5G Remotely Controlled Robot to Assist Hepatobiliary and Pancreatic Surgery

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Abstract. Based on the application of a 5G remotely controlled robot to assist Hepatobiliary and Pancreatic Surgery, this paper explores its research background, core technologies, security assurance, innovation difficulties, and future outlook. Nowadays, the incidence of hepatobiliary and pancreatic diseases is gradually increasing worldwide. Hepatobiliary and Pancreatic Surgery has a complex anatomical structure and great operational difficulty, which present challenges to the operating surgeons. With the development of 5G technology, remote surgery performed by robots has been promoted, providing a new solution to address surgical difficulties and the imbalance in medical resources. Then, this paper discusses some core technologies such as EndoChat MLLM, 5G/6G URLLC, and surgical robots, and analyzes the application value of this technology in hepatobiliary and pancreatic surgeries. 5G technologies are expected to solve various medical issues, meanwhile promoting the efficient utilization of social resources. This research provides important theoretical support for precision, minimally invasive and intelligentization of liver, gallbladder and pancreas surgeries.

Keywords: 5G Remotely Controlled Robot, Assist Hepatobiliary, Pancreatic Surgery

1 Introduction

With the intensification of global population aging, the morbidity of hepatobiliary and pancreatic diseases has increased, and China is further influenced by the regional allocation of medical resources. In addition, using the Theil index method indicates the existence of uneven allocation of urban and rural medical and health resources in China [1]. To decrease this kind of impact and achieve a balance in the allocation of urban and rural medical resources, while enabling regions with poor medical resources to also access high-quality surgical resources, the 5G remote-controlled robotic surgery has become an excellent solution. The emergence and development of 5G has become relatively mature, owning a large capacity and low signal latency, which lowers the access threshold for medical services [2]. Telemedicine cannot be separated from 5G advancements in recent years. In 2019, the Acemoglu team successfully performed an intraoral laser microsurgery of the vocal cords with an average latency of 102

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milliseconds, representing an early and significant practice in 5G-assisted surgery [3]. In the same year, according to Wang Z. [4], the Ling Pei team completed the first implantation of a "brain pacemaker" for Parkinson's disease in humans. The Tian Wei team achieved "One to Many" mode spinal surgery with an average latency of 28ms, which shows that 5G-remote robotic spinal surgery is both effective and feasible for spinal diseases [5]. In 2023, Cai Xiujun's team completed a domestic ultra-remote hepatobiliary surgery, which included cholecystectomy, hepatectomy, and pancreatic tumor resection. This time, surgery achieved a remarkable distance of 5000 km [6]. In Shanghai, a surgical team from a hospital's obstetrics and gynecology department successfully performed a single-port laparoscopic bilateral adnexectomy using the domestic Kangduo robotic surgical system, with an average latency of 108 ms [7]. This paper explores the application of 5G-remote control robots in hepato-biliary-pancreatic surgery. The core of this application lies in technologies such as URLLC (Ultra-Reliable Low-Latency Communication), high-standard image transmission systems (ZYNQ), MVVP, and EndoChat.

MLLM, and Toumai® surgical robots. The research analyzes the value of these technologies in ultra-remote surgeries, including low-latency communication, precise imaging, and intelligent decision support. However, challenges remain in technological, clinical, and ethical aspects. Moving forward, optimization of networks, improvement of evaluation systems, and strengthening of interdisciplinary talent training are necessary to promote the safety and intelligence development of ultra-remote complex surgeries, thereby enhancing medical equity.

