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Research on autonomous obstacle avoidance and automatic obstacle avoidance of minimally invasive surgical robots

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Abstract. With the development of modern society, people pay more and more attention to health and safety, especially to the development of medical techniques. The demand for higher medical standards has led to minimally invasive surgery becoming a better choice for patients. Minimally invasive surgeries involve less trauma, lower blood loss, quicker recovery, and a lower risk of infection. However, compared to traditional surgeries, these surgeries demand higher precision and skill from the surgeons, making surgical robots the preferred tool for most minimally invasive operations. Surgical robots can eliminate the surgeon's hand tremors during the operation, enhance the precision of surgical operations, and offer greater flexibility with their small end size inside human organs. Despite these advantages, minimally invasive surgical robots can not avoid obstacles and plan the path of human organs and cavities in real-time. This paper reviews the dynamic path planning and real-time obstacle avoidance of modern minimally invasive surgical robots, including their development progress and research directions. It also introduces in detail the mainstream research methods of path planning and real-time obstacle avoidance in modern research. Finally, the current technical challenges and the prediction of the future research direction are pointed out and the reference suggestions are provided.

Keywords: Minimally invasive surgical robots, Path planning, Real-time obstacle avoidance.

1. Introduction

In 1985, the first robot-assisted minimally invasive surgery was successfully completed, marking the official clinical application of surgical robots. Surgical robots account for about 37% of the four categories of medical robots, and the precision of remote surgical robots has been greatly improved with the development of the Internet of Things (IoT) and 5G technology [1]. Therefore, medical robots have great development prospects in the future. Among them, laparoscopic robots are more technologically mature compared to orthopedic, neurosurgical and vascular intervention robots. A leading company in this field is Intuitive Surgical Inc. of the United States, whose “Da Vinci” surgical robots account for half of the global surgical robot market [2]. Laparoscopic robots are often used in minimally invasive surgery, which mainly relies on natural body cavities, artificial incisions (small surgical openings) and laparoscopy. The advantages of minimally invasive surgery include smaller trauma to the human body, faster recovery of patients after the operation, reduced blood loss during and after the operation, minimal risk of anemia, and a lower chance of wound infection [3]. Laparoscopic robots can reduce hand tremors caused by physiological activity in the surgeon's hands and optimize the surgeon's ability to operate.

The physiological activity of the surgeon's hands can cause slight laparoscopic movement in the body's cavities, thus hindering the surgeon's complex anatomical movements in small cavities [4].

Although the advantages of surgical robots for traditional surgery are obvious, but their shortcomings can not be ignored. I. In the aspect of robot size optimization, there are some problems in minimally invasive surgical robots, such as poor collaborative obstacle avoidance performance and global accessibility in multiple manipulators [5]. These issues can lead to collisions between connecting rods of external manipulators and prevent them from reaching part of surgical areas. Due to the main master-slave teleoperation mode of current surgical robots, the lack of automatic trajectory planning function and dynamic obstacle avoidance functions [6], and the easy fatigue caused by long-time operation of surgical instruments by surgeons, there is a risk that surgical robots will damage the patient's normal tissues. At the same time, remote sensing operations make it more difficult for surgeons to get started and requires more experience.

The obstacle avoidance technology of surgical robots ensures the safety and accuracy during surgery. The research on these aspects is carried out at home and abroad to solve the problem of mistouching during the operation of minimally invasive surgical robots, and to optimize their ability of autonomous obstacle avoidance and real-time path planning [7].

Potential field approaches were common in the early stages of feedback motion planning. In this method, a particle is used to represent the surgical robot, and a global potential field function is used to represent the working space of the robot. By moving along the negative gradient of this global potential field function, the robot can reach the target point. The main idea of the potential field method is to combine the attractive potential field at the target position and the repulsive potential field at the obstacle position into a global potential field function. Therefore, the robot can avoid obstacles and move to the target position under the combined action of the attractive force of the attractive potential field and the repulsive force of the repulsive potential field. However, the above-mentioned method has a limitation, that is, the robot may easily fall into the local minima of these global situation field functions, and thus can not reach the predetermined end point [8].

