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Control System of Medical Robot Based on BCI and High-speed Communication

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Abstract:

This article examines the utilisation and integration of brain-computer interface (BCI) technology and high-speed communication technology in the control system of a medical robot. The article begins by providing an overview of the development of BCI technology and its significance in assisting individuals with paralysis to regain their communication abilities. This is achieved by recording brain signals through non-invasive methods, thereby enabling the control of external devices. Subsequently, the article provides a comprehensive account of the ways in which high-speed communication technologies, particularly 5G networks, can markedly enhance the real-time and stability of medical robot control systems. These technologies offer low latency and high bandwidth. This enables more precise and secure telesurgery and complex medical operations Furthermore, the article examines the optimisation of communication protocols to reduce latency and enhance the reliability of data transmission, as well as the role of artificial intelligence and machine learning technologies in improving the decision-making capabilities of medical robots. In conclusion, the article addresses the safety and ethical concerns associated with medical robot control systems. It underscores the pivotal role of design and protocols in mitigating safety hazards and examines the prospective developments of BCI and high-speed communication technologies and their profound implications for the medical domain.

Keywords: BCI; High-Speed Communication; 5G/6G; Medical Robotics; AI

1. Introduction

With the continuous progress of science and technology and the development of medical robotics, medical robots have shown great potential for application in the medical field. They can not only assist doctors to carry out precise surgical operations, but also enable patients to directly control the robots through brain signals in rehabilitation therapy, providing patients with new ways of rehabilitation and improving their quality of life.

Brain-computer interface (BCI) technology plays a key role in this process by capturing and decoding the user's brain signals and translating them into computer instructions that enable patients to operate medical robots through intent [1]. For patients who have lost some or all of their bodily functions, such as those who have suffered a stroke or spinal cord injury, BCI technology helps them regain some motor skills. Based on electroencephalography (EEG) technology, BCI systems are able to acquire brainwave signals and decode these signals using complex algorithms to enable direct control of the robot.

In particular, BCI technologies based on systems of visual evoked potentials (VEPs), such as coded modulated visual evoked potentials (c-VEPs) and steady-state visual evoked potentials (SSVEPs), provide fast and efficient command inputs, enabling patients to control medical robots more precisely [2]. This efficient signal conversion improves the system's responsiveness and user experience, providing patients with a more natural and fluid interaction and making it easier for them to take control of their external environment during the rehabilitation process.

High-speed communication technology enables medical robots to process large amounts of data in real time. Through services such as enhanced Mobile Broadband (eMBB), massive Machine Type Communication (eMTC), and Ultra-Reliable Low-Latency Communication (URLLC), 5G ensures the system's reliability and operational accuracy in dynamic environments [2]. This provides critical communication support for BCI-based medical robot systems [3]. The millimeter wave (MmWave) and 6GHz frequency band architectures of 5G further enhance the system's performance in high-speed and high-bandwidth applications, allowing medical robots to operate with low latency and high speed, providing a solid technical foundation for telemedicine and collaborative surgery [3]. This is especially important in medical environments, where the reliability of data transmission is crucial. In complex medical settings, the stability and low latency of data transmission are paramount (Fig. 1) [3].

