

A Systematic Analysis of Wearable Devices as Brain-Computer Interface Based on Neuromodulation

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Abstract. As the global health landscape deteriorates, the imperative of ensuring our well-being becomes increasingly apparent. The evolution of integrated circuit miniaturization technology has propelled the advancement of brain-computer interfaces to the forefront of research. Breakthroughs in recording and stimulating deep brain activity in humans have paved the way for a groundbreaking healthcare delivery method, referred to as the "Neural Stack" – a wearable medical device leveraging neuromodulation. This innovation contributes significantly to both the development of brain-computer technology and the broader field of neuroscience. In this article, the author delve into recent milestones within the realm of brain-computer interfaces, dissecting the associated challenges and envisioning future developments and applications. Given the interdisciplinary nature of brain-computer technology, contemporary scholars in the new era are compelled to explore and comprehend its intricacies. We are on the brink of an era where all things are interconnected, with brain-computer interfaces serving as the conduit for information exchange.

Keywords: Brain computer interface; Wearable device; Neuro-stack; Neuromodulation; Integrated Circuit.

1. Introduction

On May 5, 2023, the World Health Organization (WHO) officially announced that the new COVID-19 no longer constitutes a "Public Health Emergency of International Concern" (PHEIC) [1]. It has been three years and eight months since December 2019, which is a long time compared to the last global public health event - SARS. The new coronavirus has a huge impact on various organs of the human body, and its impact on the brain and nervous system cannot be ignored [2].

With the development of the times and technology, brain-computer technology will have greater application prospects in the face of frequent and unknown natural disasters in the future, providing more guarantees for human survival. At present, it is not only the best way for repairing damaged nerves, but it is also the most effective tool for treating neurological damage in those who have paralysis, stroke, Parkinson's disease, etc. Additionally, it is also the fundamental tool for in-depth examination and comprehension of the brain and is at the forefront of international brain science. An important tool for research.

In Chapter 2, this article first explains the definition of brain-computer interface and its processing flow; Chapter 3 then focuses on analyzing the key technological breakthroughs in the field of brain-computer interface technology in recent years, that is, the key case of the medical device as a service approach. Chapter 4 summarizes the current challenges and future development directions of brain-computer interface technology. The research in this paper will contribute to the further development of brain-computer interface technology in the future, as well as objectively trace its development process, and point out the direction for future research.

2. Theoretical Basis

2.1. Definition of brain-computer interface

The concept of "brain-computer interface" was first published in the "Annual Review of Biophysics and Bioengineering" by Professor Jacques J. Vidal of the Department of Computer

Science at UCLA in 1973. It was formally proposed in the paper "Toward Direct Brain-Computer Communication" [3]. Among them, the concept and definition of "brain-computer interface" was officially created, and thus "brain-computer interface" officially became an independent research field. Since then, the brain-computer interface system has been defined as a direct real-time information exchange and control channel established between the brain and its external electronic or mechanical devices. By definition, a brain-computer interface is a technology that studies how to use neural signals to directly interact with external machines.

Compared with other creatures on earth, human beings have the strongest brain. As the nerve center of human beings, the brain undertakes the basic task of maintaining human existence. The traditional way of communication between people and the outside world is through language and muscle activities. The main goal of the brain-computer interface system is to fully utilize the benefits of the human brain while avoiding the body's own organs and directly transmitting the brain's own activity information to the outside world. In order to realize efficient information exchange between the human brain and the device. Simply put, it is an interface that can extract signals from the brain to control external devices, which is a type of human-computer interaction. Different from traditional forms of human-computer interaction, brain-computer interfaces do not require hands or voice to transmit signals, and external devices can understand what you are thinking and what you want to do. We need to note that brain-computer interface is a multidisciplinary technology, and the core disciplines involve integrated circuits, cognitive science, neural engineering, neuroscience, etc.

2.2. The processing flow of the brain-computer interface

Through signal collecting equipment, brain-computer interface technology gathers EEG signals from the cerebral cortex and transforms them into signals that computers can understand through amplification, filtering, digital-to-analog A/D conversion, etc. The signals are then preprocessed to extract characteristic signals. And then, in order to operate external equipment, these traits are used for pattern recognition, which is then translated into precise commands. A typical brain-computer interface (BCI) system comprises four primary components: signal acquisition, information decoding and processing, re-encoding, and feedback mechanisms which is shown in figure 1.