In conclusion, although the future of minimally invasive surgical robots is promising, there are still many problems to be solved. For example, robotic arms are still too large compared to the human body and lack inflexibility; they are expensive and not widely accessible; and they can not provide real-time force sense to the primary surgeon, requiring high skill levels from operators. In the future, more real-time data can be provided to reduce the skill requirements for operation, and more and more problems will be found and solved with the development of future technology.

2. Related works

In 2015, Luis et al. proposed a motion planning method for automatic obstacle avoidance in the remote operation of concentric-tube robots, which enables the robot to move its end to a user-selected point while automatically avoiding obstacles on the axis. The concrete method involves pre-calculating a collision-free motion path in advance based on the description of obstacles, allowing the robot to avoid vascular-type obstacles. But this method requires prior medical imaging to determine the position of obstacles before calculating, so it can not avoid obstacles in real time. Moreover, this method adopts the Rapidly-exploring Random Trees (RRT) (RRT) in path planning. This sampling-based algorithm has high computational demands and is only suitable for offline motion planning in simple structured environments, which limits the use of this method in dynamic scenes [9].

Shinsuk Park et al. from Harvard University proposed a virtual fixture construction scheme for robotic cardiac surgery. This method uses CT scans to define the location of the internal mammary artery (IMA) and records the patient's anatomical structure into the image data, then generates a virtual fixture to restrict the movement of the terminal instrument of surgical robots, which can be moved to an appropriate position next to an artery at the surgeon's command. But the virtual fixture used in this method is static, so it is difficult to restrict the robot's movement and avoid obstacles in real time in dynamic environments.

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Huaque series of robots are developed by Harbin Institute of Technology and other institutions. The characteristics of this series of robots are that they have double endoscopes. However, this system also lacks the function of dynamic obstacle avoidance capabilities, so it is difficult to adapt to dynamic environments such as cardiac and pulmonary surgeries. The “Micro Hand” series surgical robots are developed by Tianjin University and other institutions. The following picture shows the “Micro Hand S” surgical robot system. The robot motion control system is also based on remote control, but the dynamic obstacle avoidance function is not realized [10].

In a word, both domestic and foreign researchers can not deal with and solve the problems of not being usable in dynamic scenes and lacking autonomous obstacle avoidance.

3. Mainstream optimization methods

The position planning algorithm of surgical robots based on improved artificial potential field is used to calculate the shortest distance between the obstacle and the connecting rod of the manipulator by improving the gravity function and using the fast convex hull algorithm and Gilbert Johnson Keerthi (GJK) algorithm, the ability to reach the planned position quickly and smoothly while avoiding obstacles is realized. With the introduction of adaptive step size and dynamic gravitation constant, this method makes the manipulator have the ability to escape from local minima, which provides a new idea for surgical robots [11].

The method of obstacle avoidance for mobile robots based on multi-sensor combines the visual sensors and infrared distance sensors. It extracts obstacle information by optical flow methods and combines distance information from infrared distance sensors, autonomous obstacle avoidance of mobile robots is realized. The effectiveness of this method is verified by experimental results. (SLAM) [12]

The online obstacle avoidance motion planning algorithm based on the improved RRT* realizes the requirements of online obstacle avoidance in dynamic environment by the strategy of pre-planning and re-planning. This algorithm can replan the path when the target point moves and form a closed-loop control until the manipulator moves to the target point [13].

Based on fuzzy control, a set of manipulator mobile robots is designed, which is composed of PLCs, motor drivers, servo motors and so on, as a research platform. The fuzzy control obstacle avoidance technology of mobile robots is studied. This system uses ultrasonic sensors to detect environmental information, and designs an autonomous obstacle avoidance control system based on fuzzy algorithm and behavior control [14].

The obstacle avoidance system of wheeled robots based on ARM is studied by using ARM controllers, multi-sensor fusion technology and fuzzy control technology. The multi-sensor is used to collect the obstacle distance information in the unknown environment, and according to the different distance information, a fuzzy control algorithm with obstacle avoidance function is developed, then the motion state of the wheeled robot is controlled.

