ISSN 2959-6157

Innovative Application of Optoelectronic Control Engineering for Safety Assurance of Surgical Robots

Zhiming Zhang

Changchun University of Science and Technology, Changchun, Jilin, China

Abstract:

As an emerging technology, optoelectronic control engineering has demonstrated a wide range of application potential in surgical robot safety and security. Through a literature review, this paper provides an in-depth discussion on the innovative applications of optoelectronics technology in enhancing the positioning accuracy, environment sensing, supple control and remote operation of surgical robots. At the same time, this paper summarizes the current research hotspots and future research directions, with a view to providing a reference for promoting the technological progress in this field. The current research focuses on improving the operating precision of surgical robots, enhancing the environment sensing ability and the application of force feedback system, while the future research will mainly focus on interdisciplinary cooperation and new technology development.

Keywords: Optoelectronic control Engineering, Safety Assurance, Surgical Robots, Practical applications of optoelectronics

1. Introduction

1.1 Research Background

The development of surgical robotics began at the end of the 20th century, and with its advantages of high precision, minimally invasiveness and stability, it has rapidly gained wide application in the medical field. Today, surgical robots are used in all kinds of complex surgical operations, covering a wide range of aspects from minimally invasive surgery to telesurgery. However, despite the many benefits of surgical robotics, its safety remains an important issue that needs to be addressed.

During surgery, any small error may lead to serious consequences, so how to ensure the operation precision and environment sensing ability of surgical robots has become the key to the further development of surgical robot technology. As an advanced control technology, optoelectronic control engineering can significantly improve the safety and stability of surgical robots by means of high-precision optical sensors and real-time environmental monitoring systems. Therefore, the application of optoelectronic control engineering provides an important technical support for solving the challenges of surgical robots in terms of safety.

1.2 Research Significance

By reviewing the application of optoelectronic control engineering in surgical robot safety and security, this paper will reveal the current state-of-the-art in the field and explore its future directions. This paper aims to provide a comprehensive reference for researchers and engineers to help them better understand the practical applications of optoelectronics in surgical robots, as well as to provide inspiration for future technological innovations.

2. Literature review

2.1 Fundamentals of Optoelectronic Control Engineering

The core principle of optoelectronic control engineering is to utilize the effects produced by the interaction of photons (the elementary particles of light) with matter to achieve high-precision control and feedback of the system. For example, optoelectronic sensors are able to obtain precise information about the environment or objects by detecting changes in parameters such as the intensity, wavelength and phase of light. Common optoelectronic devices include lasers, photodetectors, and fiber optic sensors [1].

Optoelectronic sensing technology is usually mediated by optical fibers, and fiber-optic sensors can detect changes in physical quantities such as temperature, stress, and pressure. Their high sensitivity and resistance to electromagnetic interference make them widely used in many fields [2]. Meanwhile, optical imaging technology has also been applied to real-time monitoring and localization, for example, in surgical robots, which helps to improve the precision and safety of medical operations [1].

2.1.1 Key Technologies

2.1.1 .1 Fiber-Optic Sensor Technology

Fiber optic sensors are an important part of optoelectronic control engineering. It detects changes in physical quantities in the environment through the propagation of light in optical fiber. Due to the characteristics of optical fiber such as high sensitivity, high temperature resistance, and corrosion resistance, fiber optic sensors excel in complex industrial environments [2]. For example, fiber grating sensors are able to achieve accurate data acquisition during long-distance transmission and have important applications in aerospace, ocean exploration, and other fields.

2.1.1 .2 Laser technology

Lasers play a key role in optoelectronic control engineering as precision light sources. The high coherence and monochromaticity of lasers give them unique advantages in precision measurement, processing, and medical imaging. For example, laser interferometry can be used for precision length measurements, while laser cutting technology is used in precision manufacturing [1].

2.1.1 .3 Optical imaging technology

Optical imaging is one of the most important technologies used in optoelectronic control engineering to achieve real-time monitoring and localization. It utilizes the principles of reflection and refraction of light to generate high-resolution images that help users monitor system status in real time. In the medical field, optical imaging technology is widely used for navigation systems in surgical robots to reduce errors in doctor's operations by visualizing the surgical area [1].

