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On the development of an innovative surgical parallel robotic system

Alexandru Pusca¹, Iulia Andras², Andrei Cailean¹, Nicolae Crisan², Calin Vaida¹, Corina Radu², Bogdan Gherman^{1*}, Nadim Al Hajjar², Damien Chablat^{1,3}, Doina Pisla¹

Affiliation 1: CESTER Research center, Technical University of Cluj-Napoca, Romania

Alexandru.Pusca@mep.utcluj.ro, Andrei.Cailean@mep.utcluj.ro, Calin.Vaida@mep.utcluj.ro, Bogdan.Gherman@mep.utcluj.ro, Damien.Chablat@mep.utcluj.ro, Doina.Pisla@mep.utcluj.ro

Affiliation 2: "Iuliu Hatieganu" University of Medicine and Pharmacy Cluj-Napoca, Romania

Iulia.Andras@umfcluj.ro, Nicolae.Crisan@umfcluj.ro, corina.radu@umfcluj.ro, na.hajjar@umfcluj.ro

Affiliation 3: Nantes Université, Ecole Centrale Nantes, CNRS, LS2N, UMR 6004, F-44000, Nantes, France

damien.chablat@cnrs.fr

* Corresponding author

Abstract—This paper presents the development of the experimental model of an innovative parallel robot for Single Incision Laparoscopic Surgery (SILS). The proposed solution implements the master-slave architecture. The research is mostly focused on the development of the slave robotic system, which is managed using two readily available 3D Space Mouse devices. The user interface is thoughtfully crafted to align with the specific requirements of surgeons. Additionally, we present a detail analysis of the motion trajectory of the slave robot, generated based on the kinematic model integrated within the control system is also presented.

Keywords— *parallel robot; control; single incision laparoscopic surgery; experimental model.*

I. INTRODUCTION

Laparoscopic surgery became a revolution in the medical field even if at first it was strongly criticized, coming as an alternative to classical surgery where the patient was opened by making an incision between 150 and 250 millimeters. Laparoscopic surgery is currently preferred over classical surgery due to advantages such as: reduced recovery time, less post-operative trauma, fewer incisions, and less blood loss [1]. It is divided into two techniques, namely NOTES (Natural Orifice Transluminal Endoscopic Surgery), a technique that involves making 3-4 incisions between 10 and 15 millimeters and SILS (Single Incision Laparoscopic Surgery) technique, where an incision between 15 and 25 millimeters is performed, through which the medical instruments are inserted [2].

As these techniques have become increasingly used, several limitations became evident such as: the limited working space, the tremor of the surgeon's hand, the surgeon's lack of ergonomics, the precision and positioning of the instruments and the two-dimensional vision of the laparoscopic camera. These disadvantages led to the development of this field through the appearance of robotic systems capable to eliminate or mitigate these limitations.

The first commercial robotic system used in laparoscopic surgery was the da Vinci system, developed by Intuitive Surgical in the early 2000s [3]. The system evolved throughout the years, with the introduction of new models such as da Vinci S, da Vinci Si, da Vinci Xi, and da Vinci SP, which came with a series of impressive improvements detailed in [4].

Single-Incision Laparoscopic Surgery (SILS) has proven advantages over classical laparoscopic surgery, which are presented in [5,6], and consist of: minimal scarring, decreased blood loss, better cosmesis and a short recovery time.

In 2018, Intuitive Surgical Inc. developed the da Vinci SP [7], the first dedicated robotic system for SILS. It brought clear advantages compared to the manual and classical procedures, such as vastly improved ergonomics and accuracy. Nevertheless, the surgeons have noticed a certain over compliance (or lack of stiffness) of the SILS instruments, due to their mechanical architecture and miniaturization, or the need for a larger workspace in some situations.

Due to the ongoing issues in this field, this paper aims to present an innovative parallel robotic capable of reducing the existing disadvantages, such as: collisions that may occur between the robot arms, the large occupied footprint in the operating room, the need to adjust or even build new operating rooms tailored to the needs of existing robots, as well as the problem of structural rigidity of the current, commercially available robotic systems for SILS.