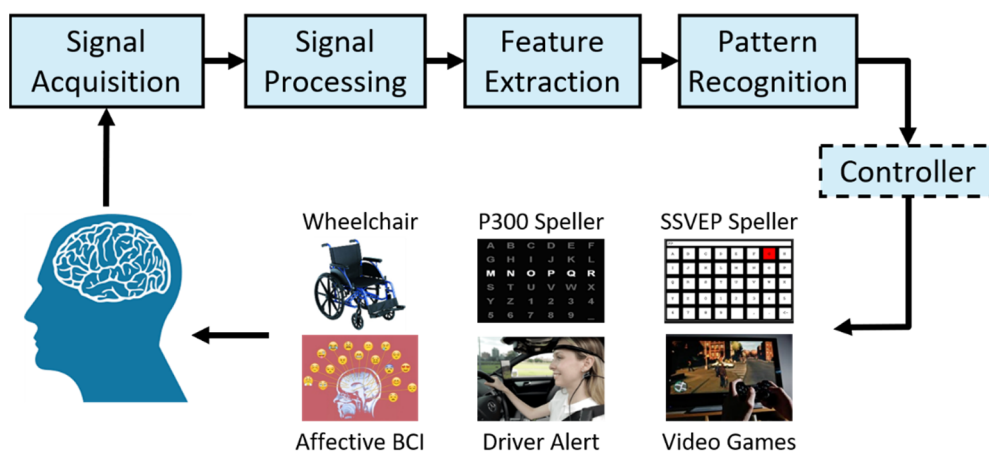


Figure 1. A typical brain-computer interface (BCI) system (Photo/Picture credit: Original)

Signal Acquisition: The categorization of BCIs hinges on their signal acquisition method. Generally, BCIs are classified into two main types: implantable and non-implantable. Implantable electrodes, known for their precision, can encode intricate commands, such as three-dimensional motion, surpassing the capabilities of scalp patches. Conversely, non-implantable electrodes, like scalp patches, are safer and more widely accepted, as they do not necessitate invasive craniotomy procedures. While their range and signal accuracy are limited, non-implantable options become essential for applications involving healthy individuals.

Information Analysis: Once sufficient data is collected, the acquired signals are decoded to address interference issues. Signal collection often faces various sources of interference, such as power

frequency disturbances, eye movement artifacts, and other electromagnetic environmental interferences. The decoding process relies on analytical models, including EEG and cortical EEG models, which are chosen based on the signal collection approach.

Re-encoding: The manner in which information is re-encoded depends on the desired outcomes. For instance, to control a robotic arm's precise movements, such as picking up a coffee cup and serving coffee, the decoded information must be converted into motion signals that govern the arm's trajectory and force application within a complex three-dimensional setting. Various encoding methods can be employed, allowing BCIs to seamlessly integrate with diverse engineering disciplines.

Feedback: Human perception of the environment involves receiving sensory input and providing feedback to the brain. The practical implementation of BCIs presents significant challenges, particularly in handling multi-modal perception analysis. The technology must effectively manage the amalgamation of various sensory inputs to create a coherent feedback loop.

3. Current key technologies and research

3.1. Animal experiment

Scientists have technically managed to exchange ideas through direct communication between brains. In the first half of 2013, the team of Professor Miguel Nicolelis of Duke University took the lead in publishing a study that successfully transmitted some simple information directly through EEG signals between two different breeds of mice that had never had mating [4]. Soon after, Professor Seung-Schik Yoo of Harvard Medical School and his colleagues used highly focused ultrasound technology that can penetrate the skull to realize the attempt of the human brain to directly control the mouse brain through EEG. When a human subject decides to move the mouse's tail, his brainwave signal will trigger the ultrasonic device to send a 350Hz ultrasonic pulse to the motor cortex of the mouse's brain. After two seconds, the mouse's tail will be raised and then lowered [5].

In July 2019, Musk even announced that the high-tech company Neuralink had achieved a breakthrough in brain-computer interface technology and would implant chips into the human brain within a year to solve all brain diseases. Neuralink uses a neurosurgery robot to implant 96 4–6-micron thin wires with a total of 3072 electrodes on a brain area of 28 square millimeters [6]. These circuits can then sense the brain's electrical signals in our brain and then transmit them to the chip for analysis; they can also transmit external electrical signals to the brain for the brain to feel. This causes less damage to the brain and transmits more data than previous technologies.

This technology has been successfully tested on the brains of mice, and human trials are planned for this year. The core of this technology is the 'micro-electro-mechanical technology', which can process circuits to the micron or even nanometer level, which evolved from the chip processing technology. Max is currently able to make circuits down to the micron level, which is only about a quarter of the thickness of our hair, and the circuit is also very soft. Inserting it into the human brain will not cause damage to the brain.

