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Development of an innovative parallel robot used in laparoscopic pancreatic surgery

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Abstract. This paper introduces the development and preliminary validation of a novel parallel robot specifically engineered for laparoscopic pancreatic surgeries. Parallel robots, unlike traditional serial robotic systems, provide superior stiffness, precision, and payload capacity, attributes that are crucial for delicate surgical procedures. The study elaborates on the design of a surgical robot aimed at assisting surgeons during laparoscopic pancreatic surgeries. Key objectives include expanding the operational field to facilitate better access to the pancreas and enhancing the efficiency of medical protocols. The design process is comprehensively detailed, starting from medical task parameters to the kinematic architecture and functional capabilities of the proposed parallel robot. The robot features a modular architecture comprising an active 3-degree-of-freedom parallel mechanism and a passive spherical parallel mechanism. This configuration supports a new active surgical instrument with four degrees of freedom, significantly enhancing dexterity and enabling surgeons to access deep organs more effectively. To assess the robot's efficacy, a series of laboratory tests were conducted to simulate conditions typical of laparoscopic pancreatic surgeries. The results indicate substantial improvements in surgical maneuverability, precision, and ergonomic efficiency, underscoring the robot's potential to enhance surgical outcomes.

Keywords: Parallel robot, Modularity, Design, Pancreatic surgery, FEA, Testing and Evaluation.

1 Introduction

Pancreatic cancer is considered one of the most aggressive and lethal types of cancer worldwide, developing when uncommon mutations occur in the DNA of the pancreas

[1]. This type of cancer ranks fifth worldwide with a low survival rate (below 5%) five years after surgery, with over 500,000 new cases reported annually worldwide [2]. According to studies presented in [3], the causes contributing to the occurrence of this type of cancer focus on family history of the disease, obesity, type 2 diabetes, and tobacco use.

Due to the deep positioning of the pancreas in the abdominal cavity, and due to the lack of symptoms associated with the onset of cancer on this organ, early detection of the pathology is very difficult, with the pathology generally being detected in the metastasis phase, resection remains the only treatment option for this aggressive pathology [4-6].

There are three types of pancreatic surgery: open surgery, laparoscopic surgery, and robot-assisted surgery. These types of surgery target all areas of the pancreas, from the head (Whipple Procedure-WP) to the tail (Distal Pancreatectomy-DP) [7, 8].

A significant milestone in surgical innovation was marked in 2000 with the introduction of the da Vinci robot by Intuitive Surgical, the first robot approved by the Food and Drug Administration [9]. Since then, additional robotic surgical systems have been developed, such as: Senhance (Asensus Surgical), Versius (CMR Surgical), Hugo (Medtronic's) and Hinotori (Medicaroid) [10, 11]. The first robotic-assisted pancreaticoduodenectomy and distal pancreatectomy was performed in 2003 [12].

The mortality of pancreatic surgery has been reduced below 3% due to the technical advantages and the integration of surgical robots [13, 14]. The main advantages of robotic surgery are improved precision, enhanced dexterity, better recovery [15, 16], but present some disadvantages such as high cost, large footprint, and restricted operative fields [17-20]. To address current limitations of robotic-assisted pancreatic surgeries [20, 21], the Athena robot was developed. The Athena robot represents an innovative parallel robot developed to assist surgeons by manipulating a third laparoscopic instrument such as a retractor or a flexible instrument during complex reconstructions such as the Whipple procedure. Improved precision and rigidity are offered compared to serial structures due to the parallel modular architecture with Remote Center of Motion (RCM) mechanical constraint [22-24].

The paper is structured as follows: Section 1 presents clinical context and the main challenges of robotic-assisted surgery. Section 2 illustrates the development phases of the Athena robot and the surgical instrument. The validation of the experimental model using training kits is presented in Section 3, while the last sections present the results, conclusions, and future developments

2 Design of the innovative parallel robot developed for pancreatic surgery

2.1 Medical protocol and medical requirements

For the development of the innovative parallel robot integrated as an assistant in minimally invasive robotic-assisted pancreatic surgery, a medical protocol was defined alongside surgeons in the field. This protocol consists of five stages and is illustrated

in Fig. 1. Based on this protocol, the robot can precisely and safely manipulate a third active instrument, whose main role is to provide the surgeon with the space required to perform the resection and reconstruction needed in WP.