2.1.2 Areas of application

2.1.2 .1 Automation field

Optoelectronic control technology has important applications in the field of automation. For example, in industrial automation, optoelectronic sensors can monitor the operation of production lines in real time to ensure the precision and efficiency of the manufacturing process. In addition, laser ranging sensors are widely used in automated robot navigation to help robots accurately locate and avoid obstacles in complex environments [2].

2.1.2 .2 Precision control

Optoelectronics is especially widely used in precision control. Through fiber optic sensors and laser interferometers and other equipment, users can obtain the state information of the controlled object in real time, and then realize the high-precision control of the system. This is of great significance in fields such as precision manufacturing, micromachining and aerospace. For example, fiber optic sensors are able to monitor the stress changes of aircraft wings, thus ensuring flight safety [2].

2.1.2 .3 Medical field

In the field of medicine, optoelectronic control technology greatly improves the precision of diagnosis and treatment by means of optical imaging and laser therapy. For example, laser surgery systems can achieve precise removal of diseased tissues through high-energy lasers while reducing damage to surrounding normal tissues. Optoelectronic technology is also widely used in medical robots to help doctors achieve more precise operations during complex surgeries [1].

2.2 Research on the safety of surgical robots

Research on the safety of surgical robots mainly focuses on the following aspects: precision control, environment sensing, supple control and force feedback, and teleoperation.

2.2.1 Precision Control

The precision control of surgical robots is the core of ensuring their safety. Current research is mainly focused on the introduction of high-precision optoelectronic sensors to realize the precise measurement of the position and angle of surgical instruments. Optical devices such as fiber grating sensors are widely used to enhance the positioning accuracy of surgical robots, especially in minimally invasive surgery, which significantly reduces surgical errors by monitoring the tiny displacement of instruments in real time [1]. Of course, some scholars have also worked out the concept of fully-aware robotic surgical environment and constructed a joint global-local localization framework [3].

2.2.2 Environment Sensing

Surgical robots must be able to operate safely in complex surgical environments, so the improvement of environment perception is also the focus of current research. By combining optoelectronics technology with machine vision, surgical robots can realize real-time monitoring of the surgical area and environment perception. For example, the development of tele-surgical robots with adaptive control and the use of haptic feedback for tissue identification [4].

2.2.3 Supple control and force feedback

Flexible control technology and force feedback systems enable surgical robots to make real-time adjustments to the applied force during operation to avoid excessive injury to the patient. Optoelectronic sensors are able to detect small force changes during surgery, thus providing more precise control signals to the surgical robot. This not only improves the safety of surgery, but also makes the robot operation more humanized and intelligent [4].

2.2.4 Teleoperation

Teleoperation is an important application direction of surgical robotics. However, remote operation has extremely high requirements for real-time and stability. Optoelectronic technology ensures the synchronization and accuracy between the surgical robot and the operating end through high-speed optical communication, which greatly reduces the delay and improves the safety of teleoperation. [3]

2.3 The application of optoelectronic control engineering in the safety and security of surgical robots

2.3.1 Accuracy enhancement

By introducing opto-electronic sensors, surgical robots are able to achieve higher operating precision in complex surgical environments. For example, fiber grating sensors can monitor the position and status of surgical instruments in real time, thus reducing the risk of misoperation. The high sensitivity and precision of these sensors enable surgical robots to perform operations in minimally invasive surgeries in a more stable and precise manner [1].

2.3.2 Environmental sensing

The integration of optoelectronics technology and machine vision enables surgical robots to sense changes in the surgical environment in real time. For example, through optical sensors, the robot is able to detect obstacles in the surgical area and automatically adjust the operation path. The application of this technology in complex surgical environments significantly improves the safety of surgery.