On May 4, 2023, the world's first non-human primate interventional brain-computer interface test was successful in Beijing. The test realized the interventional brain-computer interface brain-controlled robotic arm in the monkey brain, which is of great importance to the advancement of brain science. Field research is of great significance. Professor Duan Feng's team from Nankai University oversaw the experiment, which was carried out in collaboration with the 301 Hospital General Hospital of the Chinese People's Liberation Army and other organizations, breaking through core technologies such as intravascular EEG signal acquisition and interventional EEG signal recognition. Judging from the video data, this post-operative monkey only needs to "think about it" before it can let the robotic arm deliver food into its mouth [7].

Invasive brain-computer interfaces are traumatic. For example, Neuralink's invasive brain-computer interface test monkeys have died, and the company's human trials were not approved by the US Food and Drug Administration until May 25 this year [8]. Non-invasive brain-computer interfaces are susceptible to the brain volume conductor effect, and the long-term stability of EEG

signals is poor. The interventional brain-computer interface uses a minimally invasive intervention method to puncture blood vessels through small openings and achieves brain-computer connection through minimally invasive surgery similar to cardiac stent intervention. This method is less invasive than invasive brain-computer interfaces. The interventional brain-computer interface experiment led by Professor Duan Feng's team is to attach the interventional EEG sensor to the wall of monkey brain blood vessels through interventional surgery, and to collect intracranial EEG signals without craniotomy. Security, recognition stability.

This technology has a wide range of applications in medical, military and other fields. For example, it can help patients with stroke and frostbite recover, and even store human thinking, consciousness, and memory in the future. This series of results, which sound very miraculous, have begun to be realized.

3.2. Wearable technology

Neuro-stack: A wearable clinical research system for advanced closed-loop neuromodulation. On March 11, 2023, a research team comprising members from the University of California, Los Angeles, and other institutions unveiled an innovative path towards advancing implantable technology. They introduced a compact bidirectional neuromodulation external device named Neuro-stack. This wearable technology empowers simultaneous iEEG recordings, offering 32-channel unipolar recordings and expanding to 128-channel unipolar or bipolar recordings, leveraging 256 macro-recording contacts. Additionally, it supports 32 micro-recording connections for monopolar recording of contact, enabling the monitoring of single-unit and LFP activity during human gait for therapeutic purposes. Moreover, Neuro-stack is equipped with customizable closed-loop multi-channel stimulation capabilities. Users can configure various parameters, including pulse shape, frequency, amplitude, pulse width, inter-pulse width, polarity, channel selection, and timing, such as for PLS [9].

Based on ultra-low power and area integrated circuits, the device can record the activity of individual neurons at high resolution and stimulate neurons in the brain through a series of strategically positioned electrodes. These stimuli can be programmed remotely to investigate or treat specific brain conditions.

With Neuro-stack in a Nutshell, it has more channels and stimulators than existing stimulation devices and no longer needs another box for recording. A greater number of circuits means more signals can be transmitted. The smaller size makes it more suitable for Miniaturized neural duplex (MIND) implant. Among them, the most important Subnets Implant Device is only an integrated circuit with a length of 23mm and a width of 5mm, that is, Neuromodulator. Compared with the existing DBS equipment, it has Wide bandwidth for single-unit and LFP recording and ability to customize stimulation waveforms. Of course, more channels to select from and small size (~4cm³ for 128 channels) due to high miniaturization is also its key benefits.

In the future, neural stacks could help advance research exploring the neurophysiological basis of human disease while providing more advanced neuromodulation therapies for brain diseases. New technologies can greatly advance research in various fields, including medicine and neuroscience.

4. Challenges and future development of brain-computer interface technology

4.1. Current technical challenges

First, the processing of massive neural signals. According to statistics, the current BCI technology ability to record twice as many neurons simultaneously requires an average of 7.4 years. It will take until 2100 years to record 1 million neurons at the same time, but to record all the human brain neurons. Neurons, you have to wait until 2225. Therefore, how many electrodes to implant is enough to basically span major brain functions or fulfill a specific functional need, that is, how to solve the issue with effective bandwidth of the brain-computer interface has become the key point of academic research breakthroughs. Second, the signal recognition accuracy is low. The tens of billions of neurons that make up the human brain have roles and systems that we currently do not fully