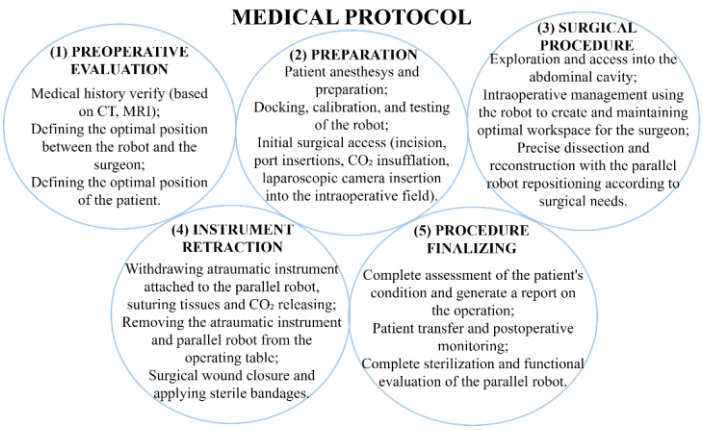


Fig. 1. Medical protocol for pancreatic cancer

According to the medical protocol, the requirements established by surgeons are defined and integrated into the robot design stage, as follows: easy to use, quick attachment of instruments, reduced setup time (positioning and robot adjusting), intuitive control, customized control adapted to the surgeon's requirements, modularity, reduced footprint, high dexterity for robot and instrument, range of motion between ±25° and maximum insertion of 250 millimeters, real-time control, restricting the workspace of the active instrument attached to the robot, remote control, high stiffness, quick integration into the operating room, ergonomic control console.

2.2 Kinematics of the innovative parallel robot Athena

Based on the medical protocol illustrated in Fig. 1 and the medical requirements, the kinematic scheme of the innovative parallel robot Athena was developed, and a patent application was filed [25], the main role of the robot being as an assistant to the main surgeon. The Athena robot can control a third surgical instrument that ensure workspace during surgery by holding the organs around the pancreas. More details about the robot's functionality are described in [26, 27]. The kinematic scheme of the robot is presented in Fig. 2. The Athena robot is composed of 9 passive revolute joint R_{iP},$i=1...9$, three passive prismatic joints T_{iP},$i=1...3$, three active prismatic joints q_{iP},$i=1...3$ and two passive universal joints, U_{iP},$i=1...2$. As for the global coordinate system it was placed in the RCM (O_{RCM}, X_{RCM}, Y_{RCM}, Z_{RCM}), while on the Athena robot a second coordinate system ($OXYZ$) was attached. The geometric parameters of the robot are: lengths a_i,$i=1...5$; a_{2min} (minimum stroke for q_3), the length of the instrument denoted by a, the inserted length of the instrument relative to the RCM point denoted by l_{ins} to which are added the lengths a_{0i},$i=1...3$, lengths that define the coordinates of the system attached on the parallel robot ($OXYZ$) in the global coordinate

system with origin in the RCM. To ensure mechanical constraint of the RCM, a spherical mechanism is used, composed of five passive revolute joints R_{iS},$i=1...5$, and a passive cylindrical joint C_{1S}, which provide the rotation and insertion motion of the active instrument, while the connection between the spherical mechanism and the robot base is achieved by means of a rod provided with two spherical joints S_i,$i=1...2$, which are used for the placement and adjustment of the RCM position of the spherical mechanism with respect to the robot coordinate system [27].