2 Key Technologies

2.1 URLLC

Relevant research suggests that URLLC, with its reliability and low-latency wireless connection, has become a core component in the next-generation wireless communication field. Firstly, URLLC has an important feature, namely reliability. Its characteristic of being able to transmit a certain amount of data packets within a specified time with a low error rate is very crucial. 10-5 is defined as the minimum error probability under 5G networks. In the field of remote surgery, efforts are being made to reduce the error rate to 10-6 to 10-9 through ultra-5G technology [8, 9]. I.e., encompasses various types of reliability, such as the reliability of data transmission, the reliability of channel control, and the reliability of the availability of a given service [10]. Secondly, low latency means that the duration of data packets traveling between two nodes is extremely low. The latency requirement for URLLC technology is stipulated at 1m. Under 5G network conditions, reliability can reach 99.99% and latency can be within 1ms [8, 9]. Even if the communication technology is iterated to 6G, its latency can be further reduced to 0.1ms, and its reliability will also increase [10]. It is of great significance for ensuring the efficient implementation of remote surgeries.

2.2 High-standard Image Transmission System (ZYNQ, ARM+FPGA)

ZYNQ is a platform developed by combining the advantages of ARM and FPGA. The ARM processor and FPGA achieve seamless communication through an on-chip high-speed interconnection bus. The ARM is responsible for serial complex tasks, while the FPGA is responsible for parallel high-speed tasks. The two work in collaboration, and resources can be flexibly allocated, balancing “software flexibility” and “hardware efficiency” [11]. The collaboration of the two can achieve high-speed and stable data acceleration in image acquisition, image data exchange, and storage, providing a guarantee for the real-time transmission of surgical images.

2.3 Multimodal Fusion Virtual Vision Platform (MVVP)

MVVP is based on head-mounted display devices and integrates multimodal data such as medical images and vital signs in a three-dimensional virtual reality space, providing users with immersive information display [12]. To enhance the spatial perception of surgeons, improve surgical navigation and accuracy, and overcome the “blindness” of remote operations, the technical maturity needs to be further improved. Head-mounted devices may affect the comfort of doctors’ operations. They are suitable for surgical scenarios that require comprehensive processing of multimodal medical information, such as precise navigation and auxiliary decision-making in liver, gallbladder, and pancreatic surgeries. By integrating multimodal data and providing immersive three-dimensional virtual visual experience, they offer new ideas for the visual systems of surgical robots.

2.4 EndoChat MLLM

EndoChat MLLM is based on the Surg-396K dataset and extracts visual information at multiple scales through the Hybrid Visual Token Engine (MVTE) to achieve multi-round dialogue and reasoning using natural language processing technology [13]. It can handle unstructured and complex contextual information, conduct multi-round conversations through natural language, and provide intelligent assistance for surgical training and guidance. Model training requires a large amount of data and computing resources and may have problems with reasoning hallucinations. It is suitable for surgical training and teaching, helping trainees better understand the surgical process and master surgical skills, and can also assist doctors in making surgical decisions. This model constructed the Surg-396K dataset, developed a hybrid visual token engine, and proposed a method based on visual contrast to reduce model hallucinations.

2.5 Toumai® Surgical robot

The surgical robot system (domestic Toumai® robot) transmits surgical control signals via 5G network to control the mechanical arm for surgical operations. This system has high-precision motion control capabilities, enabling remote surgical operations, breaking through spatial limitations, with high surgical accuracy and short docking time [14]. However, it relies on 5G network coverage and stability. The surgical robot system itself may have risks such as mechanical failures. It is applicable to liver, gallbladder, and pancreatic surgeries in remote areas or regions with scarce medical resources, as well as complex surgeries that require remote guidance from experts. The Toumai® surgical robot is independently developed in China. It has broken through technical barriers and achieved clinical application of remote surgery, offering a high cost-performance ratio.

