Study of Hardware Direction of EEG Acquisition Device in BCI

Chen Liu[a]
School of Electronic Information and Electrical Engineering, Yangtze University, Jingzhou, Hubei, 434023, China

Keywords: Brain-Computer Interface (BCI), Electroencephalogram (EEG), Acquisition Device, Hardware Technology.

Abstract: Brain-computer interface (BCI) has been the focus of research all over the world and is an important way for the human brain to interact with external devices. Electroencephalogram (EEG) acquisition device, as the main way to collect EEG signals, is an indispensable part of this field. The research results of various countries and companies in related fields are endless, and there is a wide range of application space in various fields in the future. At present, the main composition of EEG acquisition devices has tended to be stable, but there are still shortcomings in portability, accuracy, and stability in function and performance. In order to clarify the general situation of the current EEG acquisition device and the main research direction in the future, this paper will divide its overall structure into electrical signal acquisition sensor, which includes seven parts: pre-processing circuit including filter and signal amplification circuit, analog-to-digital converter, signal processing unit, data storage module, data transmission interface and power management module for analysis and description. At the same time, the current, more advanced products, the shortcomings of current research, and the direction of optimization are described and analyzed, and finally, the development trend is prospected.

1 INTRODUCTION

Brain-computer interface technology has great application potential in many fields. At present, it has been used in the treatment of patients with paralysis, neurological, and other related diseases. It can be predicted that in the future, many diseases that are currently incurable are expected to be improved and even solved. Brain-computer interface refers to the use of modern computer science, biological science, brain science, electronic information, and other fields of technology to create a human brain or other biological brain and electronic devices between the information interaction channel so as to achieve the exchange and control of information and data. The first step is to capture brain activity signals, including Electroencephalogram (EEG) acquisition, functional magnetic resonance imaging, near-infrared imaging, and so on. Among them, EEG signal acquisition is a way with the highest precision and fastest response, which is conducive to more real-time and accurate interaction and control with computers, meeting people's needs for brain-computer interaction in some scenes. Therefore, the acquisition of EEG signals has received more attention and has become the focus of brain signal acquisition.

In 1924, the German psychiatrist Hans Berger was the first to collect rhythmic point changes from the human scalp and named it electroencephalogram. This officially opened the embryonic stage of brain-computer interface theory. The accuracy and safety of early EEG acquisition devices are low. With the continuous development of brain science, neuroscience, and computer science, in the 1990s, Europe and the United States began the brain program one after another, which rapidly promoted the development of brain-computer-related technologies and reached unity in the concept of brain-computer interface. At the beginning of the 21st century, brain-computer interface technology entered a period of explosion, and various non-implanting minimally invasive and non-invasive EEG signal acquisition systems and flexible implanting acquisition systems that pursue high precision and long-term acquisition have also been developed. In 2015, Mniev et al. proposed a study related to the long-term performance improvement of neural prosthetics by flexible neural implants, which further promoted the development of invasive brain-computer interfaces

[a] https://orcid.org/0009-0008-4358-8162

Liu, C.
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DOI: 10.5220/0013679300004670

In *Proceedings of the 2nd International Conference on Data Science and Engineering (ICDSE 2025)*, pages 98-103
ISBN: 978-989-758-765-8

(Minev et al., 2015). In 2024, Yanshan University proposed a method of mixed EEG and myoelectric examination to improve the recognition rate of features. The equipment systems and methods of EEG acquisition are constantly updated and optimized, which will also promote the application of brain computers in more scenarios.

This paper mainly reviews the research status and future development trend of EEG acquisition technology and equipment, summarizes the structure of the current EEG acquisition system, as well as the optimization direction of different methods, and compares the currently developed acquisition systems. In the end, the shortcomings of current EEG acquisition technology and the key problems that need to be solved are summarized, and the future development of related directions is prospected.

2 PRINCIPLE

An electroencephalogram (EEG) is an image drawn by the electrical signals collected by various EEG acquisition devices in the head of the organism, which shows the spontaneous and rhythmic electrical activities of the brain cells of the organism. EEG acquisition device is a kind of precision measuring instrument that needs to protect the test target and ensure the accuracy of the measurement signal. In addition, it is necessary to consider the power consumption and volume of the entire measurement system as much as possible so as to reduce costs. The current brain-computer interface technology is mainly classified into three categories: invasive, semi-invasive, and non-invasive, and the acquisition of electrical signals at different locations. They generally have the following main components: electrical signal acquisition sensor, including filtering, signal amplification circuit pre-processing circuit, analog-to-digital converter, signal processing unit, data storage module, data transmission interface, and power management module. The approximate structure is shown in Figure 1.