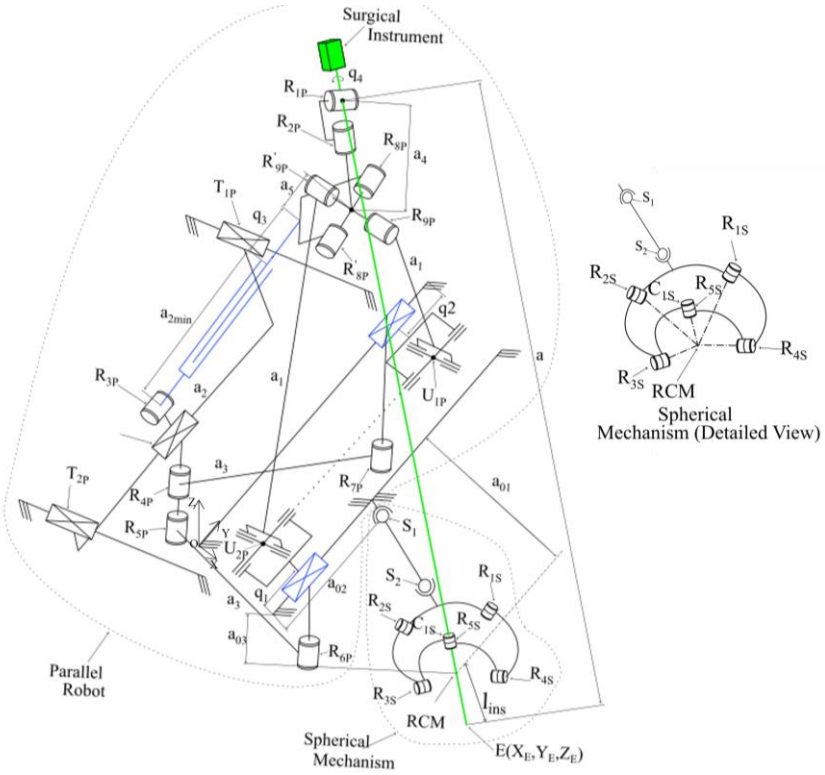


Fig. 2. Kinematic scheme of the parallel robot Athena

Based on the kinematic scheme and parameters described in [27], both forward and invers kinematic models of the Athena robot were developed and were integrated into the control system of the robot using the input/output equations [28].

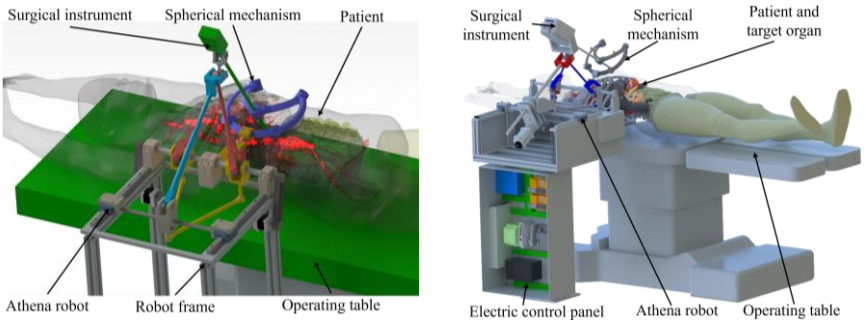
The resulting computations are both simple and robust, as they involve solving only quadratic equations [26, 28].

2.3 Final design of the Athena robot

The mechanical design of the Athena robot was based on the kinematic scheme illustrated in Fig. 2 using Siemens NX software. For this stage, several iterations of the proposed solution were carried out, with Fig. 3.a illustrating the simplified version of

the Athena robot, while Fig. 3.b illustrates the final version of the proposed solution. Both solutions presented integrate the requirements of the medical staff presented in subsection 2.1, the robot being based on a parallel architecture and a passive spherical mechanism developed with the aim of mechanically constraining the RCM point. To achieve the transmission of movements to the active instrument attached to the robot, large-pitch screw-nut transmissions are used, while also providing the high handling speeds required, especially in emergencies that require rapid withdrawal of the active instrument from the intraoperative field. The rotational movement transmitted by the three actuators in the robot's mechanical structure to the ball screws is achieved by belt wheels, with two of the three axes (*q1* and *q2*) fixed in the *XOY* plane, while the axis for *q3* is fixed in the *XOZ* plane.

