

Brain-Computer Interfaces

Pietro Boiardi, Beatrice Campo, Maria Ruiz Izquierdo

Abstract - The current report aims to define what Brain-Computer Interfaces are, review the current state-of-the-art techniques harnessed to develop and design such devices, outline the limitations and existing drawbacks to overcome, analyze the categories of the intended users that may find such technology beneficial, describe the current clinical and non-clinical applications and likely developments that might arise in the future. Furthermore, this report focuses on the electrophysiological-based BCI existing implementations in order to describe the different approaches to signal recording for further processing and feature extraction. Different technological pathways that entail magnetic or metabolic functional imaging are thus discarded because of the limited practicality.

Keywords: *Brain-Computer Interfaces, Neural Signals, Electrophysiology, Functional Restoration*

I. INTRODUCTION

Over the last four decades the scientific community has progressively shifted the field of Brain Computer Interfaces from mere scientific speculation to active research.

This shift was motivated by the hope of restoring some degree of independence in patients severely affected by disabilities or of extending human control over external devices by bypassing normal peripheral nervous pathways and muscles.

The research objective has focused on the understanding of the translation of bio-electrical signals detected from the human brain source into effective communication outputs and controls for external devices.

A Brain-Computer Interface (BCI), also known as a Brain-Machine Interface (BMI), is a direct communication pathway between the brain's electrical activity and an external device, typically a computer or robotic limb. BCIs enable real-time interaction by translating the user's neural signals, which reflect their intentions, into specific commands or actions. The concept of a brain-computer interface was first introduced in the early 1970s by Jacques Vidal at the University of California, Los Angeles [1].

Vidal's groundbreaking work laid the foundation for this field of research, which has since expanded to encompass a wide range of applications in assistive technology, rehabilitation, and human augmentation.

BCI is an emerging technological solution that holds promise to help individuals classified as *locked-in*— which means cognitively intact but lacking muscular functions (such as those with late stage amyotrophic lateral sclerosis, severe ischemic conditions, or total spinal paralysis)— to restore minimal contact with the outside world through the transduction of

bio-electrical signals and nerve impulses.

This not only improves the quality of life for these individuals but also eases the burden on caregivers, reducing both care costs and the social isolation experienced by patients.

The closed-loop adaptive nature of BCIs is crucial for their effectiveness. It enables real-time adjustments based on the user's neural state, facilitating a dynamic and reciprocal interaction between the brain and external devices.

This bidirectional flow of information—from decoding neural signals to delivering feedback is pivotal for the BCI's adaptive capabilities, allowing the system to adjust its operations real-time.

In principle, three classes of signals can be leveraged for BCI development: electrophysiological, metabolic, or magnetic [2]. Electrophysiological signals, such as electroencephalogram (EEG), are most commonly used due to their high temporal resolution and non-invasive nature.

Metabolic signals, like those measured by functional near-infrared spectroscopy (fNIRS) or via blood oxygenation level-dependent (BOLD) response functional magnetic resonance (fMRI), provide information about brain activity through changes in tissue metabolism variability and hematic perfusion.

Magnetic signals, typically measured using magnetoencephalography (MEG), offer high spatial and temporal resolution but require more complex equipment, often discarded because expensive and bulky.

Being impractical for both clinic and wide-spread use, MEG and metabolic-imaging based BCI are neglected in the present report, which focuses on electrophysiological-detection based, which can be usually classified depending on their degree of invasiveness and selectivity.

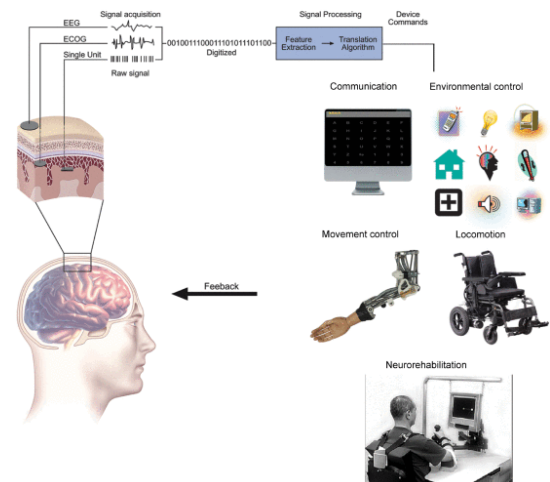


Fig. 1. Schematic Design of a BCI

II. BCI PIPELINE

Brain-Computer Interfaces (BCIs) operate through a sophisticated process that translates neural signals into actionable commands for external devices. This process begins with signal acquisition, where neurophysiological data reflecting the user's intent is captured from the brain.

Various methods can be employed for this purpose, including electroencephalography (EEG), electrocorticography (ECoG), local field potentials (LFPs), and recordings of individual neuronal action potentials.