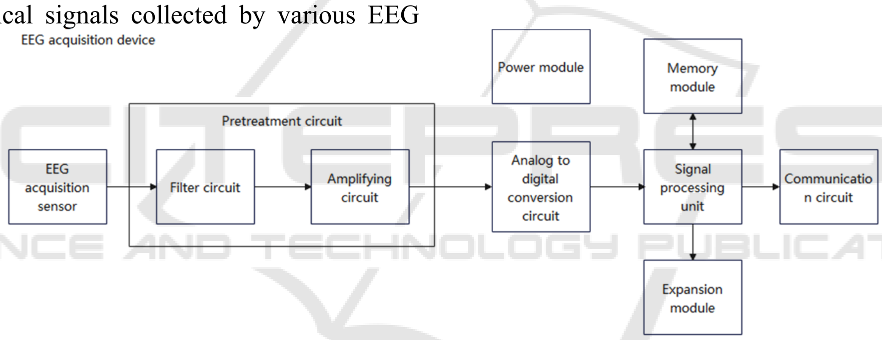

Figure 1: Structure of EEG acquisition device

The electrical signal acquisition sensor is responsible for collecting the original signal of the corresponding position of the organism into the brain's electrical equipment. The organism can be regarded as a conductor with high impedance, so the brain signals that can be detected are rather weak, and at the same time, they will be interfered with by various external factors and other strong models of the organism itself, and there will be large DC offset, which has a great impact on direct acquisition (Zhou, Du, and Duan, 2022). At present, there are three main lead modes in scientific research, namely unipolar lead, bipolar lead, and average lead. The unipolar lead connects the head measurement sensor and the reference electrode located in the earlobe or mastoid, respectively, to the amplifier. It has the advantage of higher amplitude and more stable measurement locations when recording the absolute value of changes in brain potentials. However, the reference potential at the earlobe or mastoid cannot maintain zero potential, so it is susceptible to interference from other bioelectrical signals so that abnormal signals other than the EEG signal at the target location can be measured. The bipolar leads do not use reference electrodes, but two measurement sensors at different positions are connected to both ends of the amplifier to record the difference in potential change between the two places. The advantage of this is that it can effectively suppress the interference of common mode signal to the acquisition target position signal and improve the signal-to-noise ratio of the acquisition system, but it can not measure the absolute value of point change. The average lead is to average the signals collected by multiple EEG in the head and connect them to one end of the amplifier as the average reference electrode, which is used to replace the reference electrode in the earlobe or mastoid in the single lead so as to reduce the influence of the reference electrode on the collected EEG signal.

After the original EEG signal is obtained by the sensor, it needs to be processed by the pre-processing circuit. For example, the above EEG signal itself is quite weak and susceptible to common-mode interference. Common mode interference is caused by many reasons; the most common is the human body's own physiological activities generated by other signal interference. Therefore, a good performance filter is needed to eliminate the effect of interference as much as possible. In this circuit, it is also necessary to amplify the originally weak EEG signal. This part of the circuit determines the quality of the signal collected by the whole EEG acquisition device, so it is also the key research part of the hardware circuit in the current EEG acquisition.

EEG-related research requires high accuracy of data. EEG signal acquisition device to this part of the circuit requirements are also quite high. In addition to the high-resolution requirements (usually not less than 16 bits), but also a high demand for the sampling rate of the device, the current research field of EEG acquisition device sampling rate is basically above 1kHz, but also to choose less noise devices.

At present, most processor modules are implemented on platforms such as Digital Signal Processing (DSP) or Field Programmable Gate Array (FPGA), and microcomputers are also used. This part of the module mainly sends the processed signal to the host computer or other peripherals through the communication interface for subsequent calculation processing or direct control of other peripherals.

