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Application of brain-computer interface in the field of neurobiology

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Abstract:

With people's in-depth understanding of the nervous system and the rapid development of the computer and communication fields, brain-computer interfaces have gradually become a reality. As a fusion technology in neurobiology, computer science, and communications, the brain-computer interface (BCI) has great technical advantages. It can not only help disabled people restore some body functions but also expand the field of control and achieve multi-modal control. It can help people gain a deeper understanding of human brain function and the pathogenic mechanisms of the nervous system, and it can even promote human-machine integration, which can improve learning and work efficiency. The content of this research includes the definition, development status, application value, brain-computer pathway, and problem solutions of BCI. Here are the processes of the brain-computer pathway. Firstly, the neural interface is used to extract electroencephalogram (EEG) signals. Secondly, the obtained signals are input to the filter, which can remove the original signal noise and artifacts. Then, the Complementary Ensemble Empirical Mode Decomposition (CEEMD) and Common Spatial Pattern (CSP) are used to extract features of the electroencephalogram (EEG) signals. After that, LightGBM and Harris Hawks Optimizer (HHO) are combined to classify and identify the electroencephalogram (EEG) signals. Finally, the obtained signals are decoded, encoded, and fed back to improve the human-machine fusion effect continuously.

Keywords: Brain-computer interface; Brain-computer pathway; Neurobiology; Multi-modal control; Human-machine fusion.

1. Introduction

Brain-computer interface (BCI) is a technical system that connects the human brain with external devices directly. It allows the human brain to communicate and interact directly with computers or other external devices without going through traditional muscle or nervous system output channels. By recording, interpreting, and decoding neural signals generated by the brain, individuals can use their consciousness or imagination to control external devices.

The background of BCI technology can be traced back to the 1970s. After Hans Berger first recorded the electroencephalogram in 1929, people have speculated that it could help humans get rid of the traditional media-peripheral nerves and limbs and directly communicate with the outside world. However, at that time, there was little research on the human brain, and computer technology was relatively backward, so scientists made little progress in this area. With the continuous development of computers, artificial intelligence, and the rapid exploration of neuroscience, research on BCI technology has shown an obvious upward trend. Recently, using BCIs for cognitive enhancement has shown an upward trend in interest; for instance, scientists are researching how to speed up the process of memory. Researchers have developed BCIs that can stimulate specific areas of the brain to enhance cognitive function [1], though these technologies are in their infancy. At present, BCI technology has become a research hotspot in fields such as computer technology, biomedical engineering, and communications.

BCI is a fusion product of modern technology and can play an important role in life, medical care, entertainment, and other fields. Its functions are as follows. A BCI system‘s output can substitute for natural output that has been lost because of illness or accident; for example, physicist Stephen Hawking, who suffered from ALS, was unable to move or communicate due to muscle atrophy. The intervention of the brain interface allows him to speak through the voice synthesizer, and he can also perform text output through the brain-machine interface technology. The output of the brain interface can restore the lost function; for example, artificial eyeballs can help blind patients recover their vision, plane cochlea can help deaf patients restore hearing, and the patient‘s brain sports cortex can also train the brain interface to help stroke patients restore physical control ability. For healthy people, the brain interface can achieve functional expansion. In the field of engineering psychology, the application of BCIs can improve work safety and work efficiency. Through real-time testing of the staff‘s cognitive load and fatigue level, it controls it within a reasonable range and upholds the working concept of maximizing efficiency.

Regarding the field of teaching, this BCI can monitor students‘ learning status in real time for teachers as a reference to formulate the most reasonable teaching plan. In the field of sports, the BCI can monitor the physical condition of the athletes in real time so that the coach can develop a more targeted training plan, which is conducive to producing better training results and extending the athlete‘s career. For the field of control, in addition to hand-control methods, brain control can be increased, and multi-modal control can be achieved.

Here, the BCI is supplemented as the original single control method. In the realm of entertainment gaming, the BCI gives players new operating dimensions apart from conventional game controls, adding to the meaning of the game and improving the gaming experience. In the field of rehabilitation, the application of the BCI can improve the existing treatment. The brain interface can collect signals from the damaged feeling or the sports cortex and treat stroke patients by stimulating the muscles. The brain of epilepsy patients will have abnormal discharge in a certain area. After the neuron abnormal discharge is detected through the brain interface technology, the brain can be stimulated accordingly, thereby reducing seizures. In a similar vein, children with autism benefit greatly from brain interface training when it comes to their rehabilitation. Compared with normal children, the relevant cortexes of autistic children feel a low degree of activation. The BCI can improve their self-control and ability to stimulate the sports cortex, thereby improving autism symptoms.

Similarly, the improvement function of the brain interface can also be applied to the treatment of depression and dynamic disease. The functions of the brain interface are diverse, including alternative functions, recovery functions, enhancement functions, supplementary functions, and improvement functions. To achieve the function of the robotic arm, the channel between the human brain and the robotic arm needs to be carefully analyzed.

