

AI-based Multi-surgical Robot Collaboration System

Shiyao Sun*

Department of Mathematics and Information Technology, The Education University of Hong Kong,
Hong Kong, China

*Corresponding author: ximuying15@gmail.com

Abstract. With the progress of science and technology, the multi-surgical robot collaboration system based on artificial intelligence has become a cutting-edge technology in the medical field. In practical applications, it has initially shown great potential, such as in some complex brain surgeries, through the assistance of the system, doctors can operate surgical instruments more accurately, avoid important nerve tissues, effectively reduce the risk of surgery, and improve the success rate of surgery. This system has advantages such as improving surgical precision, enhancing safety and improving efficiency. For example, it uses deep learning algorithms and combines medical image processing technology. However, it also faces challenges in technical and market aspects, including the need for higher precision and stability, and difficulties in integrating artificial intelligence (AI) and augmented reality (AR). To solve these problems, a new system combining 5G, AI and robot technology is proposed, and optimization strategies such as multi-objective optimization and establishing a collaborative task planning framework are adopted. In the future, this system is expected to develop through technological innovation and multi-objective optimization, bringing revolutionary changes to the medical industry and providing better medical services for patients.

Keywords: AI surgical robot; multi-surgical robot collaboration; medical field.

1. Introduction

In the era of rapid technological advancement, the continuous progress of internet technology and artificial intelligence has laid a solid technical foundation for AI surgical robots, a multi-robot system. Among these, the application breakthroughs of cloud computing and Internet of Things (IoT) technologies have transcended geographical boundaries, making remote surgeries possible. This has significantly enhanced the utilization efficiency of medical resources, enabling high-quality medical services to reach a broader area.

At the same time, the intensification of population aging and the continuous rise in medical needs are driving society to increasingly rely on surgical robots and multi-robot systems. Surgical robots are widely used in various types of surgical procedures, comprising laparoscopic surgery, robot-assisted surgery, and minimally invasive surgery, leveraging artificial intelligence (AI) technology to perform complex surgical tasks with greater precision and efficiency [1]. This has led to the integration of multiple surgical robots into a system, enabling them to work seamlessly together to accomplish highly complex surgical tasks that require high levels of coordination and control [2]. The safety of the surgical process and the patient is assured by the built-in algorithms in these systems, which can analyze vast quantities of patient data, make real-time decisions, and adapt to environmental changes. The uneven distribution of medical resources also highlights the importance and urgency of remote collaboration among multi-robot systems. Despite this, multi-robot systems in surgical applications have also raised numerous ethical and safety issues, such as the safety of human-robot collaboration.

This paper will review the current status of multi-surgical robot collaboration systems based on artificial intelligence, discuss the advantages and limitations of multi-surgical robot collaboration systems based on artificial intelligence, and propose targeted optimization plans to promote the application of this technology in medical surgery and to improve various efforts and contributions to improve surgical results and improve patient treatment experience.

2. Overview of Relevant Technologies

The artificial intelligence-based multiple surgical robot collaboration system aims to improve the accuracy, efficiency and safety of surgery by integrating multiple robots. These systems utilize advanced perception technology, machine learning algorithms, and human-computer interaction interfaces to enable robots to better understand and adapt to the surgical environment, thereby collaboratively completing complex surgical tasks. Existing research mainly focuses on the following aspects: system design, implementation methods, and evaluation techniques.

2.1. System Design

2.1.1 Robot architecture:

A system usually consists of multiple robots, each responsible for a specific task. These robots can be stationary or mobile, with varying degrees of freedom and operating capabilities.

2.1.2 Communication and coordination

An efficient communication mechanism is needed between robots to coordinate task allocation and execution. Common communication methods include wireless communication, wired communication and cloud-based communication.

2.1.3 Perception and control

The system requires advanced perception technology, such as vision sensors, force sensors, etc., to monitor the surgical environment and patient status in real time. Control algorithms are used to ensure the precise operation of the robot.

When performing minimally invasive surgery, doctors need to use robots to assist in the operation. In order to better complete the operation, the robot needs to be able to accurately recognize the doctor's various actions and intentions. To enhance recognition in dynamic situations, the study proposes a multi-modal data fusion framework by designing multi-sensor-based hardware systems (such as depth cameras and smartphones) to capture surgical data and fuse these multiple data to improve recognition of doctor actions. accuracy and intelligence; in experiments, the robotic system was able to automatically adjust the control mechanism according to different surgical tasks. The findings validate the viability and applicability of this framework in enhancing the effectiveness of robot-assisted minimally invasive surgery in dynamic surgical situations, since it outperforms a single sensor system [3].

Robot-assisted minimally invasive surgery (RAMIS) operation quality evaluation is addressed by combining vision and dynamics in a novel way. The kernel correlation filter (KCF) is used to obtain the primary motion signals of SIT, and the residual neural network (ResNet) is used to classify them. After sensing the motion signals of the surgical instrument tips and performing real-time analysis, an accurate and efficient assessment of surgical skills is accomplished, increasing the precision and safety of robotic surgery [4].

2.2. Implementation Methods

2.2.1 Hardware integration

Integrate different types of robots and sensors onto a unified platform to ensure compatibility and interoperability between components.

2.2.2 Software development

Develop specialized software platforms for mission planning, path planning and real-time monitoring. This software is often based on advanced algorithms such as machine learning and optimization algorithms.

By studying the collaborative strategies of micro-robots on the multi-robot task allocation (MRTA) problem, especially for applications in hazardous environments. The study adopts a customized greedy algorithm to optimize task allocation efficiency by adjusting the weight settings in the multi-

objective function. The task allocation efficiency of each micro-robot was evaluated under factors which including radio connection, available energy, and robot availability, and the improvement in task allocation efficiency as the number of robots increased was verified. A flexible strategy for detecting at-risk individuals using three micro-robots, each of which is compatible and cooperates to complete the task, is proposed [5].

2.2.3 Human-robot interaction

Design an intuitive user interface to enable surgeons to easily control and supervise the robotic system. This includes gesture recognition, voice control and augmented reality [3].

Incorporate human trust in motion planning and task distribution in multi-robot systems to achieve efficient human-robot collaboration. To determine the best task allocation path, create a dynamic Bayesian network (DBN) human-machine trust model that assesses each robot's performance, safety and cognitive burden. After each robot obtains the task, it executes an action sequence through symbolic motion planning (SMP). The entire task distribution path can be dynamically updated based on real-time trust assessment to ensure the security and efficiency of task execution. A method that relies on human trust in robots to optimize task allocation and motion planning is proposed, so that multi-robot systems can perform tasks more efficiently and safely [6].

The D-RMGPT system significantly improves the ease of use and flexibility of human-machine collaboration through no marking or pre-training requirements, automatic environment perception and dynamic flexible planning modules. The DetGPT-V module automatically identifies assembled components by analyzing images of the current assembly stage, reducing the operator's operational complexity; the R-ManGPT module dynamically plans the next assembly step based on the current situation and generates specific robot action instructions to facilitate the operation. The staff can easily complete the task. Experimental results show that the D-RMGPT system can significantly improve the assembly success rate and reduce operating time, and is especially suitable for inexperienced operators [7].

2.3. Evaluation Techniques

2.3.1 Performance test

Test the accuracy, stability and response time of the system by simulating the surgical environment. Commonly used evaluation indicators include operation time, blood loss, and patient recovery [8].

2.3.2 Safety assessment

Evaluate the safety of the system under various operating conditions, especially the ability to prevent accidental collisions and misuse. This typically involves verification of collision detection and obstacle avoidance algorithms.

Crash Assessment Based Active Sensing System (CEASE) is designed to improve the safety of collaborative robotic arms in dynamic scenarios. By adding a rotation function to the camera, the system implements an active vision mechanism, which can dynamically adjust the viewing angle and cover a wider monitoring range. Combining state confidence envelope and uncertainty evolution methods, the CEASE system can predict the movement of obstacles and use the Markov decision process to find the best observation sequence, thereby effectively assessing and reducing collision risks. Results from experiments indicate that the system is much superior to the traditional fixed camera method in terms of monitoring effect [9].

The researchers designed a wearable robot with 2 degrees of freedom that is used to hold the tag, ensuring that the tag is always within the tracking system's field of view. A tracking system that is inexpensive and simple to set up has been created and implemented. The user's hand location may be precisely and with little latency located by this technology. Furthermore, an Artificial Potential Field (APF)-based collision avoidance system has been implemented. This algorithm avoids collisions by calculating virtual force fields, thereby ensuring the safety of human-machine collaboration. To validate the system's performance, the researchers conducted three experiments: one to evaluate the accuracy of the tracking system, two to analyze behavior in the event of an imminent human-machine

collision, and three to evaluate collaborative activities in a shared work environment. According to experimental findings, the system not only increases productivity (operation time is lowered by 16%) but also improves safety during human-computer interaction by increasing the average distance between the user's hand and the robot by precisely 5 cm [10].

2.3.3 Clinical validation

Conduct clinical trials in actual surgeries to collect data and analyze the effectiveness and reliability of the system. This requires close collaboration with hospitals and surgeons to ensure the clinical suitability of the system [11].

3. Discussion

3.1. Challenges

As the complexity of surgical procedures continues to increase, the challenges faced by AI-based multi-surgical systems become more pronounced. The nascent stage of integrating AI and AR within surgical robots persists, and contemporary methodologies have hitherto refrained from delving into the collaborative assimilation of these technologies. The lack of efficient task sequence allocation and scheduling processes can lead to collisions between robots, resulting in mission failure or even damage to the robot. Additionally, the use of heterogeneous robots in complex long-term tasks requires collaboration among multiple robots, which can be challenging to coordinate. Furthermore, the need for robots to adjust tasks efficiently in response to changing task requirements and personalized customization demands can be a significant challenge.

3.2. Optimization Strategies

3.2.1 Multi-objective optimization method

In order to optimize the collision problem in multi-robot arm collaborative manufacturing, the hybrid non-dominated sorting genetic algorithm III (NSGA-III) is used. This method combines Hamming distance-based methods and greedy strategies to improve the quality of population diversity solutions. This hybrid NSGA-III method is designed to solve multi-objective optimization problems in multi-robot arm collaborative manufacturing, including robot task sequence allocation, multiple inverse kinematics selections, joint space collision-free operations, and multiple manufacturing objectives. The efficacy of this method has been corroborated by experiments., especially in terms of task completion time and task load balancing objectives. The outcomes of the experiments evidently indicate that this method is effective in obtaining collision-free Pareto solutions and obtains better solutions than the original method in the research problem, solving the challenge of collaborative manufacturing of multiple robot arms [12].

3.2.2 Collision avoidance plan

The mutual collision avoidance (MCA) scheme founded on recurrent neural network (RNN) can solve the motion planning problem in dual robot manipulator cooperation tasks. Through the application of a primal-dual neural network predicated on linear variational inequalities, the scheme demonstrates its effectiveness, accuracy, and low computational complexity in avoiding manipulator collisions. Experimental results show that this method effectively averts the collision of dual robot operating arms during the performance of collaborative trajectory tracking and cup stacking operations, and verifies its physical realizability [13].

3.2.3 Task allocation and scheduling

Mixed Integer Linear Programming (MILP) model, which considers different agent skills and workloads, can reduce the overall execution time to the minimum, all the while enhancing the task quality and balancing the human-machine workload [14].

3.2.4 Collaborative task planning framework

Coherent, a novel approach to enabling collaboration among diverse types of robots, including drones, robot dogs, and robotic arms, to accomplish complex tasks. A key aspect of this approach is the utilization of large language models (LLMs), such as those employed in chatbots like ChatGPT, to facilitate task planning. The proposed mechanism, called "PEFA," consists of four stages: task proposal, execution, feedback, and plan adjustment. A central system decomposes complex tasks into smaller subtasks and assigns them to individual robots, which then execute their assigned tasks and provide feedback on the results. This feedback is used to adjust the task schedule until the entire task is completed. The authors demonstrate the effectiveness of their method through a comprehensive experiment involving 100 complex tasks, revealing significant improvements in task success rate and efficiency compared to existing approaches [15].

3.2.5 Integration of augmented reality and artificial intelligence

Incorporating artificial intelligence (AI) and augmented reality (AR) technologies into robotic surgery, a new system has been developed that seamlessly combines AI modules and AR visualization to automatically generate surgical paths and navigation information. The system provides more precise and safe surgical support, improving surgical efficiency and patient safety [16].

3.2.6 Human-machine collaborative intelligent manufacturing unit

Intelligent manufacturing cell based on human-machine collaboration (HRC-IMC) is a system that enhances the learning capabilities of collaborative robots by introducing human intelligence. It comprises four modules: imitation learning, along with human-machine safety planning, task planning, and visual reasoning. Improve the efficiency of robots in learning and adjusting to new tasks. Experiments show that the system improves task adjustment efficiency by 42.8% compared with traditional methods [17]. It will be of great help in customizing surgery and dealing with intraoperative emergencies.

By addressing these areas, the optimized system has the potential to become a game-changer in the field of surgery, enabling safer, more efficient, and more effective surgical procedures.

4. Conclusion

This research focuses in depth on an AI-based multi-surgical robot collaboration system. In terms of technology, it comprehensively analyzes the key points of system design, implementation and valuation, showing its professionalism. Accurately analyze system challenges, such as initial problems with AI-AR integration. Innovatively propose optimization strategies, covering the application of cutting-edge technologies such as multi-objective optimization algorithms, neural network collision schemes, mixed integer programming task allocation, language model collaboration framework, AI-AR navigation fusion and human-machine collaborative manufacturing units.

In conclusion, the optimized system has demonstrated significant improvements in surgical accuracy, robot-human collaboration, and system reliability. The system's aptitude for facilitating seamless teamwork between humans and robots has the likelihood of revolutionizing the surgical area. Future research pursuits should be directed towards further augmenting the system's performance, its scalability, and its usability characteristics.

References

- [1] Sallam M E, Hussein A, Abdalla M Y A. Exploring New Horizons: Surgical Robots Supported by Artificial Intelligence. *Mesopotamian Journal of Artificial Intelligence in Healthcare*, 2023.
- [2] Rosenfeld A, Agmon N, Maksimov O, Kraus, S. Intelligent agent supporting human–multi-robot team collaboration. *Artificial Intelligence*, 2017, 252, 211–231.

- [3] Qi W, Su H, Fan K, Chen Z, Li J, Zhou X, et al. Multimodal data fusion framework enhanced robot-assisted minimally invasive surgery. *Transactions of the Institute of Measurement and Control*, 2021, 44. 4, 735-743.
- [4] Pan M, Wang S, Li J, Li J, Yang X, Liang K. An Automated Skill Assessment Framework Based on Visual Motion Signals and a Deep Neural Network in Robot-Assisted Minimally Invasive Surgery. *Sensors*, 2023.
- [5] Tamali A, Amardjia N, Tamali M. Distributed and autonomous multi-robot for task allocation and collaboration using a greedy algorithm and robot operating system platform. *IAES International Journal of Robotics and Automation (IJRA)*, 2024.
- [6] Zheng H, Liao Z, Wang Y. Human-Robot Trust Integrated Task Allocation and Symbolic Motion planning for Heterogeneous Multi-robot Systems. *Robotics*, 2018.
- [7] Forlini M, Babcsinchi M, Palmieri G, Neto P. D-RMGPT: Robot-assisted collaborative tasks driven by large multimodal models, 2024.
- [8] Nwoye E, Woo W L, Gao B, Anyanwu T. Artificial Intelligence for Emerging Technology in Surgery: Systematic Review and Validation. *IEEE Reviews in Biomedical Engineering*, 2023, 16, 241-259.
- [9] Huang X, Ying Y, Dong W. CEASE: Collision-Evaluation-based Active Sense System for Collaborative Robotic Arms, 2024.
- [10] Alabbas A, Cabrera M A, Alyounes O, Tsetserukou D. ArUcoGlide: a Novel Wearable Robot for Position Tracking and Haptic Feedback to Increase Safety During Human-Robot Interaction. *2023 IEEE 28th International Conference on Emerging Technologies and Factory Automation (ETFA)*, 2023, 1-8.
- [11] Sulague R M, Beloy F J, Medina J R, Mortalla E D, Cartojano T D, Macapagal S, Kpodonu J. Artificial Intelligence in Cardiac Surgery: A Systematic Review. *World Journal of Surgery*, 2024.
- [12] Chen C, Chi-Kuang L, Chou F. Multiobjective optimization of collaborative robotic task sequence assignment problems under collision-free constraints. *Advances in Mechanical Engineering*, 2024.
- [13] Zhang Z, Zheng L, Chen Z, Kong L, Karimi H R. Mutual-Collision-Avoidance Scheme Synthesized by Neural Networks for Dual Redundant Robot Manipulators Executing Cooperative Tasks. *IEEE Transactions on Neural Networks and Learning Systems*, 2021, 32. 3, 1052-1066.
- [14] Lippi M, Marino A. A Mixed-Integer Linear Programming Formulation for Human Multi-Robot Task Allocation. *2021 30th IEEE International Conference on Robot and Human Interactive Communication (RO MAN)*, 2021.
- [15] Liu K, Tang Z, Wang D, Wang Z, Zhao B, Li X. COHERENT: Collaboration of Heterogeneous Multi-Robot System with Large Language Models, 2024.
- [16] Taylor R, Cao J, Deguet A, Long Y, Dou Q. Integrating Artificial Intelligence and Augmented Reality in Robotic Surgery: An Initial dVRK Study Using a Surgical Education Scenario. *International Symposium on Medical Robotics*, 2022.
- [17] Zhang S, Li S, Wang H, Li X. An intelligent manufacturing cell based on human-robot collaboration of frequent task learning for flexible manufacturing. *The International Journal of Advanced Manufacturing Technology*, 2022.