Once acquired, these signals undergo feature extraction, a critical step in signal processing. This stage involves isolating specific characteristics of the neural data that correlate strongly with the user's intentions. These features may be derived from time-domain analysis, frequency-domain analysis, or a combination of both. Common examples include the amplitudes or latencies of event-evoked potentials, such as the P300 wave, or changes in frequency power spectra, like sensorimotor rhythms.

The extracted features then undergo translation, where they are converted into commands that can be understood and executed by the connected device. This translation process must be dynamic and adaptive, adjusting to variations in the user's signal features over time.

The goal is to ensure that the full range of the user's neural signals can be effectively mapped to the complete spectrum of device control options.

Throughout this process, signal processing is crucial in filtering the data and removing artifacts that could interfere with accurate interpretation.

The ultimate aim is to create a seamless interface between the user's brain activity and the external device, enabling intuitive control and communication.

This complex sequence of operations allows BCIs to serve as a direct communication channel between the brain and external devices, opening up new possibilities for individuals with limited motor functions and advancing the understanding of neural processes.

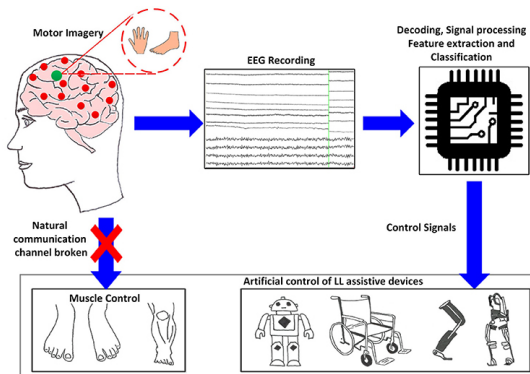


Fig. 2. BCI Pipeline

III. INTENDED USERS AND APPLICATIONS

Today, BCIs are being applied in two major areas: rehabilitation and the treatment of neurological and psychiatric

disorders. These technologies leverage the ability to interpret brain activity and translate it into actionable outputs, bypassing damaged neural pathways to enable innovative therapeutic interventions.

In rehabilitation, BCIs are proving particularly effective for restoring motor function in individuals recovering from strokes, neurological disorders, or injuries.

Techniques such as neurofeedback allow patients to adjust brain activity in real-time with visual or auditory feedback, promoting neuroplasticity—the brain's ability to form new neural connections. Enhanced motor imagery training, which engages neural pathways by imagining movements, has also shown promise in supporting recovery when direct physical movement is impaired.

Another key approach is the use of BCIs to "close the sensorimotor loop." This involves using brain signals to activate devices like orthoses or functional electrical stimulators, enabling paralyzed limbs to move.

The resulting sensory feedback strengthens the neural circuits involved in motor control. This method has demonstrated its feasibility, with many patients achieving significant progress within just a few training sessions.

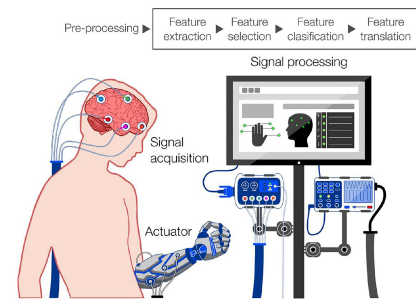


Fig. 3. BCI operation in closing the sensory-motor loop

BCIs are also being explored as innovative tools to address psychiatric conditions, including attention-deficit/hyperactivity disorder (ADHD), depression, anxiety, and substance use disorders. [3].

Brain-Computer Interfaces (BCIs) offer promising solutions for individuals with severe motor impairments, providing alternative means of communication and control.

The potential users of BCIs are categorized based on their level of neuromuscular control, ranging from those with no detectable control to those with substantial remaining abilities. While BCIs show great promise for individuals with limited neuromuscular control, their effectiveness for completely locked-in patients remains uncertain.

BCIs serve also two primary clinical purposes: direct control of assistive technologies and neurorehabilitation. In terms of communication, various EEG-based BCIs have been developed, utilizing slow cortical potentials, P300 event-related potentials, and sensorimotor rhythms. These systems enable basic communication and control, with P300-based BCIs showing particular promise due to their ease of use and minimal training requirements.

For movement control, sensorimotor rhythm-based BCIs have

demonstrated potential in achieving multidimensional cursor control and operating robotic arms. Clinical applications have shown success in restoring some motor function in paralyzed patients, particularly when combined with functional electrical stimulation.

Environmental control systems integrating BCI technology have also been explored, allowing severely impaired individuals to operate household devices and monitor their surroundings. It has been thus demonstrated the potential of such systems to increase patients' sense of independence and provide relief for caregivers.

