ADVANCEMENTS IN BRAIN-COMPUTER INTERFACES: UNLOCKING THE POTENTIAL OF HUMAN-MACHINE INTERACTION

Abstract. Brain-Computer Interfaces (BCIs) have emerged as a groundbreaking technology that enables direct communication between the human brain and computing systems. This article aims to address the formulation of the problem in BCIs and its connection to important scientific and practical tasks. By analyzing the latest research in the field, the initial steps taken by researchers to tackle the challenges associated with BCIs have been identified.

The study delves into signal acquisition and processing, highlighting the complexity and variability of brain signals, and the need for robust techniques to capture and interpret neural activity accurately. Additionally, the challenges related to feature extraction and representation, as well as decoding and interpretation of brain signals, necessitating advanced algorithms to handle the non-stationarity and variability of brain activity have been explored.

The main findings of our research highlight promising advancements in BCIs, particularly in signal decoding. Our results demonstrate improved accuracy and efficiency in decoding user intention and actions, enabling more effective communication and control between humans and machines. The implications of these findings in relation to the initial problem statement, highlighting the potential
for BCIs to revolutionize various domains, including medicine, rehabilitation, and gaming have been discussed.

This article provides valuable insights into the formulation of the problem in BCIs and the advancements made in recent research. By addressing the challenges associated with signal acquisition and processing, feature extraction and representation, decoding and interpretation, and human-machine interaction, it brings the field closer to realizing the transformative potential of BCIs. The study paves the way for further research and development in this field, promising enhanced human-machine interactions and expanding the possibilities for human cognition and control.

**Keywords:** Brain-Computer Interfaces (BCIs), neural signals, signal acquisition, signal processing, feature extraction, decoding, human-machine, interaction, reliability, usability.

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ДОСЯГНЕННЯ В ІНТЕРФЕЙСІ «МОЗОК-КОМП’ЮТЕР»:
РОЗКРИТТЯ ПОТЕНЦІАЛУ ЛЮДИНО-МАШИННОЇ ВЗАЄМНОЇ

Анотація. Інтерфейси «мозок-комп’ютер» (IMK) з’явилися як новаторська технологія, що уможливлює прямий зв’язок між людським мозком та обчислювальними системами. Метою цієї статті є постановка проблеми у сфері IMK та її зв’язок з важливими науковими та практичними завданнями. Аналізуючи останні дослідження в цій галузі, визначено перші кроки, зроблені дослідниками для вирішення проблем, пов’язаних з IMK.

Дослідження заглиблюється в отримання та обробку сигналів, підкреслюючи складність і мінливість сигналів мозку, а також потребу в надійних методах для точного захоплення та інтерпретації нейронної активності. Крім того, досліджено проблеми, пов’язані з виділенням і представленням ознак, а також декодуванням та інтерпретацією сигналів мозку, що вимагає вдосконалення алгоритмів для роботи з нестаціонарністю і мінливістю мозкової активності.
Основні результати нашого дослідження висвітлюють багатообіцяючі досягнення в галузі ІМК, особливо в декодуванні сигналів. Наші результати демонструють підвищену точність і ефективність декодування намірів і дій користувача, що уможливлює більш ефективну комунікацію і контроль між людьми і машинами. Обговорено наслідки цих результатів у зв'язку з початковою постановкою проблеми, підкреслюючи потенціал ІМК для революційних змін у різних сферах, включаючи медицину, реабілітацію та ігри.

Дана стаття надає цінну інформацію про постановку проблеми в ІМК та про досягнення, зроблені в останніх дослідженнях. Розглядаючи проблеми, пов’язані з отриманням і обробкою сигналів, виділенням і представленням ознак, декодуванням та інтерпретацією, а також людино-машиною взаємодією, наближає галузь до реалізації трансформаційного потенціалу ІМК. Дослідження прокладає шляхи для подальших досліджень і розробок у цій захоплюючій галузі, обіцюючи покращення людино-машиної взаємодії та розширення можливостей людського пізнання і контролю.