comprehend. The correct identification of brain signals by BCI technology is also restricted, and it is more difficult to record more neurons at the same time. This also makes BCI less accurate in identifying brain signals. Third, the signal processing and conversion speed is slow. BCI technical engineers need to convert the EEG signals input by the user (read by BCI) into control signals or commands that the computer can understand. The conversion algorithm is a major difficulty. In addition, sufficient computing power is needed to quickly process the information. Processing, so that the nerve electrical signal can be converted into a command or operation signal that can be recognized by the computer through the BCI system in real time, quickly and accurately [10]. At present, progress in direct feedback (signal input) to the brain is relatively slow (currently it mainly relies on the human body's own visual, auditory and other feedback systems), because if it is not careful, it may cause damage to the fragile brain.

In the future, we may need to consider not only issues based on health, safety and medical aspects, but also the audio-visual and emotional impact of human beings in the environment of brain-computer interface technology and their acceptance of AI intervention [11]. Brain-computer interfaces run the potential of being invaded or even taken over by adversaries as a non-impeccable middleman between humans and the real world, which objectively increases the complexity and unpredictability of human decision-making. The final application of brain-computer interface technology will undoubtedly be on people as well. How to achieve a perfect balance between minimizing injury to the brain and maximizing utilization of the brain will also be a core challenge in the future.

4.2. Future Prospects and Development of Brain-Computer Interface

It can be expected that with the development of micro-electromechanical technology, circuits can be made to the nanometer level, and circuits can be implanted into the human brain on a large scale, and then use 5G or the 6G low-power Internet of Things high-speed transmission technology and advanced Computer connection, transmit consciousness to the computer, control the computer through the brain-computer interface, and then control various intelligent equipment, realize brain-machine integration, improve the computing power of the organism's brain, and develop a sufficiently powerful brain [12]. Machine-to-machine interfaces can cure human brain diseases, allow paralyzed patients to walk like normal people, and can help a traumatized person forget some terrible memories. At the same time, it gives the human brain more powerful functions, and is even expected to transform non-human perception capabilities into human perception capabilities, such as obtaining the ability to perceive ultrasonic waves from bats, or sensing magnetic fields, etc., which is like having superpowers. The field of brain-computer fusion, which involves the merging of so-called silicon-based organisms and carbon-based organisms to produce super humans and naturally expand the human brain, can also use brain-computer interface as a new means of communication and control [13].

If brain-computer interface technology can be popularized and promoted in the future, and computers can accurately identify people's thinking in real time and work better with people, then perhaps the energy consumption and storage density of artificial brains will catch up with or even exceed biological brains, which is also expected to give rise to more intelligent robots, self-driving cars, medical diagnosis and other artificial intelligence interactive systems.

At the same time, research shows that brain-computer interfaces can improve students' learning efficiency and memory and help them receive information faster. For example, artificial intelligence technology-BCI is used for teaching and assessment to improve learning effects. Although existing research shows that the improvement of memory by brain-computer interface is not statistically significant, what can be proven now is that it can only improve short-term memory [14]. However, in the future, whether it will be possible for the human brain to quickly learn a certain language or directly communicate with artificial intelligence, this is also the research direction we will conduct. In addition, when facing danger, brain-computer interface technology can help us better control various wearable devices, avoid unnecessary injuries, and have safer choices when facing

emergencies. In a highly intelligent future society, we will also use various wearable devices and not only brain-computer interfaces to command various robots to overcome various difficulties [15].

Various domains, including EEG processes, brain cognition, brain rehabilitation, signal processing, pattern recognition, chip technology, and computing technology, have new demands as a result of the development of brain-computer interfaces. People's knowledge of the composition and operation of the brain will also significantly deepen.

5. Conclusion

The conclusions drawn by this article through the above research are as follows. First, in Chapter 2, this article summarizes the definition and composition of brain-computer interface, obtains the processing flow of brain-computer interface and current solutions to problems, and points out the direction for research. Secondly, in Chapter 3, this article analyzes and summarizes the landmark experimental cases in recent years and obtains the key technological progress results and development status of the current wearable medical equipment, namely brain-computer. Finally, in the fourth paragraph, this article summarizes the current difficult problems of BCI technology and its expansion and prospects for future applications.

With the rapid development of society, the technical level is also changing with each passing day. Based on the review of previous brain-computer research, this article summarizes the previous research results and the problems faced to make up for the current international application of brain-computer interfaces. Summary blank. In future research, by introducing deep transfer learning and neural networks, the application of brain-computer interface will be further expanded to provide help to more people.

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