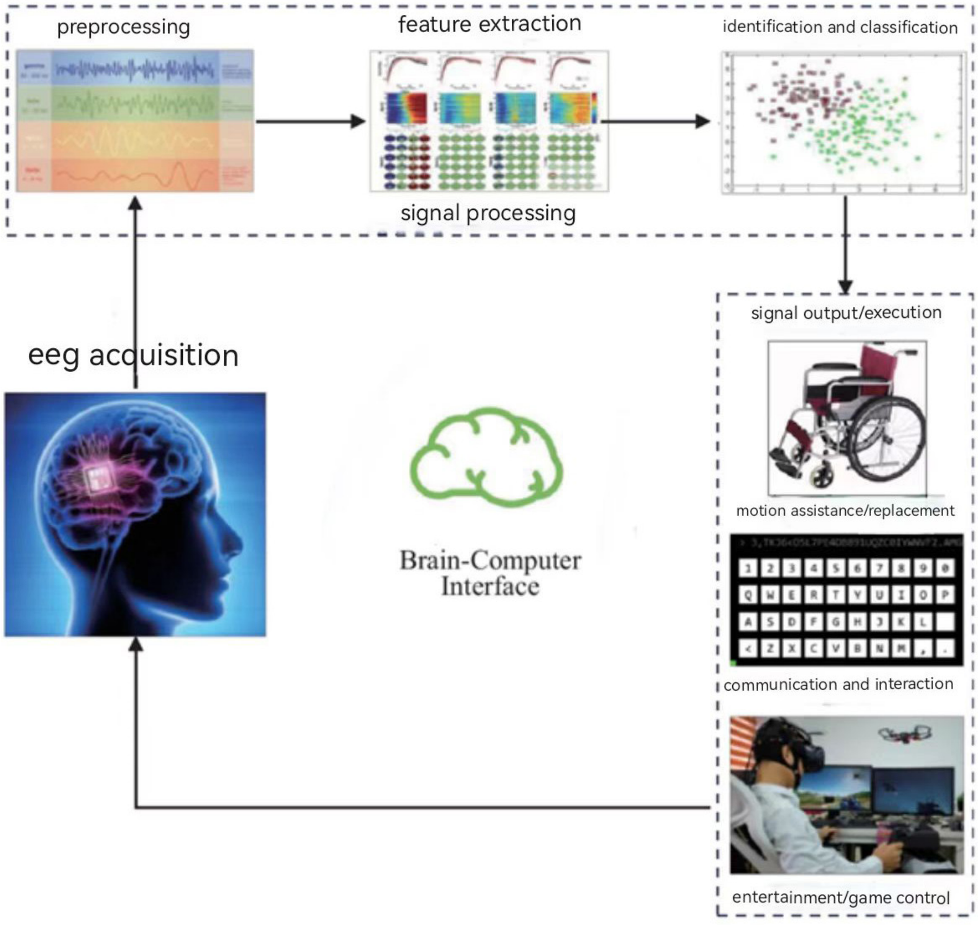

Fig. 1 basic working principle of brain-computer interface (BCI) [3].

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In addition, the medical robot control system introduces the Multi-Manipulation Software Framework (MMSF) to support multiple human-robot collaboration modes and flexible task allocation. The MMSF enables different types of medical robots to work together in a unified system to meet a variety of surgical needs [4]. Through modular design, MMSF can quickly adapt to different tasks and environments. For instance, it can seamlessly switch between different surgical tools or adjust to unexpected changes during a procedure, thus improving the efficiency and safety of surgery [4].

This study explores how to deeply integrate BCI technology with high-speed communication technology to develop a more advanced medical robot control system that provides a more intelligent and user-friendly solution for clinical applications. This technological integration not only brings greater convenience to patients and healthcare professionals, but also opens up new directions and possibilities for future medical technology innovation.

2. The Impact of High-Speed Communication Technology on System Performance

2.1 Evaluating the Impact of High-Speed Communication Technology on the Real-Time and Stability of Control Systems for Healthcare Medical Robots

The application of high-speed communication technologies, especially 5G networks, has a significant impact on the real-time performance and stability of medical robot control systems. First, 5G networks greatly enhance the real-time performance of medical robotic systems with their ultra-low latency (typically 1 ms), which is a significant improvement over previous network technologies. This feature is particularly important in remote surgery, where any latency can negatively impact the accuracy and outcome of the procedure. With 5G networks, data can be transmitted rapidly, allowing surgeons to receive instant feedback and make the necessary operational adjustments, thus ensuring high precision and efficiency in surgery (Fig. 2) [5].

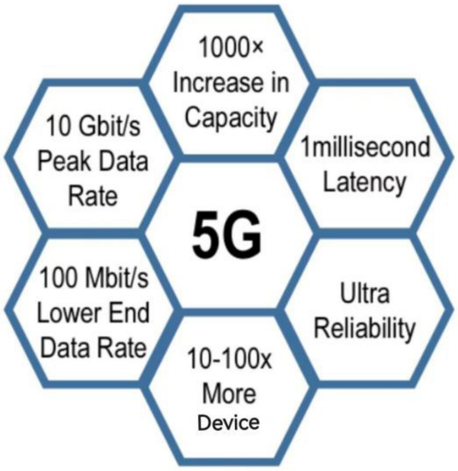

Fig. 2 Some major goals articulated for 5G [5].

In addition, the high-speed communication of 5G enhances the stability of the system. 5G greatly reduces the problems of interference and network congestion that often affect traditional communication networks. Its higher bandwidth and more stable connections ensure smoother data transmission.. A stable communication environment is crucial for remote surgery and other medical medical robot operations that rely on high-precision control, as it prevents operational errors triggered by data loss or delay [6].

Meanwhile, the high throughput capabilities of 5G networks allow for the rapid transmission of large files, such as high-definition images and real-time video streams, which are essential for visual guidance and diagnostic support in telesurgery. With a more reliable communication channel, doctors are able to obtain a clearer and more detailed view of the surgery, thus improving the accuracy and safety of the operation [6].

Therefore, the application of high-speed communication technology significantly improves the real-time and stability of medical medical robot control systems, supports more accurate and safe telemedicine operations, and provides a solid foundation for future medical technology innovations.