As BCI technology continues to evolve, the focus is shifting towards developing practical clinical products that can be used in everyday life, potentially enhancing the independence and quality of life for individuals with severe disabilities

IV. EEG

EEG signals are obtained from the scalp via the surface application of recording electrodes in a noninvasive manner and therefore provide the safest and simplest solution.

However, as a consequence of the good accessibility, a trade-off with low resolution both in space and time, more impactful insulation provided by the dura mater and the skull, enhanced susceptibility to power-line interference as well as to EMG-derived artifacts has to be taken into account when it comes to signal detection and feature extraction.

The improved topographical resolution in invasive recording comes along with better Signal-to-Noise Ratio (SNR) figure of merits (because of higher signal amplitudes and selectivity) and wider frequency ranges.

A possible front-end specification design for surface EEG can comply with the following guidelines. The EEG signal acquisition system includes essential components such as pre-amplifiers, filters, and gain amplifiers for efficient signal processing.

It may use *INA333* precision instrumentation amplifier, known for its low power consumption, high accuracy, and small size - making it suitable for compact designs- efficient common mode rejection [4]. Buffer amplifiers link the electrodes to the system.

As restoration of communication probably can be seen as the field in the most pressing need for the intervention of BCI instrumentation, a little review of common electrical features used for this purpose is here shown.

BCIs primarily use three distinct EEG-based signal types: Slow Cortical Potentials (SCPs), Sensorimotor Rhythms (SMRs), and P300 Event-Related Potentials.

SCPs involve slow changes in cortical voltage (up to 10 s cycle in the EEG trace) that require extensive user training, while SMRs (recorded at the level of the sensory motor cortex and characterized by changes in amplitudes known as event-related desynchronization) enable motor imagery-based control through modifications of the brain wave pattern. P300 signals, characterized by a positive EEG deflection following significant stimuli with a latency of 300 ms, offer minimal training requirements and remarkable clinical applicability.

V. ECoG

Electrocorticography (ECoG) has emerged as a promising platform for brain-computer interface (BCI) applications due to its ability to capture detailed signals linked to actual and imagined actions. Its technical attributes, including high spatial resolution, high signal fidelity, resistance to noise, and robustness during extended recording periods, make it particularly suitable for chronic use in humans.

ECoG signals are obtained by placing electrodes above or beneath the dura mater. Commercial ECoG arrays are often composed of platinum-iridium discs and embedded in silastic sheets, and can be placed in a grid or strip disposition. They typically range from 3 to 6 mm in diameter, with slightly smaller exposure areas, and with an interelectrode distance ranging from 5 to 15 mm. There is also growing interest in using microfabricated electrode arrays composed of thin, biocompatible films, as well as combining clinical arrays with FDA-approved microelectrode arrays to enhance functionality. The placement of these electrodes is done by intracranial surgery, such as craniotomy or burr holes.

Their proximity to the cortical surface allows for precise detection of brain activity. Through frequency analysis, the ECoG features have been found to be related to motor function, sensory perception or cognition. In the frequency analysis, the frequency bands of interest are either the lower frequency bands, mu and beta, or the high frequency bands, gamma. Mu and beta oscillations are associated with the thalamocortical modulation of motor cortex, while gamma band represents cortical processing. Regarding signal acquisition, due to the amplitude attenuation of ECoG with increasing frequency, high-fidelity amplifiers/digitizers with a sampling rate of at least 1 KHz, high voltage sensitivity and a 16-24 bit resolution are required. In addition, the use of an intracranial reference and non-cortical grounding provides better fidelity to capture signals than scalp or cortical electrodes.

However, ECoG-based BCIs face significant limitations. The most important one relies on the subject population, as the current research is limited to short-term ECoG implantation in epilepsy patients. This presents some challenges, as there is a considerable variation in the cognitive ability of the subjects. In addition, ECoG recordings may have environmental noise as a result of general acquisition in a hospital setting. Other limitations include ECoG's lower spatial resolution compared to single-neuron recordings and the invasive nature of electrode implantation, which poses risks such as infection. Additionally, current ECoG systems are primarily designed for seizure localization and are unsuitable for long-term BCI use. A chronically implanted ECoG-based BCI system would consist of passive or active recording structures on biocompatible substrates that include amplification/digitization/wireless electronics and are powered by a battery at a remote site and permanently implanted through a burr hole [5]. Another key challenge is the biological response to long-term electrode implantation, including inflammation and electrode-tissue interface degradation. In long term implantation, signal quality is degraded and there is a thickening in the dura mater. Despite having various research works, it is still challenging to develop a chronic

recording device with minimal invasiveness, and the current research focus is on the development of new materials to improve the quality of these electrodes [6]. Some progress has been achieved, exemplified by WIMAGINE [7], a wireless 64-channel ECoG recording device designed for long-term human implantation. This system has undergone design validation and in-vivo studies in nonhuman primates, yielding promising results. However, it still requires validation in human subjects.