3 TECHNOLOGY STATUS

In the aspect of non-invasive EEG acquisition devices, due to their advantages of relative convenience and high security, they have great potential in various civil industries. Traditional EEG acquisition devices usually have 8-128 acquisition channels with a collection frequency of 100-1000Hz and use earlobes and papillae as reference electrodes (Gao et al., 2015). However, with the continuous improvement of demand and technology, the relevant performance of the instrument is also improving. In May 2023, Cumulus Neuroscience published a certified dry-sensor EEG headset with 16 electrodes, a sampling frequency of up to 500Hz, and a sampling bandwidth of 0.5Hz to 250Hz. Such conditions enable the recording and analysis of more complex EEG signals with low latency (Julie, 2023). It has great advantages in the number of channels, and the use of electrodes, and the dry sensor maintains high accuracy while avoiding the cleaning problems that are prone to the use of traditional electrodes. In the same year, non-invasive EEG acquisition devices were also used in medical applications, such as Cognixion combined with AR technology to develop Cognixion ONE Axon (COA) to help improve the quality of life of patients with muscular dystrophy, traumatic brain injury, and other diseases. The device has six infinite EEG sensors and one infinite eye movement sensor to record brain signals and eye movement signals, with a sampling frequency of 250Hz and a sampling bandwidth of 0.5Hz to 125Hz. Compared with traditional electrode caps, it has great advantages in terms of comfort, portability, and flexibility (Sagar, 2023). China's Changzhou Boricon Technology Co., Ltd. has also developed a non-invasive EEG acquisition device, NeuSen W, with 128-1024 channels, 0.5Hz to 70Hz sampling bandwidth, and 16kHz sampling rate, and equipped with a nine-axis motion sensor, which can eliminate motion noise. It has the advantages of good portability, strong signal stability, and strong shielding ability (Neuracle, 2020). At the same time, it can be connected through WIFI, supporting multiple devices for simultaneous acquisition and multi-end synchronous EEG imaging and data interaction analysis. The above equipment parameters are shown in Table 1.

Table 1: Hardware information of non-invasive EEG acquisition device

Name	Number of channels	Sampling frequency/Hz	Sampling bandwidth/Hz	Reference electrode
Traditional EEG acquisition device	8-128	100-1000	0.1-1000	Earlobe, mastoid, average reference electrode
dry-sensor EEG headset	16	500	0.5-250	average reference electrode
COA	6+1	250	0.5-125	average reference electrode
NeuSen W	128-1024	16k	0.5-70	

In addition to non-invasive technologies, there are also companies that focus on invasive technologies and related equipment, such as Neuralink, BrainGate, and others. Neuralink used monkey brains to control computers in 2019, implanted devices in the brains of live pigs in 2020, and completed the first device implantation of human brains in 2024, where a brain-computer interface system the size of a coin is implanted in the brain region to record EEG signals, but this technology is not yet mature. A few weeks after surgery, part of the wiring connected to the brain falls off, resulting in a loss of signal acquisition, and the system cannot work properly (Xu, Xue, and Xu, 2024). In February 2022, Xuanwu Hospital Capital Medical University completed China's first closed-loop neurostimulator CNS 061 and used it to achieve the implantation of the first patient with Parkinson's disease. Its acquisition system has 16 channels, which can connect various types of probe electrodes or chip electrodes, and has the function of 16 channels for stimulation and eight channels for collection. Its communication function can also realize Bluetooth communication and near-field communication, through which the collected information can be transmitted to the relevant monitoring equipment and synchronized to the corresponding server through WIFI. EEG acquisition devices with relatively less trauma have also made great progress. In April 2023, brain technology company Precision Neuroscience completed the implantation of an EEG acquisition device with a wound of just 1mm. The device is a flexible membrane of just 1cm square, containing 1024 channels. Higher accuracy of EEG measurements was achieved with less overall biological damage. The technique has been implanted in three patients with tumors in the language region of the brain (Ho et al., 2022). In the less invasive technology, in 2022, the personnel of relevant research institutions in China implanted the EEG acquisition device through functional magnetic resonance to precisely locate the target location and realized the use of the device to complete the character output of the brain-computer interface, and the speed reached 12 characters per minute. The device used two Utah electrodes made of miniature silicon, with a total of 192 channels. And the equivalent information transmission rate of each channel reaches 2 bits per minute.