2.2 Discuss how to optimize communication protocols to reduce latency and improve the reliability of data transmission

In the Internet of Things (IoT) and cloud computing, the speed and reliability of real-time data transmission is critical. To ensure that data can be transmitted quickly and consistently, optimizing communication protocols is an integral part. The following are several approaches that can effectively reduce latency and improve transmission reliability:

First of all, the application of edge computing and fog computing has proved its remarkable effect in reducing latency [7]. Edge computing and fog computing bring data processing closer to the data source, shortening the transmission path and significantly reducing latency [8]. This approach not only improves the responsiveness of the system, but also better meets the demands of real-time data processing. Second, the reliability of data transmission can be further enhanced by using the Multipath Transmission Control Protocol (MPTCP). This protocol is capable of transmitting data over multiple paths simultaneously, ensuring continued data transmission even if one path encounters problems. the other paths ensure that the data continues to be transmitted. This mechanism effectively reduces the delay caused by network congestion [9].

Optimizing packet scheduling and resource management is likewise key to reducing latency. For instance, intelligent routing algorithms can help prioritize critical data packets, ensuring they reach their destination with minimal delay. By using techniques such as multi-agent systems and reinforcement learning, data transmission paths and resource allocation can be managed more intelligently so that data can reach its destination faster and smoother.

In addition, software-defined networking (SDN) and network functions virtualization (NFV) technologies play an important role in reducing latency. These technologies allow the network to dynamically adjust resource allocation based on actual traffic demand, ensuring that data does not suffer from a lack of resources during transmission [10].

Another important aspect to consider is the use of integrated caching techniques and optimized data partitioning strategies. These approaches can significantly enhance data management and transmission efficiency.. Repeated data transmission can be avoided by caching technology, while optimized cache partitioning strategy can ensure efficient data storage and transmission. The combination of these techniques not only improves system performance, but also significantly reduces latency [7]. Finally, enhanced error detection and data recovery mechanisms are crucial for improving the reliability of data transmission [7]. Another important aspect to consider is the use of integrated caching techniques and optimized data partitioning strategies. These approaches can significantly enhance data management and transmission efficiency.

By combining these various technologies and strategies, people can significantly optimize communication protocols. This results in reduced latency and improved reliability of data transmission. The implementation of these strategies will greatly improve the performance of real-time data transmission in IoT and cloud computing environments, ensuring faster and more reliable data services in various application scenarios

3. Autonomy and Intelligent Decision-Making Capabilities of Medical and Healthcare Robots

Artificial Intelligence (AI) and Machine Learning (ML) technologies play a crucial role in improving the decision-making capabilities of medical robots. These technologies enable medical robots to process and analyze large amounts of data from which they can identify complex patterns and trends, leading to more accurate decision-making in the face of a variety of environments and tasks. Through AI and ML, medical robots are able to not only learn from past data, but also adjust operational strategies in real time, especially in dynamic and uncertain environments. This real-time decision-making and environment adaptation capability enables medical robots to be more flexible and efficient in performing tasks [11] [12].

AI and ML technologies endow medical robots with powerful predictive capabilities. For instance, they can anticipate potential complications during surgery based on real-time data analysis, allowing for preemptive actions. This predictive ability allows medical robots to recognize potential risks and problems in advance, so that they can take preventive measures to reduce risks and ensure the success of their tasks [13][14]. For example, in surgical medical robots, AI can instantly adjust surgical strategies by analyzing image data and sensor feedback in real time, greatly improving the precision and safety of surgery.

Much like human professionals, medical robots can continuously improve their decision-making ability. They achieve this through self-learning and ongoing optimization of their machine learning algorithms, essentially “learning from experience” with each task they perform.. Over time, medical robots are able to adjust their algorithms based on accumulated experience and data, enabling them to maintain efficient decision-making capabilities even in complex and changing environments [11]. AI and ML technologies enable medical robots to synthesize data from various sensors, including vision, touch, and sound. This comprehensive environmental understanding allows them to make more accurate and contextually appropriate decisions [12]. This ability to fuse data from multiple sources ensures that medical robots are able to perform tasks smoothly in complex environments.

4. Conclusion

Medical robotics and brain-computer interface (BCI) tech-

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nology are rapidly advancing, revolutionizing the medical field. However, these cutting-edge technologies also present significant safety and ethical challenges that need to be addressed. During the operation of medical robots, various issues may arise. These include patient injuries, increased risk of infection, and secondary injuries due to mishandling. For instance, a robot might accidentally apply excessive pressure during a procedure, leading to tissue damage. For example, robots may trigger patient limb movement beyond the safe range, create pressure points at the contact site, or pinch the skin due to structural gaps. To reduce these risks, various design optimizations and protocol improvements can be implemented. These include equipping robots with alarm systems, emergency stop buttons, automatic shut-off functions, and quick-release mechanisms. Additionally, ensuring the proper balance of flexibility and rigidity in the robot's mechanical interfaces can help meet the needs of both patient comfort and effective treatment.. In addition, the use of an easy-to-clean design and strict infection control measures, as well as the incorporation of redundant systems and performance monitoring, can significantly improve the safety and reliability of the system.