VI. INTRACORTICAL SIGNALS

Brain-computer interfaces (BCIs) utilizing intracortical signals represent a significant leap forward in neural interface technology, providing unparalleled precision in decoding brain activity. These systems employ microelectrode arrays implanted directly into the cortex to capture neuronal action potentials and local field potentials, offering both exceptional spatial and temporal resolution for the accurate recording of individual neuron activity. Early successes in humans have demonstrated the capability to decode complex motor skills, such as handwriting and speech, directly from cortical activity, enabling applications like cursor control, prosthesis operation, direct-to-text communication, and speech synthesis [8].

However, the use of intracortical signals in BCIs presents several challenges. The primary limitation remains the invasiveness of the procedure, as implantation requires a surgical intervention that carries risks such as infection, inflammation, and tissue damage. Additionally, the body's immune response can lead to the formation of scar tissue around the electrodes (known as Foreign Body Reaction), which significantly compromises signal quality over time [9]. These factors limit the long-term stability and performance of the devices. Another concern is the durability of the implanted device itself. Electrodes may degrade due to mechanical stress and biological factors, necessitating replacements and maintenance, which complicates the practical use of intracortical BCIs for long-term patient care. The shift from traditional cabled to wireless systems marks a crucial advancement in intracortical BCIs. Cabled systems, while effective, limit patient mobility and introduce potential risks such as cable wear and entanglement, which can degrade both device performance and patient comfort. Moreover, cables reduce the user's independence, as they remain tethered to external equipment. In contrast, wireless BCIs eliminate these issues, offering greater freedom of movement, improved patient comfort, and a reduction in infection risks associated with physical connections. Wireless systems also promote long-term usability by minimizing mechanical failure and enabling easy integration with other devices, such as robotic prosthetics.

One notable example of this technological shift is the Implantable Wireless Chargeable Neural Interface, developed by Brown University [10]. This device features a 100-element silicon-based microelectrode array (MEA) for sensing, which is connected to a small, head-implanted, subcutaneous electronic module. The microelectronics are housed in a hermetic feedthrough titanium enclosure, with validation in

both swine and non-human primates confirming the device's electrical stability, broadband neural data capture (0.1 Hz to 7.8 kHz), and safety over one year of testing.

Key innovations of this device include the integration of a brazed single-crystal sapphire window in the case for electromagnetic transparency and the hermetic feedthrough assembly, which ensures a reliable and secure connection for data transmission. The overall microelectronic functions are split between two printed circuit boards (PCBs): one for amplification and the other for radio frequency transmission.

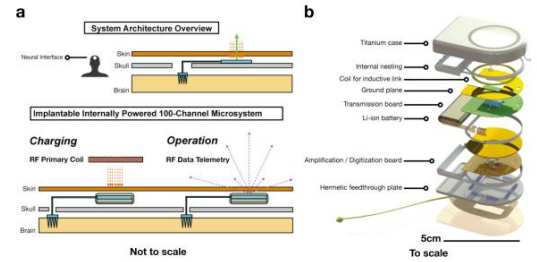


Fig. 4. Architecture, assembly, and functions of the interface.

Focusing on ultra-low power circuitry and efficient radio telemetry, this device supports continuous use for up to 7 hours on a single charge cycle. However, a critical challenge that remains is the heat generation during inductive charging (an expected increase of 7°C), which does not yet meet the ISO 14708-1:2000 E standard for implantable medical devices.

In conclusion, although BCIs utilizing intracortical signals have made significant progress, further research is necessary to address current challenges. Key advancements in signal processing, power efficiency, and wireless communication will be essential for the successful clinical translation of these systems. Once these challenges are overcome, BCIs could provide transformative solutions for neurological disorders, offering precise treatments for conditions like paralysis and stroke recovery. Furthermore, the integration of emerging technologies such as machine learning will expand the potential of BCIs for neuroenhancement, improving quality of life and functional independence. With continued innovation, BCIs have the potential to revolutionize both medicine and human-computer interaction, benefiting a broader population.

VII. CONCLUSION

In conclusion, Brain-Computer Interfaces (BCIs) represent a transformative technology with significant potential to improve the quality of life for individuals with severe neuromuscular impairments, as well as to advance neuro-rehabilitation and enhance human-computer interaction. While current implementations, particularly those using EEG, ECoG, and intracortical signals, have demonstrated promising results, challenges such as invasiveness, signal quality, and long-term device stability remain. Continued innovation in signal processing, non-invasive methods, and integration with emerging technologies like machine learning will be critical in realizing the full potential of BCIs for both clinical and non-clinical applications.

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