In order to obtain a solution that covers the anatomical parameters of patients as much as possible, we added an additional axis that moves the Athena robot up and down (along the Z axis), as well as a connecting element with two spherical joints that facilitates the connection and adjustment of the passive spherical mechanism to the structure of the Athena robot.



(a) (b)

Fig. 3. The 3D evolution of the Athena robot (a - first version, b - final version)

To provide a complete solution, our own active instrument was developed and integrated with the Athena robot. The proposed active instrument consists of a 10 mm diameter shaft with an articulated distal head. To provide improved surgical dexterity and an extended workspace compared to standard minimally invasive surgical instruments, the instrument integrates four degrees of freedom (DOF), q_{insi}, $i=1...4$. The design of the flexible active instrument is depicted in Fig. 4 and comprises four main components: (a) - the distal head, (b) - the flexible segment, (c) - the rod and (d) - the instrument driver housing.

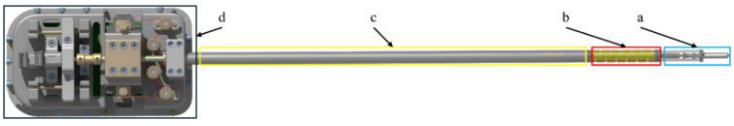


Fig. 4. 3D Model of the flexible active instrument

A detailed view of the instrument's driver housing is illustrated in Fig. 5, where the five motors used to control the flexible instrument can be seen.

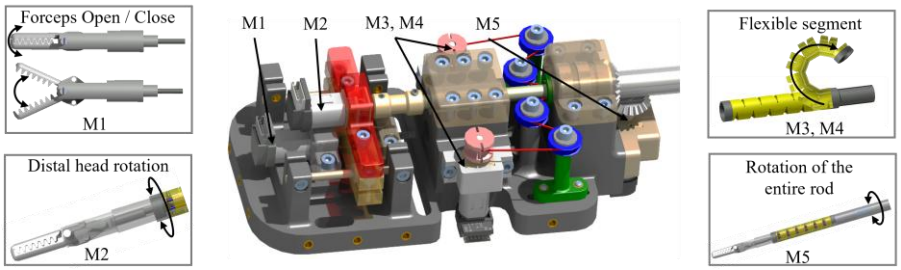


Fig. 5. Main components of the surgical instrument

The first motor (M1) manages the opening and closing of the grasper jaws through a linear actuation system. A rod inside the main tube transmits this linear motion to the distal head, where it is converted into angular movement by a scissor mechanism. The translation flange, which includes a nut and lead screw, converts the rotational motion from M1 into linear movement. The second motor (M2) controls the rotation of the distal head. The rod is connected to M2 via a coupler, and its rotation is smoothly transmitted to the distal head through a wire rope. The bending movement of the flexible segment is controlled by two motors (M3 and M4). These motors use rollers and a tensioning mechanism to adjust the tension of the wires, allowing the segment to bend. Reversing the rotation direction of these motors returns the segment to its initial position. The final motor (M5) rotates the entire instrument shaft using a conical gearbox. This setup allows for stable rotation of the instrument. Fig. 6 and Fig. 7 illustrate the correlation between these movements and the 3D Space Mouse device used to control the system. For the control of the proposed solution, two control modes are used, the first mode for controlling the robot's 3 DOF and the second mode for controlling the active instrument. Switching between the two control modes is performed using buttons 1 and 2 labeled on the 3D Space Mouse (1 for controlling the robot and 2 for controlling the active instrument composed of the five motors shown in Fig. 5).