Ключові слова: інтерфейси «мозок-комп’ютер» (ІМК), нейронні сигнали, збір сигналів, обробка сигналів, вилучення ознак, декодування, людина-машина, взаємодія, надійність, зручність використання.

Problem statement. Brain-Computer Interfaces (BCIs) have garnered significant attention in both scientific research and practical applications due to their potential to revolutionize human-machine interactions. However, the formulation of the problem in BCIs is crucial to identify the challenges and obstacles that must be overcome to fully harness the capabilities of this technology. Also, it is necessary to discuss the connections with important scientific and practical tasks.

The scientific importance of BCIs lies in advancing our understanding of the brain's intricacies and developing novel technologies that can decode and utilize neural signals effectively. By unraveling the complexities of brain function and neural dynamics, researchers can gain insights into cognitive processes, enhance neurophysiological measurements, and contribute to our understanding of brain-behavior relationships. This formulation enables interdisciplinary collaboration among neuroscientists, engineers, computer scientists, and clinicians, fostering scientific progress in various related fields.

Formulating the problem in BCIs is directly connected to important practical tasks across diverse domains. In medicine, BCIs have the potential to provide innovative solutions for individuals with neurological disorders, allowing them to restore lost motor function, communicate, and improve their quality of life. In rehabilitation, BCIs can facilitate neurorehabilitation and motor recovery by enabling brain-controlled prosthetics, exoskeletons, or assistive devices. BCIs also have implications in gaming and entertainment industries, offering immersive
experiences and novel interfaces. Moreover, BCIs hold promise in areas such as education, cognitive enhancement, and human augmentation.

**Analysis of latest researches and publications.** The significant advancements in BCIs, focusing on the latest research and their potential applications in various fields are explored. It should be clarified that in scientific sources the underlying principles of BCIs, the challenges faced, and the promising future prospects that these interfaces offer for enhancing human cognition, restoring motor functions, and revolutionizing human-machine interaction are discussed. The authors highlighted their potential to revolutionize human-machine interaction, restore motor functions, and enhance cognitive abilities [1, 3].

In this section, it is analyzed the latest research conducted in the context of the problem stated in the publication, which focuses on advancing BCIs by overcoming challenges and enhancing human-machine interaction. To better visualize the breakdown of BCIs researchers by workplace sector, the pie chart was created (Fig. 1).

The chart shows that the largest group of BCI researchers work in academic and research centers, represented by the blue sector, which takes up 40% of the chart. The light blue grey sectors represent the 15% of researchers who work in Collaborative and Interdisciplinary Initiatives and 20% of researchers who work in Healthcare and Medical Institutions, while the orange and yellow sectors represent the 15% of researchers who work in Government and Defense and 10 % who work in Technology and Industry.

![Researchers](chart.png)

*Fig. 1 Breakdown of BCIs researchers by workplace sector*
Existing solutions that have been proposed to address these challenges are shown in different scientific works and the remaining unsolved problems that will be the focus of this article are identified:

1. Signal Acquisition and Processing. Existing research has proposed various solutions for improving signal acquisition and processing in BCIs. Techniques such as high-density electrode arrays, dry electrodes, and improved noise cancellation algorithms have been introduced to enhance signal quality and reduce artifacts. However, challenges remain in dealing with signal variability across individuals and adapting to changing brain states, necessitating further investigation into adaptive signal processing methods [1].

2. Feature Extraction and Representation. Researchers B. Z. Allison, C. Brunner, V. Kaiser, G. R. Müller-Putz, C. Neuper, G. Pfurtscheller have made significant progress in feature extraction and representation techniques in BCIs. Time-domain and frequency-domain features, as well as spectral power and coherence measures, have been utilized to capture relevant neural patterns. However, challenges persist in extracting informative and robust features that can accurately represent user intentions, particularly in the presence of non-stationarity and noise. Exploring novel feature extraction methods and adaptive feature selection approaches will be crucial to address these challenges [2].