Following the Introduction section, the rest of the paper is structured as follows: Section II presents a brief description of the innovative parallel robotic system used for SILS and its control system and architecture. Section III presents a motion trajectory of the robot for the laparoscope positioning and orientation. Section IV contains conclusions about this work and future developments.

II. MATERIALS AND METHODS

A. The innovative parallel robotic system used for SILS

The innovative robotic system, PARA-SILSROB, consists of a 6 Degrees of Freedom (DoF) parallel architecture which hosts on its mobile platform three modules designed to drive the laparoscope and the two active instruments for SILS, as in Figure 1.

The 6 DoF parallel robot is composed of three identical kinematic chains mounted on a triangular shape frame, having a 3-R-PRR-PRS configuration, each kinematic chain having two active prismatic joints, three passive revolute joints and one passive spherical joint placed on the mobile platform, [8]. The mobile platform can perform translations along the three axes of the Cartesian coordinate system (Ox , Oy , Oz) and it can be oriented around these axes with the angles corresponding to each axis (ψ , θ , ϕ), using the X - Y - Z rotation convention. The kinematic scheme of the parallel robot, its functionality, and an analysis of its workspace are extensively presented in [5], where the author demonstrates that the robot's maximum workspace occurs when the angle $\phi = -60^\circ$.

The 6 DoF parallel robot mobile platform hosts three serial modules designed to drive the two active instruments (as the left and right hands of the surgeon) and the laparoscopic camera (in the center), as in Figure 2. The two modules which are used for the orientation and insertion of the active instruments have 3-DOF and use a circular track mechanism with architecturally constrained Remote Center of Motion (RCM). The motions of this mechanism, performed around the RCM are: rotation around the RCM, translation along the circular track and instrument insertion, through the RCM, as in Figure 2, [9]. The module which drives the laparoscopic camera coincides with the RCM of the mobile platform. This module has 1-DOF, which performs laparoscope insertion along its axis. In conclusion, during surgical procedures, the laparoscopic camera's positioning and orientation is achieved through the 6 DoF parallel robot.

The experimental model of PARA-SILSROB, presented in figure 1, is developed based on the studies presented in [5], [6], and [10].

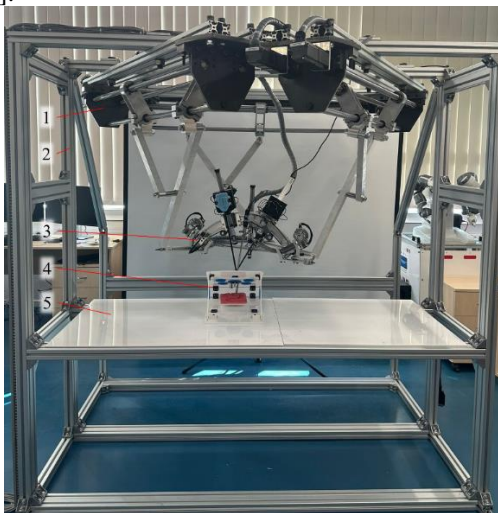


Fig. 1. The PARA-SILSROB experimental model

Figure 1 shows the main components of the PARA-SILSROB experimental model where: 1 is the robotic structure with all kinematic chains, 2 is the robotic frame made by aluminum profiles, 3 is the mobile platform, 4 is the training stand and 5 is the operating table.

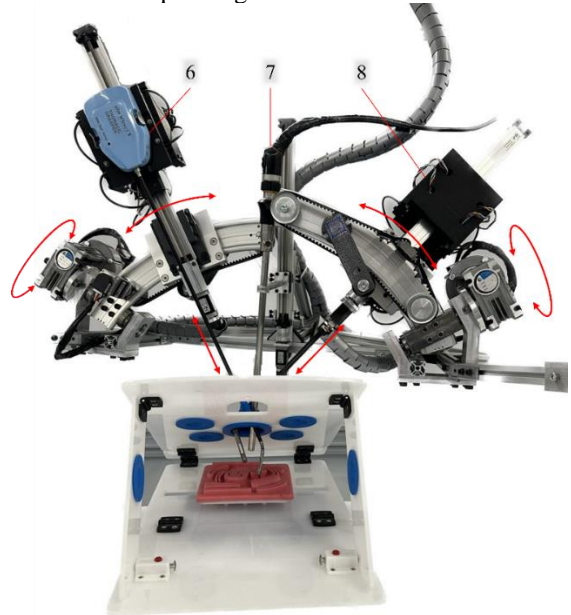


Fig. 2. A detailed view of the mobile platform and its orientation modules within its components.