4 TECHNICAL CHALLENGES AND IMPROVEMENTS

With the continuous research and exploration of scientists in this field, the relevant technologies of EEG acquisition devices are also maturing step by step. At present, there are still many difficulties to be overcome, from the research field to the application of various fields. The current development mainly focuses on the following:

1. Portability. In the future, the brain-computer interface will be applied in daily life, and the daily brain-computer interface in many application scenarios needs to be portable and comfortable enough while being wearable, so the volume and weight of the device and even the material will have relatively demanding requirements. At the hardware level of the EEG acquisition device, power consumption is an important point that needs to be optimized. At present, the weight of the power supply in wearable EEG acquisition devices accounts for a large part, so reducing power consumption can effectively reduce the weight of the device itself and thus reduce the pressure borne by the wearer (Le et al., 2022). In terms of volume, the current optimization direction is to integrate the entire system on one chip as much as possible, thereby reducing the volume of the overall device (Guo et al., 2023).

2. Information processing and transmission rate. A major shortcoming of the current wearable EEG acquisition device is that the transmission rate is relatively low, which cannot meet the needs of the current application environment. At present, the rapid development of communication technology has led to the commercial use of 5G communication and the research and development of 6G. In the future, the problems in communication will be further solved with the development of related fields.

3. Hardware performance. The bandwidth, acquisition rate, accuracy, and speed of analog-to-digital conversion mentioned above are the keys to determining the quality of the signal finally collected by the equipment, and the sufficiently accurate and reliable signal is the basis of the subsequent processing and decoding process. At present, from the product comparison of various EEG acquisition device manufacturers, it can be seen that the equipment at the front end of the industry has obvious advantages in its hardware configuration. With the further improvement of scientific research in this field, the understanding of EEG signals is becoming more and more profound, and the hardware will be more targeted and optimized for the acquisition of EEG signals, such as more accurate positioning of specific signals, widening of the spectrum range of EEG signals, and the development of electronics will also derive hardware with ideal sampling rate and bandwidth. At present, the acquisition signal is still subject to a lot of interference in the acquisition process, and the power frequency interference of hardware equipment is one of them. In future research,

we should try to remove the corresponding interference signal without affecting the signal of the same frequency in the original EEG signal (He et al., 2020).

3. Expansion of sensors and peripherals At present, many brain-computer devices have assembled a variety of peripherals, such as the nine-axis motion sensor mentioned above, and currently, in the field of application, there are already peripherals such as the use of EEG acquisition device to control robotic arms, character input, and drones. In order to optimize the collected information or adjust the wearing problems, flexible sensors for ear acquisition, combined with myoelectric acquisition devices, etc., are also constantly being developed. In the future, the development of brain peripheral devices will also extend to various industries, such as the game industry, transportation, industry, furniture, and even other strategic fields, which will further change people's lifestyles (Ruan et al., 2024).

5 CONCLUSION

The current EEG acquisition device technology is still improving, the overall structure of the EEG acquisition device will not change much in the short term; the key area is mainly in the pre-processing circuit and analog-to-digital conversion circuit, the acquisition rate, the size of the bandwidth range, the accuracy and speed performance of the analog-to-digital converter, to a large extent, determine the quality of the final EEG signal. The current mainstream equipment has a high measurement accuracy, as small as possible input noise, and a fast sampling rate, but there are still some shortcomings, in the medical aspect, invasive EEG acquisition devices also have long-term connection problems. For future applications in various fields, the volume and weight, information processing and transmission rate, hardware performance, sensor, and peripheral expansion are all areas that need to be further developed and optimized for EEG acquisition devices and even brain-computer interfaces to meet the needs of wireless, portable, comfortable and high-density in future daily or medical fields.

The current EEG acquisition device still has unsolved problems in some aspects because of hardware and other problems. There are still problems with the stability of EEG sensors such as electrodes and probes, and it is difficult to maintain the acquisition accuracy or other effects during long-term wearing or implantation. In the case of interference by other signals of the organism itself and power frequency interference, the signal quality will also be affected in the process of acquisition. After continuous optimization and improvement to solve these problems in the future, EEG acquisition devices and even brain-computer interfaces will have a wider range of applications.

It can be predicted that EEG acquisition devices will still be one of the key research directions in the field of brain-computer interface. When the technology becomes more mature in the future, EEG signals can be more accurately observed to better interpret the intention of the human brain and better establish the information interaction channel between the human brain and electronic devices so as to treat patients with disabilities or neurological diseases in the future medical industry. In terms of entertainment, it is combined with movies and games to create new entertainment ways, and in terms of life, it is combined with smart homes to further optimize life experience and so on. Brain-computer interfaces may become a new type of terminal to replace mobile phones in the future.

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