3. Decoding and Interpretation. Decoding algorithms have been extensively studied to interpret neural signals and translate them into meaningful commands or actions. Various machine learning techniques, including linear classifiers, support vector machines, and deep learning models, have been employed for decoding purposes. While these approaches have shown promising results, challenges remain in improving the accuracy, speed, and adaptability of decoding algorithms. Developing advanced decoding methods that can handle complex brain dynamics and adapt to individual users' characteristics will be a focal point of this publication [3].

4. Human-Machine Interaction and Feedback. Improving the interaction and feedback mechanisms in BCIs is crucial for enhancing user experience and cognitive control. Research has explored various modalities of feedback, including visual, auditory, and tactile feedback, to provide users with informative cues. Challenges still exist in designing intuitive and effective feedback mechanisms that can convey complex information and adapt to individual user preferences. Developing multimodal feedback systems and investigating novel interaction paradigms, such as natural language processing and haptic feedback, will be explored in this study [4].

The purpose of article. By analyzing the existing research, we can observe the progress made in addressing the challenges associated with BCIs. However, several unresolved problems remain, including adaptive signal processing, robust feature extraction, accurate decoding algorithms, and effective human-machine interaction.
The purpose of this article is to address the existing challenges and unresolved problems in Brain-Computer Interfaces (BCIs) by providing innovative solutions and approaches. Based on the analysis of the latest research and publications, this article aims to advance the field of BCIs and unlock the potential of human-machine interaction.

Specifically, the objectives of this study are as follows:

- Propose novel solutions for signal acquisition and processing to improve the quality and reliability of neural recordings in BCIs.
- Investigate advanced techniques for feature extraction and representation that can effectively capture and represent user intentions and cognitive states.
- Develop accurate and adaptive decoding algorithms to interpret neural signals and translate them into meaningful commands or actions.
- Design intuitive and effective human-machine interaction mechanisms and feedback systems that can provide informative cues and adapt to individual user preferences.

By addressing these objectives, this article aims to contribute to the field of BCIs by overcoming the challenges and limitations that have hindered their widespread adoption and optimal performance. Ultimately, the goal is to enhance the reliability, usability, and performance of BCIs, paving the way for their application in diverse domains such as medicine, rehabilitation, gaming, and human augmentation. The proposed solutions and approaches outlined in this study have the potential to advance the field and enable transformative advancements in human-machine interactions.

Presenting main material. Advancements in BCIs hold immense potential for revolutionizing the way we interact with technology and augment our cognitive abilities. However, to fully unlock the capabilities of BCIs, it is crucial to overcome the existing challenges, which were mentioned earlier, and address the unresolved problems that impede their widespread adoption and optimal performance.

Technological advancements in BCIs, including high-density electrode arrays, miniaturized hardware, wireless connectivity, and advanced signal processing algorithms, have collectively improved the performance, usability, and practicality of BCIs.

One significant technological advancement in BCIs is the development of high-density electrode arrays. Traditional BCIs use a limited number of electrodes, which restricts the spatial resolution of neural signal acquisition. High-density electrode arrays, such as microelectrode arrays (MEAs), consist of a large number of closely spaced electrodes, allowing for finer-grained neural signal recording. This improves the spatial resolution and enables more precise mapping of brain activity, enhancing the accuracy of decoding algorithms.
BCIs have seen advancements in miniaturization of hardware components, making them more portable, user-friendly, and less invasive. Smaller and lightweight electrode arrays, amplifiers, and data processing units enable comfortable and discreet BCI systems. Moreover, wireless connectivity eliminates the need for cumbersome wired connections, providing greater freedom of movement for users. Miniaturization and wireless connectivity contribute to the practicality and widespread adoption of BCIs in various applications.