Figure 2 displays the mobile platform with the two modules (6, 8) for guiding the active SILS instruments and the module (7) for the laparoscopic camera, which is fixed at the center of the mobile platform. Da Vinci instruments were initially used for the preliminary validation of the mobile platform's functionality. In the next stage of development personalized instruments will be designed and manufactured.

B. Control system architecture

The block diagram for the drive system of the PARA-SILSROB parallel robot is depicted in Figure 3, consisting of three levels: User interface, PLC (Programmable Logic Controller) and the Robotic Structure.

The User interface level is built using the PC's hardware and software resources, where the applications are implemented. The user interface has the following components:

- Keyboard & 3D Space Mouse: These components allows the user to interact with the robotic system through inputs provided by the two 3D Space Mouse devices, each being used to control an active instrument. Using the programmable buttons on the space mouse, the user can switch and control the laparoscopic camera module;
- Video data laparoscopic system: This component provides video from the laparoscopic camera;
- Graphical User interface: The GUI serves as the user's window into the robot's operations. It offers real-time data on the robot's state, position and speed of the robot and allows the user to control the robot by either using a 3D Space Mouse, or upon request, using a traditional keyboard and mouse. This architecture

follows the concept of master-slave control presented in [11].

The Programmable Logic Controller: controls the displacements of each actuator for a given command from the user using specific hardware for commanding and controlling the robot actuators. The following internal modules are integrated:

- Actuation driver: It is used to perform the connection between software and motion elements;
- AI agents are integrated in the command part and are used both for the image segmentation stage and for providing recommendations to the surgeon, without directly stepping into the decision-making process, attributed to the surgeon. The AI agents are presented in detail in [12] and [13].
- Mathematical model: provides the kinematic model of the robot;
- Path definition: based on the user's inputs and the kinematic model, it calculates the position variation for each motor;
- Positioning parameters calculation: correlates the position of the actuators with the mathematical model, calculating the trajectory;
- Safety workspace analysis and trajectory validation using the VR module: Used in pre-planning stage to validate if the chosen trajectory is satisfactory for the user;

Communication module: ensures the communication between the PLC and robot actuators based on the X2X protocol.

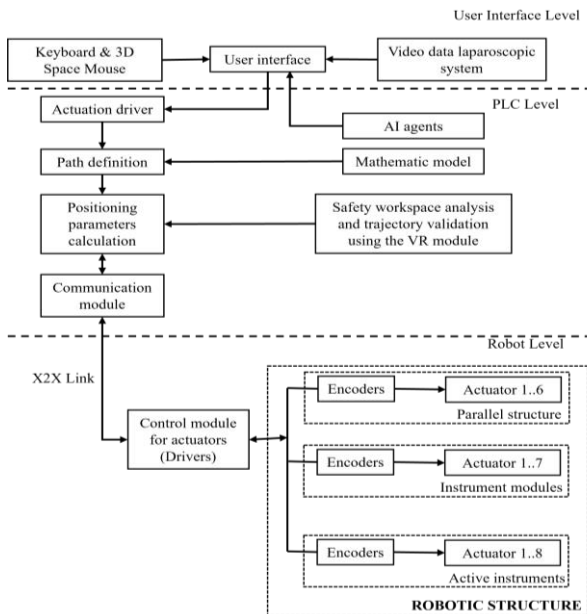


Fig. 3. Block diagram on the development for the PARA-SILSROB robot
The Robotic Structure level consists of the parallel robot itself, with all the actuators, sensors, and the mechanical structure. Based on the input provided by the user, the PLC controls the parallel structure, the modules driving the SILS

instruments and the laparoscopic camera and the or the active instruments themselves.

