-nearest neighbor (K-NN), Extreme learning machine (ELM), Support vector machine (SVM), Naive Bayes (NB).

In addition, advancements in machine learning could enable BCIs to interpret more complex brain activity intentions, including emotions. The classification model was also developed by AI to identify emotions. For example, an experiment of BCI detection of emotions could have an accuracy rate up to 97.56% and with an estimated average of 85% [22]. This result shows that the model generated by machine learning could successfully understand deeper human thoughts.

3.2 Integration with Wearable Technologies

The integration of BCIs with wearable technologies is another area for future development. As sensor development permit it to become smaller, more portable and comfortable, BCIs could then be incorporated into everyday life. Wearable EEG devices, for instance, could monitor brain activity throughout the day [23]. The user then could receive their current mind from the device, which helps them maintain a comfortable mental state.

These wearable BCIs could be used to manage stress, improve focus, or even monitor mental health conditions such as depression or anxiety. The combination of BCIs with augmented reality (AR) and virtual reality (VR) technologies could enable new forms of interaction with digital environments. Researchers could also use the data and the result of AR/VR test to further gain understanding of the interaction of brain waves [24].

Future envision of BCI in the future involves dry electrodes, which do not require conductive gels, will further enhance the usability of wearable BCIs. This adaptation could promote a greater accessibility to the consumer markets.

3.3 Ethical Considerations and Public Reflection

As non-invasive BCIs become more widespread, ethical and privacy concerns will need to be carefully addressed. BCIs have the ability to access and interpret brain messages that is buried within one's mind, which is controversial of whether how much is technology could go [25]. To address these concerns, Governments and industry leaders would need to collaborate on setting new laws and regulations to control this technology.

A survey conducted in the UK shows that over 90% of the respondents are concerned about the possible personality changes after BCI. And that over half of the responded wrong about BCI being hacked [26]. Most of the result reported issues about the current price and the historical evidence regarding BCIs. Although there does exist a problem regarding BCI entering the market, there are also positive results from the survey, such that the majority of people would prefer a non-invasive BCI to enhance cognitive abilities. Also, despite the issue mentioned above, most of the participants had never used a BCI before, although the sample shows that most of them are curious. This demonstrated that the market is still not yet ready for revolution of BCI and that people needed time before they could fully accept BCI in their lives.

4. Conclusion

The applications of non-invasive BCIs are vast, including fields like healthcare, communication, cognitive enhancement, military, and consumer technologies. As more and more non-invasive BCI are already being implemented, the future depicted in sci-fi stories could have just become our future. It is also expected to find a notable increase in

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BCI's usage in the proceeding decade. Advancements and integration made alongside BCI like signal processing and wearable technology would continue to reshape the entire world. AI, particularly, could formulate and eventually predict the instructions signal received from the brain, raising the possibility of erasing the distinction between brain and machine entirely. BCIs will become more accurate, accessible, and efficient in casual life. However, with this growth comes the responsibility to address ethical concerns and ensure that BCI technologies are developed and used in ways that respect individual rights and privacy. Preceding the widespread and the commercialization of BCI, humanity as a whole, must recognize the potential danger of this field and that this power should only be allowed for the benefit of people. Yet, the future development of non-invasive BCIs seemed bright, withholding infinite potential to revolutionize how to interact with technology, our environment, and each other.

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