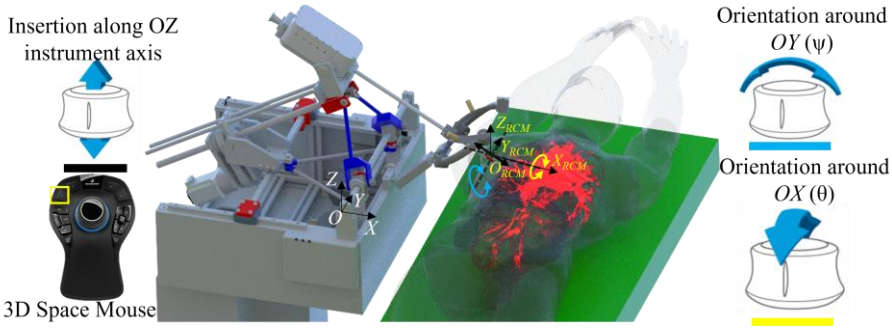


Fig. 6. ATHENA robot movements correlated with 3D Space Mouse

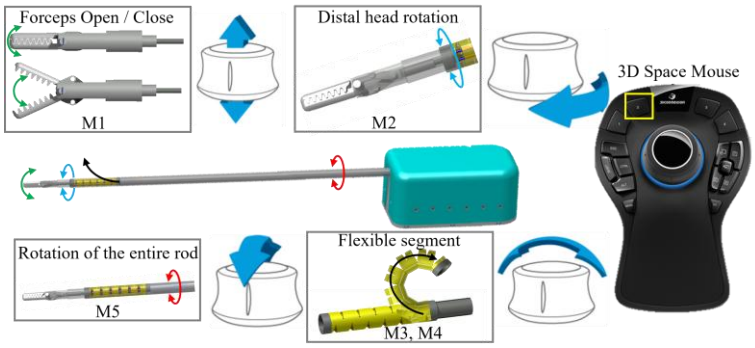


Fig. 7. Active instrument movement correlated with the 3D Space Mouse

2.4 Finite element analysis for the main components of the Athena robot

To validate the mechanical design stage of the Athena robot and to achieve high stiffness according to medical requirements, finite element analyses (FEA) were performed on all designed mechanical components. This subchapter illustrates only the analyses and results obtained for the most loaded mechanical elements in the robot's structure. A finite element analysis was also performed on the entire robot structure, applying a collinear force of 30 N on the active instrument axis, which is the maximum force when discussing tissue manipulation [29-31]. The results obtained from this study are detailed in [32], where a deformation of 0.23 mm and a maximum von Mises stress value of 15.29 MPa, a value lower than the yield strength of the materials used in the mechanical construction of the proposed solution. Also, in [32], the stiffness analysis presented, the values obtained being encouraging for further studies, matching the values of commercial variants of robots developed for robot-assisted laparoscopic surgery. The most overloaded elements presented in this subchapter are illustrated in Fig. 8, which also illustrates their positioning on the mechanical structure of the Athena robot.

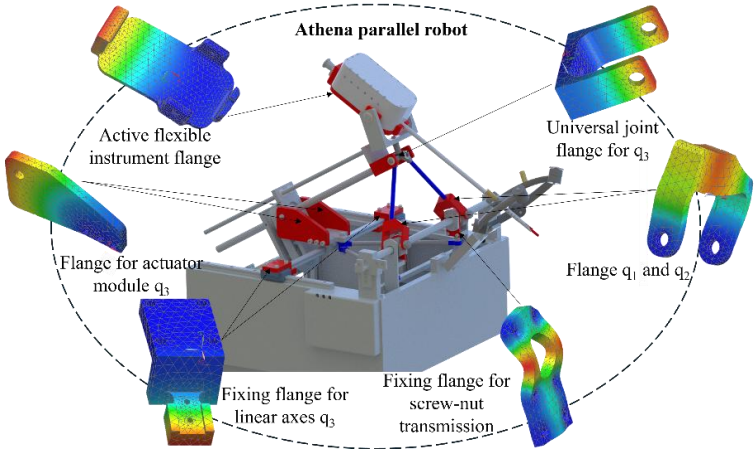


Fig. 8. The most overloaded elements of the Athena robot

Siemens NX software was used to perform the FEA, in which friction forces and joints clearances are not included, as the joints are considered perfect. The force applied to the mechanical elements illustrated in Fig. 8 was between 15 N for the active instrument flexible flange and 110 N for the q_3 linear axis fixing flange (the force of 15N was applied according to the force required during the procedure, while the maximum force was applied based on the mass of each element of the proposed solution), while the materials included ABS, aluminum, and steel.