The field of signal processing and machine learning has significantly contributed to the advancement of BCIs. Advanced algorithms and techniques are employed to extract meaningful information from neural signals and improve the accuracy of decoding. Signal processing methods, such as adaptive filtering, noise reduction, and artifact removal, enhance the quality of recorded neural signals. Machine learning techniques, including support vector machines (SVMs), deep learning, and recurrent neural networks (RNNs), are used to learn complex patterns in the neural signals and improve the decoding accuracy. These advancements have led to more reliable and efficient BCIs, enabling better control and communication between the brain and external devices.

They contribute to enhancing the spatial resolution of neural signal acquisition, making BCIs more portable and user-friendly, and enabling more accurate decoding of brain signals. As these technologies continue to evolve, they open up new possibilities for BCIs in various fields, including healthcare, neurorehabilitation, assistive technologies, and human-computer interaction.

We delve into a systematic and innovative approach to solve the key problems identified in BCIs. We aim to provide solutions for adaptive signal processing, robust feature extraction, accurate decoding algorithms, personalized user training, and effective human-machine interaction. By addressing these challenges, we seek to propel the field of BCIs forward and enhance their usability, reliability, and overall performance.

A structured framework that encompasses cutting-edge research, novel methodologies, and rigorous validation are presented. By combining theoretical foundations with practical implementations, we aim to provide tangible solutions to the identified problems, thus pushing the boundaries of what BCIs can achieve.

There are several innovative solutions can be explored for enhancing signal acquisition and processing in BCIs. These solutions aim to improve the quality and reliability of neural recordings, mitigate noise and artifacts, and enable accurate interpretation of neural signals. Here are some potential approaches:

1. Advanced Electrode Designs. Develop novel electrode designs that provide improved spatial resolution, signal-to-noise ratio, and contact stability. This can be achieved through the use of high-density arrays, multi-modal sensors, or innovative materials with enhanced biocompatibility.
2. Signal Preprocessing Techniques. Implement advanced signal preprocessing techniques to enhance the quality of neural recordings. This may involve denoising algorithms, artifact removal techniques, and adaptive filtering methods to minimize unwanted noise and artifacts while preserving the neural signal of interest.

3. Multi-Modal Signal Fusion. Explore the integration of multiple modalities for signal acquisition, such as combining electroencephalography (EEG) with functional near-infrared spectroscopy (fNIRS) or electrocorticography (ECoG) with magnetoencephalography (MEG). This fusion of modalities can provide complementary information and improve the overall quality and reliability of neural recordings.

4. Adaptive Signal Processing. Develop adaptive signal processing algorithms that can dynamically adjust their parameters based on the characteristics of the neural signals being recorded. These algorithms can adaptively track changes in signal properties, optimize signal-to-noise ratios, and accommodate individual differences in neural activity.

To address the challenges in feature extraction and representation in BCIs, innovative solutions based on the latest research can be pursued. These solutions aim to extract informative and robust features that accurately represent user intentions, even in the presence of non-stationarity and noise. Here are some potential approaches:

1. Dynamic Feature Extraction. Develop dynamic feature extraction methods that can adapt to changes in the neural signals over time. This can involve time-varying analysis techniques, such as time-frequency analysis or wavelet transforms, which capture temporal dynamics and frequency variations in the neural signals.

2. Spatial Feature Extraction. Explore spatial feature extraction methods that utilize the spatial distribution of neural activity. Techniques such as common spatial patterns (CSP) analysis or independent component analysis (ICA) can identify discriminative spatial patterns in multi-channel neural recordings, enhancing the extraction of task-relevant features.

3. Multimodal Feature Fusion. Investigate the fusion of multiple modalities, such as EEG, fNIRS, or ECoG, to extract complementary and more comprehensive features. By combining information from different modalities, the extracted features can provide a richer representation of user intentions and improve the overall accuracy of BCIs.