The obstacle avoidance techniques of surgical robots include improving artificial potential field algorithm, multi-sensor fusion, fuzzy control and online obstacle avoidance motion planning algorithm. These methods have their own characteristics and can meet the obstacle avoidance requirements in different surgical environments and requirements.

4. Research progress

The latest progress of obstacle avoidance technology for surgical robots is focused on autonomous obstacle avoidance algorithm based on deep learning. By using deep learning convolutional neural network, combining with high efficient fusion modules, multi-scale detection modules and multi-receptive field aggregation detection modules, the technique can detect obstacles with high accuracy and high speed. In addition, it combines binocular stereo vision technology to build a system that can detect obstacles in three-dimensional space, which enables the robot to accurately identify and avoid obstacles in a complex environment.

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Specifically, the obstacle avoidance technology based on deep learning improves the precision and speed of image processing by training network models, so that the mobile robot system has the end-to-end output capability, and intelligent obstacle avoidance decision is realized. For example, the experiment of this technique in the scene of building passage shows that the robot can make accurate obstacle avoidance decision, calculate the obstacle avoidance angle in time, and guide the robot to avoid the obstacle effectively.

5. Performance of salm technology in robot autonomous obstacle avoidance

The obstacle avoidance method based on multi-sensor for mobile robots performs well in practical application, and has high flexibility and robustness. By integrating and fusing data from different sensors, these methods improve the recognition accuracy of obstacles and the efficiency of obstacle avoidance decision.

Multi-sensor systems can provide rich environmental information, such as distance, angle and shape, which is essential for accurate navigation and effective obstacle avoidance. For example, using millimeter-wave radar, LiDAR, and binocular vision sensors can effectively detect and avoid obstacles. In addition, by using algorithms such as Kalman filter, we can further reduce the impact of environmental noise and improve the accuracy of data.

The application of multi-sensor information fusion technology improves the autonomous obstacle avoidance ability of mobile robots significantly. By effectively fusing the data from different sensors, the position and size of obstacles can be estimated more accurately, thus making more accurate obstacle avoidance decisions. For example, the combination of neural network and fuzzy neural network not only reduces the uncertainty of sensor information, but also improves the flexibility and adaptability of the system.

6. Conclusion

In this paper, the mainstream methods of real-time obstacle avoidance and path planning in dynamic environments for surgical robots as well as their significant impact and applications in the field of modern surgical robots are reviewed. Through the combination of multi-sensor methods and the construction of virtual fixtures, the obstacle avoidance and dynamic path planning of minimally invasive surgical robots are optimized in many directions. Researchers have made significant progress with SLAM, fuzzy control, multi-controllers and multi-sensors, providing more flexible and standardized solutions for real-time obstacle avoidance in dynamic environments. This advancement contributes to the development of safer, more widespread, and higher-quality surgical robots in the future. In this paper, we summarize many kinds of domestic and international real-time obstacle avoidance schemes for surgical robots and application cases of practical problems, and analyze the cases objectively and comprehensively. This paper also discusses the main challenges that minimally invasive surgical robots are facing at present, including the inability of the robot to plan its path in real time under dynamic environments, issues related to the safety of surgical robots, high operational threshold, and the lack of true automatic mechanical arm's adjustment and the movement in the human body.

The future of surgical robots with the advancement of SLAM, multi-controller and dynamic fuzzy control techniques is very bright. The potential field method will continue to play an important role in dynamic path planning of surgical robots. In the future, surgical robots will be more widely used with the support of a variety of technologies, such as orthopaedics, cardiovascular, and neurosurgery to heal more patients. In the future, surgical robots should be developed in the direction of materials and system operations, which can reduce the manufacturing costs, lower the operation threshold and improve the universality of minimally invasive surgical robots. With the rapid development of software, the size of robots becomes smaller and smaller, and the size of robot arms becomes more and more fine, which can meet more operating conditions.

Through continuous research on path planning and real-time obstacle avoidance for surgical robots, based on SLAM technology and fuzzy control, surgical robots will provide power for the development of surgery in more aspects. Of course, the development of surgical robots is not limited to the efforts of

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researchers, but also needs the support and cooperation of social departments to ensure that surgical robots can be recognized and widely used in society.

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