Following the application of FEA, the maximum displacements of the mechanical elements (Fig. 8) resulting from the application of forces fall within the elastic range, and the von Mises forces are below the yield strength of the materials (ABS - 45 MPa, aluminum - 240 MPa, steel - 310 MPa), which validates the mechanical design stage of the Athena robot. The main deviation of the instrument tip obtained from the analyses is 0.1 mm, and the main deviation of the RCM is 0.23 mm, compared to commercial robots, where the deviation is 1.06 mm. Based on these studies and the data presented in [25-28], the experimental model of the Athena robot was developed and tested under laboratory conditions, with the results presented in the next chapter.

3 Testing and validation of the Athena robot under laboratory conditions

The experimental model of the Athena robot and the experimental setup used for testing under laboratory condition is illustrated in Fig 9. The testing stages of the Athena robot is performed by surgeons, manipulating different objects attached in a test kit developed for minimally invasive surgery, the test scenarios addressed in this testing stage as well as the simulators used are presented and detailed in Fig. 10-13 where it can be observed the objects manipulated as well as the different manipulation tasks performed with the active instrument developed and integrated with the mechanical structure proposed in this work.

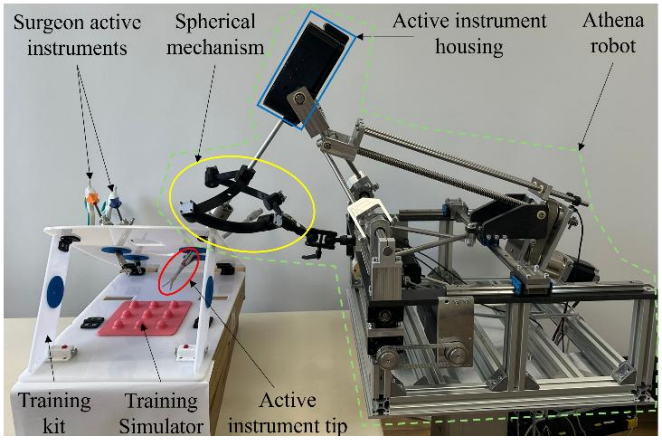


Fig. 9. Experimental setup of the Athena robot

During the manipulation testing stage, the developed active instrument with a 10 mm diameter was evaluated using plastic springs within a training simulator environment. The instrument was operated through controlled movements to demonstrate its grasping and manipulation capabilities in the workspace, simulating minimally invasive surgical conditions.

The results from this test are presented in Fig. 10, which shows the successful manipulation and of the plastic springs using the prototype instrument.

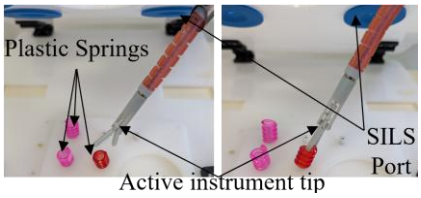


Fig. 10. Manipulating plastic springs

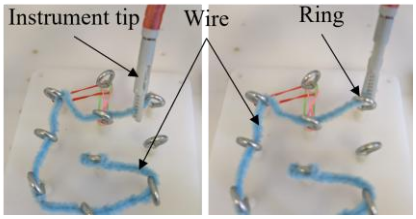


Fig. 11. Wiring manipulation in rings

The developed 10 mm diameter active instrument was used to insert a wire through a ring within a training simulator and Figure 11 illustrates the results of this evaluation. Another surgical procedure that was performed is represented by the cutting of a spherical tissue structure. This assessment involved the developed active instrument working in coordination with surgical scissors through trocar ports in the training simulator and Fig. 12 presents the outcome of this evaluation.