2.3.3 Flexible control and force feedback

Optoelectronic control technology also plays an important role in the pliable control and force feedback system of surgical robots. Through real-time monitoring of the force exerted during surgery, optoelectronic sensors can provide precise mechanical feedback for the surgical robot to ensure the safety and effectiveness of surgical operations. The importance of force feedback systems in precise control is increasingly emphasized, especially in minimally invasive surgeries and complex operations, where they can prevent excessive forces from harming the patient [1].

2.3.4 Telesurgery

The realization of remote operation cannot be realized without the support of optoelectronic technology. Optoelectronic sensors can transmit the operation information of the surgical robot to the remote control terminal in real time through a high-speed communication network to ensure the accuracy and safety of the operation. This is not only widely used in traditional operating rooms, but also shows great potential in telemedicine and battlefield medicine.

2.4 Innovation points and challenges

There are several innovation points in the application of optoelectronic control engineering in the safety and security of surgical robots. First, the development of new optoelectronic sensors has greatly improved the precision and stability of surgical robots. For example, sensors based on fiber grating can work stably in harsh environments such as high temperature and high pressure, which provides a reliable guarantee for the application of surgical robots in complex surgeries.

Secondly, the combination of optoelectronic control technology and machine learning has become a research hotspot. Through machine learning algorithms, surgical robots are able to autonomously adjust their operating strategies on the basis of real-time monitoring data, thus improving the intelligence of surgery.

However, the application of optoelectronic control engineering in surgical robots still faces many challenges. First, the precision of optoelectronic technology is limited by the performance of optical devices, and the robustness and stability of optical systems in complex surgical scenarios still need to be improved. In addition, the problem of time delay and data loss in remote surgery is still a technical challenge that needs to be solved.

2.5 Future Research Directions

Future research should further improve the precision and stability of optoelectronic sensors, especially in complex surgical environments. The development of new optoelectronic technologies, such as fiber optic sensors, will provide surgical robots with higher operating precision and stability. At the same time, the combination of optoelectronic technology and artificial intelligence will further promote the intelligent development of surgical robots.

Interdisciplinary cooperation will also become one of the focuses of future research. The application of optoelectronics technology is not only limited to surgical robots, but also has a wide range of application prospects in automation control, precision manufacturing and other fields. Therefore, promoting the further development of optoelectronic control technology through interdisciplinary cross-cooperation will bring new opportunities for the advancement of surgical robot technology.

3. Conclusion

Optoelectronic control engineering shows a wide range of application prospects in the safety and security of surgical robots. By enhancing the capability of surgical robots in terms of precision, perception and supple control, optoelectronic technology can significantly improve the safety of surgery. Future research should focus on technological innovation and interdisciplinary cooperation to promote the continuous development of this field.

4. References

[1] B. W. Cunningham, D. M. Brooks, and P. C. McAfee, “Accuracy of Robotic-Assisted Spinal Surgery—Comparison to TJR Robotics, da Vinci Robotics, and Optoelectronic Laboratory Robotics,” International Journal of Spine Surgery, vol. 15, no. s2, p. S38, 2021, doi: 10.14444/8139.

[2] P. Niu, L. Pei, Y. Mei, H. Bai, and J. Shi, “Optoelectronic Materials, Devices, and Applications,” Applied Sciences, vol. 13, no. 13, p. 7514, 2023. [Online]. Available: https://www.mdpi.com/2076-3417/13/13/7514.

[3] H. Wang, T. Liu, J. Chen, C. Fan, Y. Qin, and J. Han, “Full-Perception Robotic Surgery Environment with Anti-Occlusion Global–Local Joint Positioning,” Sensors, vol. 23, no. 20, p. 8637, 2023. [Online]. Available: https://www.mdpi.com/1424-8220/23/20/8637.

[4] Y. Sheng, H. Cheng, Y. Wang, H. Zhao, and H. Ding, “Teleoperated Surgical Robot with Adaptive Interactive Control Architecture for Tissue Identification,” Bioengineering, vol. 10, no. 10, p. 1157, 2023. [Online]. Available: https://www.mdpi.com/2306-5354/10/10/1157.