2. Brain-computer pathway of robotic arm

2.1 Information processing stage

2.1.1 Collection of electroencephalography signals

Fig. 1 shows a brain-machine channel flowchart. Invasive, non-invasive, and semi-invasive are the three categories of neural interfaces according to their degree of invasiveness. Placing intracortical microelectrodes (IM) directly inside the brain is the most effective way to implement invasive neural interfaces, which comes with greater risks. Semi-invasive BCIs have electrodes located under the skull bone on the surface of the brain, such as electrocorticography (ECoG) [2]. As shown in Fig. 2, neuronal interfaces that are non-invasive can analyze superficial activities of the brain through functional near-infrared spectroscopy (fNIRS), magnetoencephalography (MEG), electroencephalography (EEG), or functional magnetic resonance imaging(fMRI) without the use of electrodes. Classified according to autonomy, BCI can operate either synchronously or asynchronously [3]. There is a possibility of interactions between the computer and the user that are either time-independent or time-dependent. Synchronous BCI is the term used to describe the system when the interaction takes place within a certain window of time in reaction to a trigger that the system provides. In asynchronous BCI, the user has the option to set up a mental exercise at a specific moment to interact with the computer. Synchronous BCIs are not as user-friendly as asynchronous BCIs, but their design is significantly simpler than asynchronous BCI development.

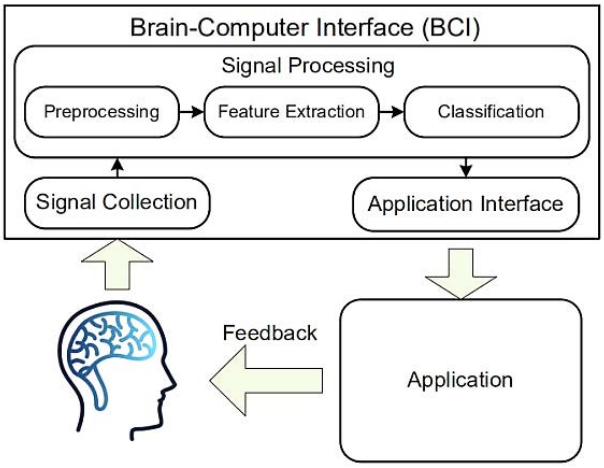

Fig. 1 Brain-machine channel flowchart [2].

EEG platforms measure the electrical motion generated from neurons in the brain by placing an electrode in the head or other body regions. EEG signal is a visual representation of the human brain frequency activity, it is usually used as the input of the BCI system. On account of its non-invasive signal-gathering technique and simple interpretation, BCI technology is widely used.

NIRS is a method of non-invasive brain imaging. The measurement of oxygen-containing and deoxymal hemoglobin concentrations in the brain uses light. Neural activity may be detected in real-time by using infrared to quantify the area and total activity of the cortex.

MEG is a non-invasive brain imaging technology that is accustomed to measuring the magnetic field generated by the current in the neuron. It provides high time resolution and high space correctness for tracking neurological activities related to mental processes, such as paying attention to or memorizing the formation of time.

ECoG is an invasive brain imaging technology. Positioned on the cerebral cortex's surface, it directly records the electrical signal from the cerebral cortex's surface. ECoG has high time resolution, superior quality of signal, and extremely low decibel levels. It can directly access the potential nerve source, which makes it particularly suitable for the intricate psychological state.

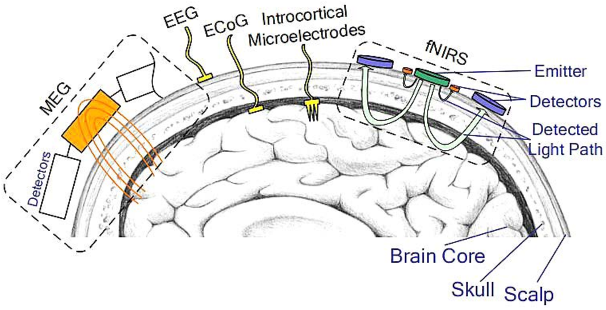

Fig. 2 Distribution of different nervous interfaces [2].

An experimental paradigm of single-joint motion imagination of three kinds of upper limbs on both sides [4] is designed to make the measured person‘s imaginative shoulder forward flexion, back extension, and external exchanges. At the same time, the electrical signal is extracted.

2.1.2 Pre-processing of EEG

EEG signal is a low-frequency biological electrical signal with a range of 5-100 μV. It usually needs to be enlarged to observe and display it. However, during the EEG signal collection process, a series of interferences such as personal psychology, collection equipment, and line noise will be received. If used directly, it will affect the accuracy of the subsequent analysis and the implementation of commands. EEG‘s pre-processing methods include Independent Component Analysis (ICA), Common Average Reference (CAR), Adaptive Filters, Principal Component Analysis (PCA), Surface Laplacian (SL), and Signal De-Noising.