3 Analysis of technical application scenarios

3.1 5G/6G URLLC

5G URLLC already has a reliability of 99.999%, and 6G URLLC further improves its performance on this basis. The latency is reduced to 0.1 ms (1/10 of 5G), and the reliability is increased to 99.999999% (100 times that of 5G), with the ability of “near real-time” communication. Zhao Junhui systematically sorted out six core technologies, including the foundation of low-latency communication and the integrated network of air, space, and ground. Through means such as edge computing deployment, optimization of transmission time intervals, and simplification of protocol stacks, he solved the key problems of excessive latency and insufficient stability in remote communication[6,8-10]. Meanwhile, this technology supports 4K and even 8K resolution video transmission, capable of carrying real-time data from multiple high-definition cameras, such as the main knife, assistant, microscope, and endoscope. It maintains an extremely low packet loss rate and connection interruption rate during large-scale data transmission. Its application scenarios cover ultra-remote hepatobiliary and pancreatic surgery. For instance, the 5,000km external cholecystectomy and hepatectomy completed by CAI Xiujun's team in 2023 were precisely based on the low-latency feature of 5G URLLC, ensuring real-time response to surgical instructions, guaranteeing the continuity and stability of communication during the operation, and effectively avoiding the interruption of the surgery due to communication issues.

3.2 High-standard Image Transmission System (ZYNQ)

The ZYNQ platform integrates the technical advantages of ARM and FPGA, achieving seamless communication between the two through an on-chip high-speed interconnection bus. ARM excels in serial complex logic processing and has mature peripheral drivers. FPGA features hardware reconfigurability, supports parallel high-speed computing, has low latency, strong real-time performance, and a rich array of high-speed interfaces. Meeting the high-bandwidth requirements for high-speed image acquisition and transmission [11, 15]. The two work in collaboration and can flexibly allocate resources, considering both "software flexibility" and "hardware efficiency". The research team achieved seamless collaboration between the two through an on-chip high-speed interconnection bus, resolving the contradiction of "serial processing lag" and "insufficient parallel computing capacity" of traditional single processors, and achieving high-speed and stable acceleration in the image acquisition, data exchange, and storage links [11, 15]. On-chip interconnection has high efficiency, better power consumption, relatively high cost, high development threshold, and resource trade-offs. The application scenarios of this system focus on the transmission of effects in hepatobiliary and pancreatic surgery, and are suitable for medical endoscopic imaging, surgical robot vision systems, nanoknife ablation treatment systems, etc.

3.3 Multi-modal Fusion Virtual Vision Platform

In response to the limitations of traditional visual systems (such as the human eye and ordinary displays) in complex surgeries, including insufficient spatial perception and single information, MVVP builds an immersive interactive environment through VR/AR rendering engines, integrating image acquisition and processing from high-definition endoscopes and microscopes. It achieves functions such as three-dimensional reconstruction and real-time registration of preoperative CT/MRI/PET images, instrument tracking, and anatomical structure annotation. At the same time, it combines haptic feedback technology with real-time display of intraoperative physiological parameters (heart rate, blood pressure, blood oxygen). Research shows that by comparing the surgical outcomes of traditional stereoscopic vision systems (SV) with MVVP, MVVP significantly enhances the surgeon's spatial perception, shortens operation time, and increases the success rate of surgery. Especially for novice doctors in scenarios such as complex liver lesion resection, it can solve the problem of "blind operation" in remote surgery by superimposing virtual anatomical structures on the real surgical field [12].

3.4 EndoChat Multimodal Large Language Model

The EndoChat model is trained on the Surg-396K dataset containing 396,000 image-instruction pairs and integrates a hybrid visual token engine, enabling multi-scale visual information extraction and fusion [13]. It mitigates the target hallucination problem of multimodal large language models (MLLMs) through a visual contrast method and supports five dialogue paradigms and sub-tasks related to endoscopic surgery attributes. The research and development team of this model addresses the need for surgeons to quickly obtain information, such as instrument recognition, lesion localization, and operation guidance, during endoscopic surgery, solving the problems that traditional auxiliary systems have difficulty handling unstructured surgical contexts and lack interactivity [13]. Its application scenarios focus on intelligent assistance and training in hepatobiliary and pancreatic surgery. For example, in laparoscopic pancreatic tumor resection, it can real-time identify the types of surgical instruments, mark the boundaries between tumors and pancreatic ducts, provide operation step guidance for novice doctors, and support multi-round dialogue-based consultation, thereby enhancing surgical decision-making efficiency and training effectiveness.