On the other hand, the development of BCI technology raises ethical issues such as privacy protection and patient autonomy. BCI technology directly decodes neural signals from the brain. This raises serious privacy and security concerns, as any external interference or data leakage could potentially lead to manipulation of the nervous system. For this reason, strict security standards and protection measures are needed to prevent unauthorized access or malicious interference. In addition, BCI devices may be subject to control errors or algorithmic misinterpretation, leading to loss of control of patient behavior, a "black box" problem that can weaken the patient's sense of control over his or her own behavior, especially in special populations such as children. Therefore, ensuring transparency in the use of the technology and the patient's right to know is the key to safeguarding their autonomy.

As BCI systems continue to be optimized, they will become more efficient and precise. This will lead to better decoding of brain signals, with reduced noise and improved accuracy. High-speed communication technologies (e.g., 5G and future 6G) will provide low-latency and high-bandwidth support for BCI and medical robotics, greatly enhancing real-time data transmission capabilities and making remote control and precise feedback possible. At the same time, the application of artificial intelligence, especially generative artificial intelligence (GAI), will provide more intelligent control and decision-making support by better understanding and predicting user intent through deep learning models, further optimizing the collaboration of BCIs and medical robots, and improving their autonomy and resilience.

In the future, the human-robot collaboration model will become more complex, and medical robots will provide more personalized healthcare services by interacting with human doctors or patients through the BCI system, especially playing an important role in the field of rehabilitation and nursing care. In conclusion, by balancing technological advances with safety and ethical issues, BCIs and medical robots will achieve significant breakthroughs in the coming years, driving precision and personalization of healthcare services, and enhancing patients' health outcomes and overall healthcare experience.

References

[1] Valle G. The connection between the nervous system and machines: commentary. Journal of Medical Internet Research, 2019, 21(11): e16344.

[2] Chaudhary U, Birbaumer N, Ramos-Murguialday A. Brain–computer interfaces for communication and rehabilitation. Nature Reviews Neurology, 2016, 12(9): 513-525.

[3] Cheng Liwei, Zhang Qian, Liang Liyan, et al. High-Speed Communication Requirements and Related Application Scenarios for Brain-Computer Interfaces. Information Communication Technology and Policy, 2024, 50(05): 12-17.

[4] Nichols K A, Okamura A M. A framework for multilateral manipulation in surgical tasks. IEEE Transactions on Automation Science and Engineering, 2015, 13(1): 68-77.

[5] Latif S, Qadir J, Farooq S, et al. How 5G (and concomitant technologies) will revolutionize healthcare. arXiv preprint arXiv:1708.08746, 2017.

[6] Shukla S, Hassan M F, Tran D C, et al. Improving latency in Internet-of-Things and cloud computing for real-time data transmission: a systematic literature review (SLR). Cluster Computing, 2023: 1-24.

[7] Name H A M, Oladipo F O, Ariwa E. User mobility and resource scheduling and management in fog computing to support IoT devices. 2017 Seventh International Conference on Innovative Computing Technology (INTECH), IEEE, 2017: 191-196.

[8] Tsuru T, Hasegawa M, Shoji Y, et al. An implementation and evaluation of MPTCP-based IoT router. Multimedia Tools and Applications, 2023, 82(18): 28389-28404.

[9] Botez R, Pasca A G, Sferle A T, et al. Efficient Network Slicing with SDN and Heuristic Algorithm for Low Latency Services in 5G/B5G Networks. Sensors, 2023, 23(13): 6053.

[10] Hashimoto D A, Rosman G, Rus D, et al. Artificial intelligence in surgery: promises and perils. Annals of Surgery, 2018, 268(1): 70-76.

[11] Andras I, Mazzone E, van Leeuwen F W B, et al. Artificial intelligence and robotics: a combination that is changing the

operating room. World Journal of Urology, 2020, 38: 2359-2366.
[12] Turki T, Al-Sharif A, Taguchi Y. End-to-end deep learning for detecting metastatic breast cancer in axillary lymph node from digital pathology images. Intelligent Data Engineering and Automated Learning–IDEAL 2021: 22nd International Conference, IDEAL 2021, Manchester, UK, November 25–27, 2021, Proceedings 22. Springer International Publishing, 2021: 343-353.
[13] Elendu C, Amaechi D C, Elendu T C, et al. Ethical implications of AI and robotics in healthcare: A review. Medicine, 2023, 102(50): e36671.
[14] Bessler J, Prange-Lasonder G B, Schaake L, et al. Safety assessment of rehabilitation robots: A review identifying safety skills and current knowledge gaps. Frontiers in Robotics and AI, 2021, 8: 602878.