EEG signals and sounds are treated as distinct entities in ICA, allowing for their separation. Additionally, the data is saved while noise is removed. The EEG data is divided into components that are both spatially fixed and temporally independent using this method. The ICA is more efficient when it comes to computing and noise demonstrable. It is the basic technique of dimensionality reduction. The reduction of noise across all the channels that are recorded is achieved through this approach, but it does not address noise that is specific to a channel and may introduce noise into other clean channels. CAR is a spatial filter that retains only the idle action of each electrode in the EEG, thereby removing common EEG activity.

An apparatus used in computation for mathematical operations is the adaptive filter. Iteratively, it joins the input and output signals of the adaptive filter. An adaptive approach is used to generate self-adjusting filter coefficients. Depending on the features of the signals being studied, the signal‘s attributes are modified.

PCA is a method for finding patterns in data that can be seen as a coordinate axis rotation. Rather than being aligned with individual time points, these axes display a signal pattern made up of linear pairings of intervals of time. To optimize variance along the first axis, PCA rotates the axes while maintaining their orthogonality. Finishing ranking lowers feature dimensions and facilitates data classification. PCA compresses independent data more effectively than ICA, regardless of whether noise is removed.

The term „SL“ describes a technique for showing high spatial resolution EEG data. Since their estimations are reference-free, SL can be produced by using any EEG system that can record references. Volume conduction details are not necessary; Rather, based on the external form of the volume conductor, it approximates the current density entering or leaving the scalp through the skull. SL improves the spatial resolution of the EEG signal, which is an advantage. Even so, SL does not seem to require additional operating neuroanatomy underpinnings despite its sensitivity to spline patterns and artifacts.

For wavelet de-noising and thresholding, the EEG signal is transferred to the discrete wavelet domain using the multi-resolution examination. Certain coefficients related to the noise signal are reduced by using the threshold level that is adaptive or contrasting. In a wavelet representation that matches nicely, noise features would often be defined by shorter coefficients throughout time and scale. On the other hand, one of the most crucial components of effective wavelet de-noising is threshold selection. In this situation, the signal and noise can be separated via thresholding, which is why thresholding techniques vary widely in size and form. In hard thresholding, all coefficients below a given threshold value are set to zero. Soft thresholding is one method for reducing the values of the remaining coefficients by a factor of two.

2.1.3 Feature Extraction of EEG

After the Butterworth filter filters the original signal noise, the obtained signal is decomposed into multiple inherent modular functions by using CEEMD. Enter the decomposable brain electrical signal to the CSP, and finally get the feature vector.

2.1.4 Classification and recognition of EEG

Combined with the instruction application of the mechanical arm brain machine signal, identifying the extracted signal and sending a corresponding exercise instruction are needed. By constructing LightGBM and HHO, EEG is identified and studied, respectively. After the construction of LightGBM, signal features are sorted by the level of their importance. Then combine the HHO to achieve superior treatment of signals, select signals with key characteristics to achieve classification recognition of EEG, and improve the accuracy and efficiency of the signal recognition process. Finally, the LightGBM parameter is optimized based on HHO, improves the accuracy of the model, and lays the foundation for the optimization control of the robotic arm.

2.2 Information output stage

The classified and identified EEG sends its results to the instruction encoding module and converts the signal into an instruction that the machine can recognize. The signal is compounded through AR control and EEG instructions to use the action of the robotic arm to capture the target area and dodge obstacles. At the same time, the robotic arm can feedback on the instruction signal generated after the action, so that the entire system forms a closed-loop feedback control and corrects the error in the action process.

3. Challenges

At present, most BCIs will cause a lot of fatigue because they need a lot of attention. In addition to the fatigue generated by the electrode, the brain interface will not be operated due to the lack of concentration of attention and not collecting sufficient features. Similarly, EEG is not accurate enough after encoding and decoding by BCI, even error coding and error execution will occur. Therefore, the small amount and poor quality of the feature EEG are the challenges that scientists must conquer. The author thought that focusing on the selection of invasive nerve interfaces and signal processors is the correct direction, by using more suitable devices to improve the problems caused by human-computer interaction.