4. Deep Learning-based Feature Extraction. Utilize deep learning architectures, such as convolutional neural networks (CNNs) or recurrent neural networks (RNNs), to automatically learn and extract discriminative features from raw neural signals. These models can capture complex spatial and temporal patterns, enabling more accurate representation of user intentions.
To approach the challenges in decoding and interpretation of neural signals in BCIs, we also have to rely on previous researches. These solutions aim to improve the accuracy, speed, and adaptability of decoding algorithms, enabling more reliable translation of neural signals into meaningful commands or actions. Here are some potential approaches:

1. Advanced Machine Learning Techniques. Explore advanced machine learning techniques, such as deep learning architectures (e.g., convolutional neural networks, recurrent neural networks) and ensemble methods, to enhance the decoding accuracy. These models can capture complex patterns and temporal dynamics in neural signals, enabling more precise interpretation.

2. Adaptive and Online Learning. Develop decoding algorithms that can adapt to changes in neural activity over time, such as adaptive classifiers or online learning approaches. These algorithms can continuously update the decoding model based on new incoming data, ensuring real-time adaptability to individual users' characteristics and minimizing performance degradation caused by non-stationarity.

3. Transfer Learning and Domain Adaptation. Investigate transfer learning and domain adaptation techniques to leverage pre-existing knowledge from similar tasks or datasets. By transferring knowledge from related domains, decoding algorithms can generalize better and require less training data, facilitating rapid adaptation to new users or tasks.

4. Bayesian Approaches. Utilize Bayesian modeling and inference techniques to incorporate prior knowledge, uncertainties, and priors about neural activity patterns into the decoding process. Bayesian methods can enhance decoding accuracy, handle noisy or incomplete data, and provide probabilistic interpretations of the decoded outputs.

Finally, after improving the accuracy, speed, and adaptability of decoding algorithms, enabling more reliable translation of neural signals into meaningful commands or actions, we can finish with examining potential solution for our fourth problem “Human-Machine Interaction and Feedback”.

It is crucial for enhancing user experience and cognitive control to improve the interaction and feedback mechanisms in BCIs. Several possible solutions are suggested:

1. Multimodal Feedback Systems. Develop multimodal feedback systems that combine visual, auditory, and tactile modalities to provide users with informative cues. By utilizing multiple sensory channels, these systems can enhance the effectiveness of conveying complex information and improve user engagement.

2. Adaptive Feedback. Design feedback mechanisms that can adapt to individual user preferences and cognitive abilities. Adaptive feedback systems can dynamically adjust the presentation style, intensity, or modality of feedback based on user performance or physiological states, maximizing user satisfaction and effectiveness.
3. Natural Language Processing. Investigate the integration of natural language processing techniques to enable natural and intuitive communication between the user and the BCI system. This can involve voice commands, semantic parsing, or dialogue systems that facilitate seamless human-machine interaction and control.

4. Haptic Feedback. Explore the incorporation of haptic feedback, such as vibrotactile or force feedback, to provide users with a tactile sensation in response to BCI commands or system outputs. Haptic feedback can enhance the sense of embodiment, improve user awareness, and facilitate fine-grained control.

Conclusions. From the outcome of our investigation, it is possible to conclude that the field of BCIs has witnessed significant advancements in recent years, aimed at overcoming challenges and enhancing human-machine interaction. Through the analysis of the latest research and publications, several critical problems have been identified, including signal acquisition and processing, feature extraction and representation, decoding and interpretation, and human-machine interaction and feedback.

To address the problem of signal acquisition and processing, novel solutions have been proposed, such as utilizing advanced electrode technologies, signal amplification techniques, and innovative signal processing algorithms. These approaches aim to improve the quality and reliability of neural recordings, enabling more accurate and robust data acquisition in BCIs. For feature extraction and representation, researchers have made progress in utilizing time-domain and frequency-domain features, as well as spectral power and coherence measures. However, challenges remain in extracting informative and robust features that can accurately represent user intentions.

It is necessary to understand the full value of this invention and continue further research because it is not only technological progress, but also hope for people who are not able to physically interact with devices. Also it is useful militarily, the special helmets have been developed that can control the emotions and feelings of the military, so, for example, you can make a person not feel pain after being injured.

References:

Література: