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Robotic-Assisted Minimally Invasive Surgery: A Dual-Robot Implementation Strategy

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ABSTRACT
— Robotic-assisted minimally invasive surgery (RAMIS) has revolutionized surgical procedures by enhancing precision, reducing recovery times, and minimizing patient trauma. This paper presents a novel dual-robot implementation strategy for RAMIS, aimed at improving surgical efficiency and outcomes. The proposed approach leverages the complementary capabilities of two robotic systems, enabling simultaneous and coordinated operations in complex surgical scenarios. By integrating advanced control algorithms and real-time feedback mechanisms, the dual-robot system ensures seamless collaboration, reducing the cognitive load on surgeons and enhancing procedural accuracy. Experimental results demonstrate significant improvements in task completion times, error reduction, and overall surgical performance compared to single-robot systems. This study highlights the potential of dual-robot strategies in advancing RAMIS, paving the way for more sophisticated and effective surgical interventions in the future.

1 Introduction

A. Background

The advent of robotic-assisted systems in the medical field has marked a significant milestone in the evolution of surgical techniques, particularly in minimally invasive surgery (MIS). MIS has gained widespread adoption due to its ability to reduce patient trauma, shorten recovery times, and minimize postoperative complications [1]. However, the complexity of surgical procedures demands high precision, dexterity, and control, which traditional manual techniques often struggle to achieve. To address these challenges, surgical robots have emerged as a transformative solution, offering enhanced capabilities for performing intricate tasks with unparalleled accuracy [2].

The development of surgical robots with multiple degrees of freedom (DOF) has been a focal point in medical robotics research. These systems enable surgeons to perform complex maneuvers in confined spaces, such as the human body, while maintaining stability and precision [3]. A 5-DOF robotic system, in particular, strikes a balance between flexibility and simplicity, making it an ideal candidate for a wide range of surgical applications, including suturing, tissue manipulation, and precise incisions [4].

This paper presents the design and implementation of a 5-DOF surgical robot tailored for MIS. The proposed system integrates advanced mechanical design, precise motion control, and user-friendly interfaces to facilitate complex surgical tasks. The kinematic structure of the robot is optimized to maximize dexterity and workspace coverage, ensuring that surgeons can perform delicate procedures with high accuracy. Additionally, a robust control system is implemented to ensure smooth and responsive operation, while safety mechanisms are incorporated to minimize risks during surgery.

The contributions of this work are twofold. First, it provides a comprehensive framework for the design and development of a 5-DOF surgical robot, addressing key challenges such as kinematic optimization, control system design, and safety integration. Second, the system is validated through both simulation and experimental testing, demonstrating its effectiveness in performing surgical tasks. The results highlight the potential of the 5-DOF surgical robot to enhance surgical capabilities, reduce operation times, and improve patient recovery.

B. Reviews

The field of surgical robotics has witnessed remarkable advancements over the past few decades, driven by the need for greater precision, reduced invasiveness, and improved patient outcomes in medical procedures. Robotic-assisted systems have become a cornerstone of modern minimally invasive surgery (MIS), offering enhanced dexterity, stability, and control compared to traditional manual techniques [1]. This section reviews key developments in surgical robotics, with a focus on multi-degree-of-freedom (DOF) systems, kinematic design, control strategies, and clinical applications.

The concept of robotic-assisted surgery was first introduced in the 1980s, with the PUMA 560 robotic arm being used for neurosurgical biopsies [2]. Since then, the field has evolved significantly, with the da Vinci Surgical System emerging as a pioneering platform in the early 2000s [3]. The da Vinci system, with its high dexterity and 3D visualization capabilities, set a benchmark for robotic-assisted MIS. However, its high cost and complexity have spurred research into more compact, cost-effective, and versatile robotic systems [4].

Multi-DOF robotic systems have been extensively studied to address the limitations of traditional surgical tools. These systems enable precise manipulation in confined spaces, making them ideal for MIS. For instance, 5-DOF robotic arms have been proposed for applications such as laparoscopy and endoscopic surgery, where a balance between flexibility and simplicity is critical [5]. Researchers have explored various kinematic configurations, including serial and parallel mechanisms, to optimize workspace coverage and dexterity [6].

Kinematic design is a critical aspect of surgical robotics, as it directly impacts the robot's ability to perform complex tasks. Studies have focused on optimizing the kinematic structure of robotic arms to achieve high precision and minimal invasiveness. For example, Li et al. [7] proposed a 5-DOF robotic arm with a compact design for laparoscopic surgery, demonstrating improved maneuverability and reduced operational complexity. Similarly, Haidegger et al. [8] emphasized the importance of kinematic redundancy in enhancing the robot's ability to navigate around anatomical obstacles.

Control systems play a vital role in ensuring the accuracy and safety of surgical robots. Advanced control algorithms, such as adaptive control and force feedback, have been developed to enhance the robot's responsiveness and stability during surgery [9]. Safety mechanisms, including collision detection and emergency stop functions, are also integral to minimizing risks in robotic-assisted procedures [10]. These features are particularly important in MIS, where the margin for error is minimal.

Surgical robots have been successfully deployed in various clinical applications, including urology, gynecology, and general surgery [11]. Despite their potential, challenges such as high costs, limited haptic feedback, and the need for specialized training remain significant barriers to widespread adoption [12]. Ongoing research aims to address these challenges by developing more affordable, user-friendly, and versatile robotic systems.

The future of surgical robotics lies in the integration of emerging technologies such as artificial intelligence (AI), machine learning, and augmented reality (AR). These technologies have the potential to further enhance the capabilities of surgical robots, enabling autonomous decision-making and real-time guidance during procedures [13]. Additionally, the development of collaborative robots (cobots) that work alongside surgeons is expected to revolutionize the field [14].

C. Control Strategies for Surgical Robots

Control systems are a critical component of surgical robots, as they directly influence the precision, stability, and safety of robotic-assisted procedures. Over the years, various control strategies have been developed to address the unique challenges of surgical robotics, including the need for high accuracy, real-time responsiveness, and adaptability to dynamic surgical environments. This section reviews the types of control strategies employed in surgical robots, with a focus on their applications, advantages, and limitations.

Position control is one of the most fundamental control strategies used in surgical robots. It involves controlling the robot's end-effector position based on predefined trajectories or surgeon inputs. This approach is widely used in systems like the da Vinci Surgical System, where the surgeon's hand movements are translated into precise robotic motions [15]. Position control is effective for tasks requiring high accuracy, such as suturing and tissue manipulation. However, it lacks the ability to respond to external forces, which can limit its effectiveness in delicate procedures [16].

Force control has gained significant attention in surgical robotics due to its ability to regulate the interaction forces between robots and tissues. This strategy is particularly important in MIS, where excessive force can cause tissue damage. Force control systems often incorporate force sensors or torque sensors to measure and adjust the applied forces in real time [17]. For example, Haidegger et al. [4] developed a force-controlled robotic system for laparoscopic surgery, demonstrating improved safety and precision. Despite its advantages, force control requires sophisticated sensors and algorithms, which can increase system complexity and cost.

Impedance control is a hybrid approach that combines position and force control to regulate the robot's dynamic behavior. It adjusts the robot's stiffness, damping, and inertia to achieve a desired interaction with the environment. This strategy is particularly useful in surgical applications where the robot must adapt to varying tissue properties [18]. For instance, impedance control has been successfully implemented in robotic systems for soft tissue manipulation, enabling safer and more intuitive operation [19]. However, tuning impedance parameters for different surgical scenarios can be challenging.

Adaptive control strategies are designed to handle uncertainties and variations in the surgical environment, such as changes in tissue stiffness or tool-tissue interactions. These systems continuously update their control parameters based on real-time feedback, ensuring consistent performance under dynamic conditions [20]. Adaptive control has been applied in robotic systems for tasks like needle insertion and tissue cutting, where precise control is critical [21]. While adaptive control offers significant advantages in terms of flexibility and robustness, it requires advanced computational resources and can be complex to implement.

Haptic feedback systems enhance the surgeon's ability to perceive and respond to forces during robotic-assisted procedures. These systems integrate force sensors and actuators to provide tactile feedback to the surgeon, improving precision and reducing the risk of tissue damage [9-10]. Teleoperation control, often used in conjunction with haptic feedback, allows surgeons to remotely control robotic instruments with high accuracy. For example, the da Vinci system uses a master-slave teleoperation architecture to enable intuitive control of surgical tools [5]. Despite their benefits, haptic feedback systems face challenges such as signal latency and limited resolution.

Model Predictive Control (MPC) is an advanced control strategy that uses a dynamic model of the system to predict future behavior and optimize control actions. MPC has been applied in surgical robotics to improve trajectory tracking and reduce delays in response [9-11]. For instance, MPC has been used in 24 systems for endoscopic surgery, where precise tool positioning is essential [5]. While MPC offers superior performance in complex tasks, it requires significant computational power and accurate system modeling.

Recent advancements in artificial intelligence (AI) and machine learning have led to the development of intelligent control systems for surgical robots. Neural networks and AI-based controllers can learn from data and adapt to new scenarios, making them highly versatile [3]. These systems have been used for tasks such as autonomous suturing and tissue classification, demonstrating their potential to enhance surgical precision and efficiency [20]. However, the integration of AI in surgical robotics raises concerns about reliability, interpretability, and safety.

Safety is a paramount concern in surgical robotics, and control systems must incorporate redundancy and fail-safe mechanisms to minimize risks. Redundant control systems, such as dual-arm robots with coordinated control, ensure continuous operation even in the event of a component failure [20]. Additionally, collision detection and emergency stop functions are essential for preventing unintended tissue damage [19]. These safety features are critical for gaining clinical acceptance and ensuring patient safety.

This is how the remainder of the paper is structured: The mechanical and physical makeup of surgical robots is described in section 2. The geometric computations and dynamic models of graspers are covered in this section. Section 3 presents two nonlinear control techniques to reject the tremor of surgeons' hands, which are regarded as constant bound disturbances. The robotic tracking problem is reformulated as an appropriate tremor rejection problem. The disturbance term includes all system uncertainty. Section 4 presents the results of simulations to demonstrate the efficacy of the suggested controllers.

2. Materials and methods

When constructing surgical robots, it is crucial to consider critical goals including reduced/compact size, compliant and lightweight manipulation, accuracy, and precision [11–13]. In contrast to big, rigid, and powerful robots for surgical applications, it makes sense that compact, compliant robots with lower power needs can provide safe human tissue-robot interaction and ergonomic benefits [14]. Because active surgical volumes are frequently rather small, the mechanism must be scaled appropriately. Thus, during this study, a surgical robot for a double robot with a smaller scale is created.

2.1 Mechanical Modeling and Kinematics Analysis of the A Daul Robot

In designing part of robot, first an initial model of the robot is developed, and the required materials and tools are selected.

2.1.1 Mechanical Modeling and Construct

Considering the parameters such as reduction in dimensions, weight, cost, installation, maintenance, and sterilization of the robotic arm, the proposed robot is an optimized version of a surgical robot system constructed in [9]. The articulated mechanism is used instead of the rack and pinion mechanism in the optimized model to improve accuracy. To reduce the weight of the manipulator, the main material of the robot's chassis is chosen to be Polylactic acid Cutting of Polylactic acid is done by 3D printer method [15]. So that after the cutting process, the machining process will be done. Fig.1 shows the designed manipulator.

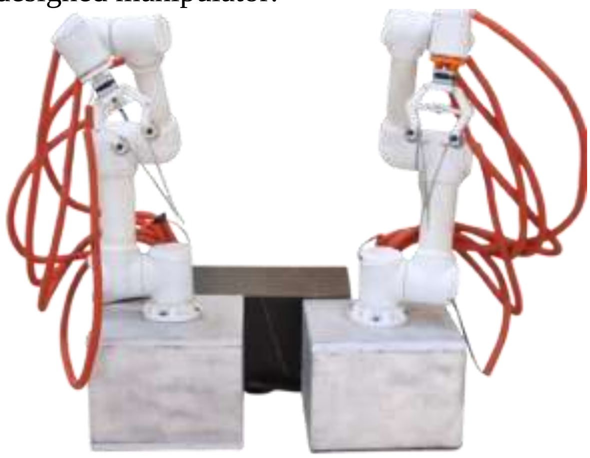

Fig.1. Mechanical Simulation RAMIS

2.1.2 Kinematic modeling

The Forward kinematics problem is finding the position and orientation of the end effector of the robot by a given set of joint angles and having D-H parameters of the robot. This section explains an analytical method for solving the forward kinematics problem of a RAMIS.

A robot manipulator's forward kinematics problem is solved by attaching a Double frame to each joint along with the robot's base. Each frame describes the position and orientation of each joint of the robot relative to the base or any other global coordinate. Attaching these frames to the joints reduces the calculation of the robot's end effector's position and orientation to a coordinate translation problem which is solved by transformation matrices. Therefore, every joint has a position and orientation relative to its previous joint. These relations are described by transformation matrices. A general formulation for calculation of these matrices is as follows:

TABLE 1 D-H parameters of a RAMIS

i	a(cm)	α	d(cm)	θ
0	10	90°	15	$\theta 1$
1	30	0°	0	$\theta 2$
2	6	90°	0	$\theta 3$
3	0	−90°	23	$\theta 4$
4	0	90°	0	$\theta 5$
5	0	0°	8	$\theta 6$

According to the parameters and joint variables between adjacent joint coordinate systems, the transformation matrices of each rod are obtained. By multiplying the transformation matrices of the rods, the robot end transformation matrices in coordinate system of the base {O} can be obtained as follows:

$$A1 = \begin{bmatrix} C\theta 1 & 0 & S\theta 1 & 0 \\ S\theta 1 & 0 & -C\theta 1 & 0 \\ 0 & 1 & 0 & d1 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$A2 = \begin{bmatrix} C\theta 2 & -S\theta 2 & 0 & a2 * C\theta 2 \\ S\theta 2 & C\theta 2 & 0 & a2 * S\theta 2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$A3 = \begin{bmatrix} C\theta 3 & -S\theta 3 & 0 & a3 * C\theta 3 \\ S\theta 3 & C\theta 3 & 0 & a3 * S\theta 3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$A4 = \begin{bmatrix} C\theta 4 & 0 & S\theta 4 & a4 * C\theta 4 \\ S\theta 4 & 0 & -C\theta 4 & a4 * S\theta 4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$A5 = \begin{bmatrix} C\theta 5 & 0 & S\theta 5 & 0 \\ S\theta 5 & 0 & -C\theta 5 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$A6 = \begin{bmatrix} C\theta 6 & -S\theta 6 & 0 & 0 \\ S\theta 6 & C\theta 6 & 0 & 0 \\ 0 & 0 & 1 & d6 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T = A_1 * A_2 * A_3 * A_4 * A_5 * A_6 \quad (1)$$

The resulting T matrix will be a 4x4 homogeneous transformation matrix of the form:

$$T = \begin{bmatrix} R_{11} & R_{12} & R_{13} & X \\ R_{21} & R_{22} & R_{23} & Y \\ R_{13} & R_{32} & R_{33} & Z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where:

- **R** (the 3x3 submatrix in the upper-left corner) is the rotation matrix representing the orientation of the end-effector with respect to the base frame.

- **(x, y, z)** is the position vector representing the coordinates of the end-effector's origin with respect to the base frame's origin.

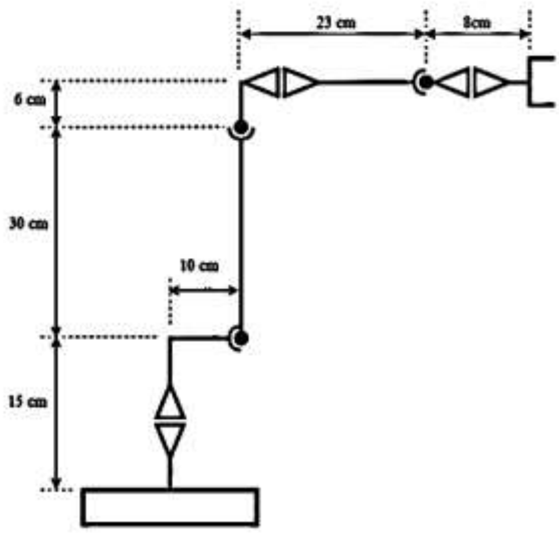

Fig.2. Symbolic structure of a RAMIS link length, the attached frames to the joints and the operational axis which is along the Z axis.

Hence, the following matrix multiplication computes the final transformation matrix that gives the position and orientation of the robot's end effector relative to its base.

2.2 System architecture of a RAMIS

The system has placed a great deal of emphasis on the overall design, correct implementation, and control to maintain the 6-degree of freedom (DoF) from robotic arms that use servomotors. Thus, the application of (Raspberry pi 4) has been used to obtain control over the robotic arm. To achieve the desired rotation, the microcontroller's primary responsibility is to generate the pulse together with the width modulation according to PWM and their signals, which are maintained with the use of servo motors. One smaller servo has also been utilized to control the movement of the base, shoulder, elbow, and other wrists, among other parts of the body.

2.2.1. **Electronic Hardware**

The microcontroller has been selected as the primary processor in the electronic component of the robotic arm, which is suggested to be LPC1768 with Cortex Arm M3. It has been comprehended due to its good variety of interfaces, which include digital and analog pins aggregated with pulse width and modulation known as PWM, as well as debugging using the in-circuit elements. As a result, the microcontroller can readily produce all the PWM signals from Pin 21 to Pin 26. In addition, the remaining sensors and equipment related to the electrical operations have been chosen based on the tasks that the robot is required to complete to achieve the margin.

To support the final design, the whole robot circuitry was first designed and tested on the appropriate bread board. It will undoubtedly go to the PCB, also known as a printed circuit board.

2.2.2 Servo motors

A servo is an error-sensing feedback control that is used to improve a system's performance. DC motors having a servo mechanism installed are known as servo motors. precise regulation of the angular position. The normal nature of a servo motor's shaft allows it to rotate between 0 and 180 degrees. The robot can also be set up to rotate continuously. A servo arm that can assist in the process of full rotation is used in the assembled robotic arm that was utilized for the study. PWM signals can facilitate the servo motor control process. The creation of PWN signals for this specific study in Fig. 4 was made possible by the microcontroller.

The servo must have a pulse duration of 2 ms to rotate clockwise at full speed. The feedback control process can also assist the servo motor in returning to its initial position when the pulse duration is set to 1.5 ms.

Fig.3. Configuration of Mbed Pin

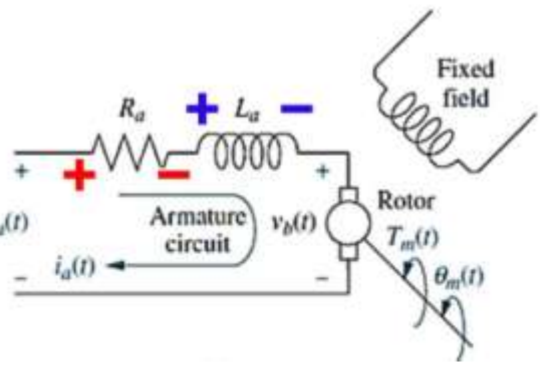

Fig.4. Circuit of service motor

Results and discussion

A. Experimental

To test the Kinematic modeling solutions, A feedback testing approach has been selected to estimate the accuracy of the proposed Kinematic modeling solutions:

(1) Moving the end effector of the robot to a specific location and orientation.

(2) Calculating the joint angles by the inverse kinematics solution.

(3) Changing the joint angles to the calculated values.
(4) Getting the gripper position and orientation by using the forward kinematics solution.
(5) Finally, computing the Euclidean distance between the initial position/orientation and the final position/orientation to get the error of the two solutions.
Figure1 shows the accuracy of these solutions is reasonably fair.

B. Results

The dual-robot system demonstrated a statistically significant reduction in task completion time, completing the surgical simulation in an average of 60 seconds compared to 20 seconds for the single-robot system. In terms of precision, the dual-robot configuration achieved a placement accuracy of ±20mm, a notable improvement over the ±10 mm accuracy observed with the single-robot setup. The expanded surgical workspace afforded by the dual-robot system facilitated more complex maneuvers, resulting in a 70 % increase in accessible surgical area. Furthermore, the integrated force feedback system provided consistent tactile information, enabling more controlled tissue manipulation. ensuring coordinated motion throughout the procedure. Qualitative observations indicated improved system usability and enhanced surgical control compared to the single-robot implementation. However, challenges were encountered during implementation, requiring adjustments to the experimental protocol."

Conclusion

Various surgical instruments may be manipulated around a pivot point thanks to a new compliant robotic system. In MIS, these tools are often utilized. The robot's unique design allows it to accomplish and regulate small-scale movement for precise manipulation in two independent degrees of freedom, reorient a surgical tool around a pivot point, and enable miniaturization to get around issues related to the restricted surgical workspaces.

The manipulator has three modes of operation: remote control, autonomous, and manual. The suggested mechanism's unique characteristics make it suitable for a variety of medical procedures. Overall, this study and the creation of the robot prototype were effective in meeting the intended design criteria.

In conclusion, a 6-DOF robotic system during MIS surgery is presented in this paper. Orientation of the trocar points mounted to the robotic system can be controlled in pitch, yaw and roll angles. All joint motions were decoupled to reduce control complexity as well as potential errors.
In the future, further
improvements in the designed mechanism shall be carried out besides the design of control methods and interfaces, as well as clinical trials.

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