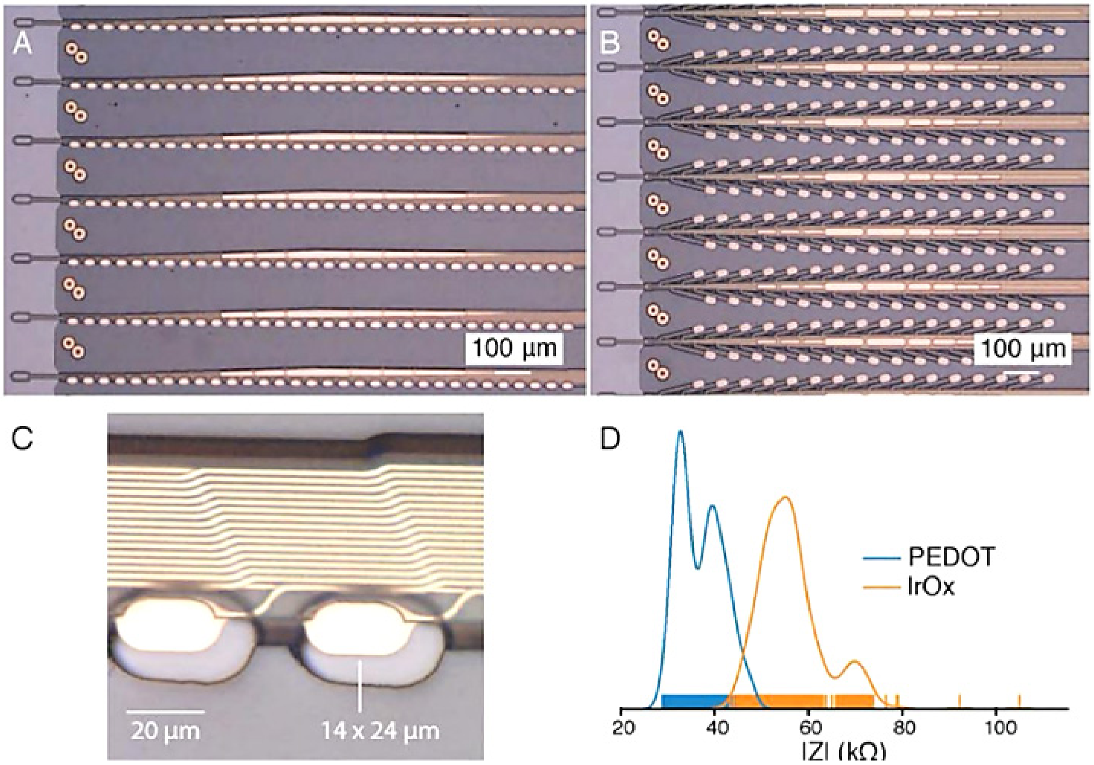

Fig. 3 The developed polymer probes [5]. (A) "Linear Edge" probes. (B) "Tree" probes. (C) Magnification of individual electrodes. (D) Distribution of electrode impedances with different surface treatment.

The author reckons that starting from the structure of the platform and choosing to build a small and flexible electrode array is a possible choice. Integrated chips are bonded to the contacts on the sensor area of the thin film using a flip-chip bonding process [5]. Maintaining a tiny thread cross-sectional area is one of the objectives of this strategy, which aims to reduce brain tissue displacement. Stepper lithography and other microfabrication techniques are employed to produce the metal layer at submicron resolution to achieve this while maintaining a high channel count.

From the author’s point of view, starting with the material of the platform is also a great idea. Since a single gold electrode site has a small geometric surface area, surface modification can be used to reduce the electrophysiological impedance and raise the interface‘s effective carrying capacity. By doping polystyrene sulfonate (PSS) and iridium oxide (IrOx), the impedance can be greatly reduced to obtain clearer EEG signals, as shown in Fig. 5. However, due to the uncertainty of long-term stability and biocompatibility, it is possible to enhance and expand these technologies and procedures to encompass more categories of conductive electrode materials and coatings.

Choosing an excellent signal processor can also greatly improve the quality of EEG signals, it is made up of on-chip analog-to-digital converters (ADCs), peripheral control circuitry for serializing the digitized outputs, and 256 independently programmable amplifiers, or „analog pixels.“ The analog pixel is highly configurable: The gains and filter properties can be calibrated to account for variability in signal quality due to process variations and the electrophysiological environment [5]. At the same time, the signal processor needs to use minimum power to process the output results in real-time to ensure the clarity and stability of the resulting EEG signal.

4. Conclusion

The robotic arm is one of the many applications of BCI technology. It has a unique EEG signal extraction method, signal processing method, decoding, and encoding mode, which can promote the perfect integration of the robot arm and the human body. As a key research object nowadays, the BCI has made breakthrough progress in many aspects. However, scientists still face many difficulties, such as a lack of data analysis methods, heavy training tasks and poor effects slow information transmission speed. The unremitting efforts of neuroscientists, engineers, computer scientists, and medical professionals will accelerate the transformation of BCI from the laboratory to the real world. This will become an important node in human history because the development and improvement of BCI technology is an important step in improving the lives of patients. In the same way, the BCI will completely change the way ordinary people live their lives. Through further research development and transformation, BCI will reshape the future.

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