The last evaluation that was evaluated is represented by the tissue cutting. This evaluation involved the developed diameter active instrument working alongside a laparoscopic camera, a surgical scissor and surgical forceps within the training simulator setup. The results of this evaluation are illustrated in Fig. 13.

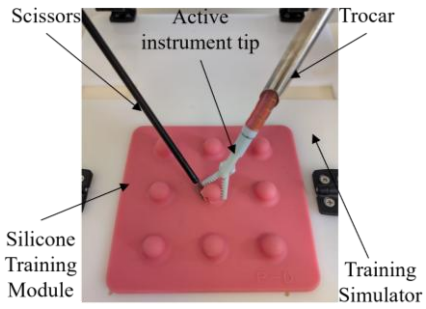


Fig.12. Spherical tissue structure cutting

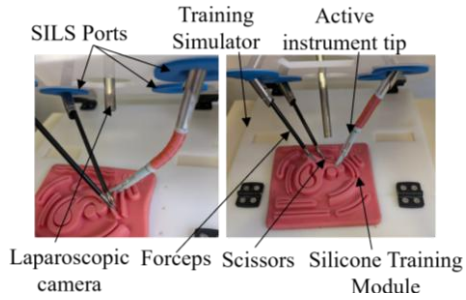


Fig 13. Tissue cutting evaluation

Throughout the entire testing phase, the time required to perform each scenario was improved by 10% compared to manual laparoscopic surgery, where the time per procedure, depending on complexity, is estimated at between 2 and 10 minutes. The 10% reduction was achieved thanks to the improved dexterity of the flexible instrument compared to rigid instruments.

4 Results

The results that were obtained during the finite element analysis and testing stages demonstrated successful development and validation of the Athena parallel robot for pancreatic surgery procedures.

The stiffness of the Athena robot under operational conditions was evaluated using the finite element analysis. The structure of the robot displayed a maximum deformation of 0.23 mm and a maximum von Mises stress of 15.29 MPa at the spherical mechanism when was subjected to a 30 N collinear force along the axis of active instrument and all stresses remained within the yield limits for the critical components analyzed in subsection 2.4 by applying forces between 15 N and 110 N.

The robot's operational capabilities in multiple surgical simulation scenarios were successfully validated during experimental tests, with the data being transmitted in real time and no delays in the command section.

Both robot positioning and active instrument manipulation were successfully achieved, reducing the operating time for the illustrated tasks by 10% compared to the classic procedure, thanks to the dexterity of the active instrument.

5 Conclusions

This paper introduces the development and validation of the Athena robot, designed to serve as a surgical assistant in minimally invasive laparoscopic pancreatic surgery, capable of manipulating a third instrument. The robot uses a parallel modular structure that combines a 3-DOF parallel structure with a passive spherical mechanism. This design maintains the RCM constraint essential for minimally invasive surgery. We have developed kinematic models and integrated them into the robot's control system. Finite element analysis confirmed that all mechanical components operate within safe stress limits, ensuring reliability and safety during surgical procedures. The active instrument of the Athena robot features four degrees of freedom, providing the necessary flexibility for pancreatic procedures. Controlled via a space mouse, this instrument allows for intuitive and user-friendly manipulation of its movements. Experimental validation using a minimally invasive surgery training kit demonstrated positive results across various scenarios. These tests confirmed the robot's ability to assist in complex surgical tasks while maintaining the precision and dexterity required for such delicate operations. Future work will focus on defining and integrating into the robot's control logic a model able to generate smooth trajectories so that vibrations are reduced or even eliminated, as well as implementing force control to detect collisions between the robot, the surgical instrument, and the environment. We will also test additional instruments, such as actuated endoscopes and multi-finger retractors. Finally, we plan to develop automatic motions for the tools and the RCM by analyzing surgeons' gestures, further enhancing the robot's capabilities and integration into surgical practices.

Acknowledgements

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