3.5 Surgical robot system

The surgical robot system integrates haptic feedback technology (with a sensitivity threshold as low as 0.1N), which can sense the forces between instruments, tissues, and sutures in real time [14]. It can provide an additional control layer for the operation, which can improve surgical accuracy and reduce the risk of tissue damage. This system consists of a doctor's console, a patient's surgical platform, and an image platform, featuring microsecond-level response capability. The real-time image processing delay of the FPGA is less than 50ms, achieving nearly instantaneous visual feedback [14]. The R&D team verified its core advantages through comparative experiments: the master-apprentice response frequency reaches 4000Hz (far exceeding the 1333Hz of similar products), the steady-state deviation is ≤0.001mm, and the repeat positioning accuracy is ≤0.2mm, solving the problems of response lag, lack of tactile perception, and imaging delay of traditional surgical robots [14]. Its application scenarios cover complex liver, gallbladder, and pancreatic surgical operations, such as total endovascular radical surgery and precise resection of liver tumors. It is particularly suitable for scenarios where the surgeon cannot directly contact the patient during ultra-remote surgery. Through high-precision robotic arms and real-time feedback technology, it replicates the expert and operational accuracy.

4 Challenges and Development

4.1 Key Difficulties

Firstly, inadequate network coverage and stability pose a challenge, with 5G signals in some remote areas failing to meet surgical requirements. Secondly, equipment costs are high, and compatibility issues are prominent, making collaboration between devices from different brands and with different technologies difficult. In terms of clinical complexity and surgical practice, difficulties arise from real-time control challenges. Hepato-biliary-pancreatic surgeries demand high precision and real-time feedback. Furthermore, a lack of long-term efficacy and follow-up data means that a comprehensive evaluation system for the long-term effects of remote surgery is yet to be established [8, 10].

4.2 Technological Development

Achieving deep compatibility between 5G and domestic robots will optimize the synergy between communication and mechanical operation [8, 10, 14].

The introduction of a dual-dimensional latency standard based on "distance-surgical difficulty" will more accurately define latency requirements for different scenarios. Concurrently, the innovative "One to Many" multi-center surgical model will enhance the efficient utilization of surgical resources.

Innovations in safety and ethical frameworks will involve establishing robust safety assurance mechanisms and improving multi-dimensional ethical and legal regulations to provide institutional guarantees for technological application.

The expansion of scenarios and ecosystems can facilitate the implementation of ultra-remote complex surgeries, such as carrying out high-difficulty hepato-biliary-pancreatic surgeries remotely. Establishing an interdisciplinary talent training system will cultivate composite talents possessing knowledge in medicine, engineering, and communications.

5 Conclusion

This paper systematically investigates the application of 5G-controlled robotic surgery in hepato-biliary-pancreatic surgery. It clarifies the logical adaptation and clinical value of core technologies such as 5G/6G URLLC and EndoChat MLLM and validates the feasibility of domestic robots like Toumai® and the ZYNQ image transmission system in ultra-remote complex surgeries. Through capabilities such as low-latency communication, high-definition image transmission, and intelligent decision support, these technologies effectively overcome the issue of uneven geographical distribution of medical resources, providing high-quality surgical services to patients in remote areas. Research indicates that this technological system can enhance surgical precision and medical accessibility, serving as a crucial pathway to promote healthcare equity. In the future, the industry needs to further optimize network stability and equipment compatibility and improve the long-term efficacy evaluation system. With the deep integration of 6G, VR/AR technologies, the safety and intelligence of ultra-remote complex surgeries will continue to advance. Simultaneously, the establishment of an interdisciplinary talent training system will inject sustainable momentum into the standardized development of this field.

Authors Contribution

All the authors contributed equally, and their names were listed in alphabetical order.

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