- Drivers: based on commands received from the PLC and data from the encoders, it automatically adjusts the electrical current used to regulate the acceleration and speed of the actuators, to accurately reach the desired position;
- Encoders: returns data about the actual position of each actuator;
- Actuators: accomplish the displacement of the parallel robot in direct relation to the electrical current provided by the drivers.

C. The hardware system architecture of the PARA-SILSROB

The hardware system architecture of the PARA-SILSROB is presented in figure 4, being split into three categories: The user level, command & control level, and physical level.

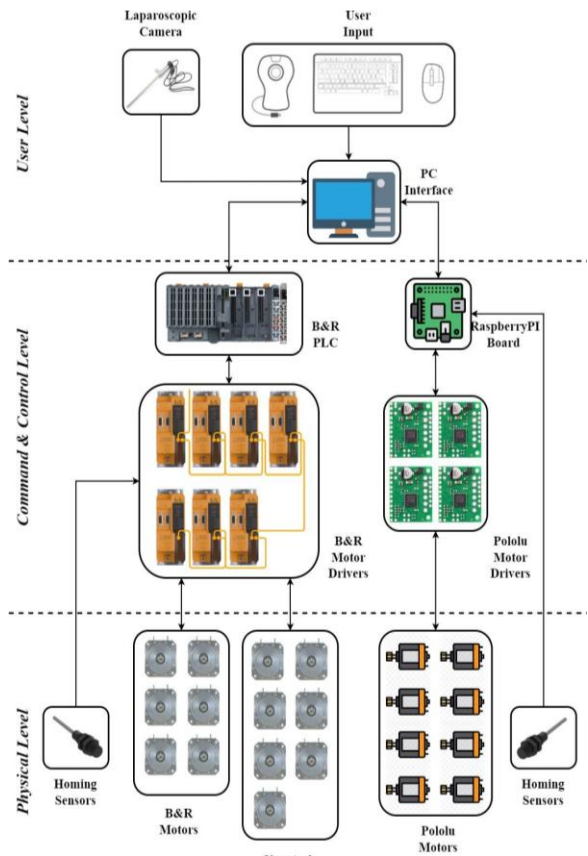


Fig. 4. The hardware system architecture of the PARA-SILSROB
The user level consists of a computer and its peripherals, specifically two 3D Space Mouse devices that allow the surgeon to move the instruments of the robot properly and easily. A screen provides video feedback from the laparoscopic camera.

The command & control level includes the following hardware: The PLC, microcontroller boards and motor drivers (B&R drivers and pololu motor drivers). The PLC establishes an ethernet connection to the user interface and the Raspberry

PI boards establish the wireless connection. This ensures that both the robotic structure and the instruments can be driven at the same time if necessary.

Lastly, the physical level consists of proximity sensors mounted on the mechanical structure (one sensor for each motor) which allows the robot to properly perform the homing procedure. All the motors utilized in the robot are equipped with incremental encoders. In addition, the B&R motors are also equipped with an electromagnetic brake. The motors have been divided into three blocks as seen in figure 4. The B&R motors are used to drive the 6 DoF parallel structure, the Nanotech motors for the instrument's modules and camera modules and the Pololu motors, which are significantly smaller, to drive the instruments themselves.

D. PARA-SILSROB master-slave architecture

The control between the surgeon and the PARA-SILSROB is performed based on the master-slave [11] concept shown in figure 5. The master console is composed of the two 3D Space

Mouse devices, Mouse & Keyboard, monitor and a graphical interface. The slave robotic system consists of the 6 DoF parallel robot with the three modules used for manipulating the instruments and two SILS active instruments. The surgeon is seated in front of the master console and can perform the surgery remotely by using peripherals to accurately guide the instruments within the patient's body. The video output of the laparoscopic camera is shown on a screen where the surgeon can observe the operating field. The 3D Space Mouse devices are used to control the slave system and using the available programmable buttons of these devices, specific functions can be further added and implemented according to the surgeon's requirements. The devices can be used to perform different several types of motion. An important advantage of the 3D Space Mouse consists in its neutral position in which it returns after being actuated. This means that once the surgeon moves away from the console, it naturally stops sending any kind of input to the slave robot, thus immediately holding the system in place until further input is provided.

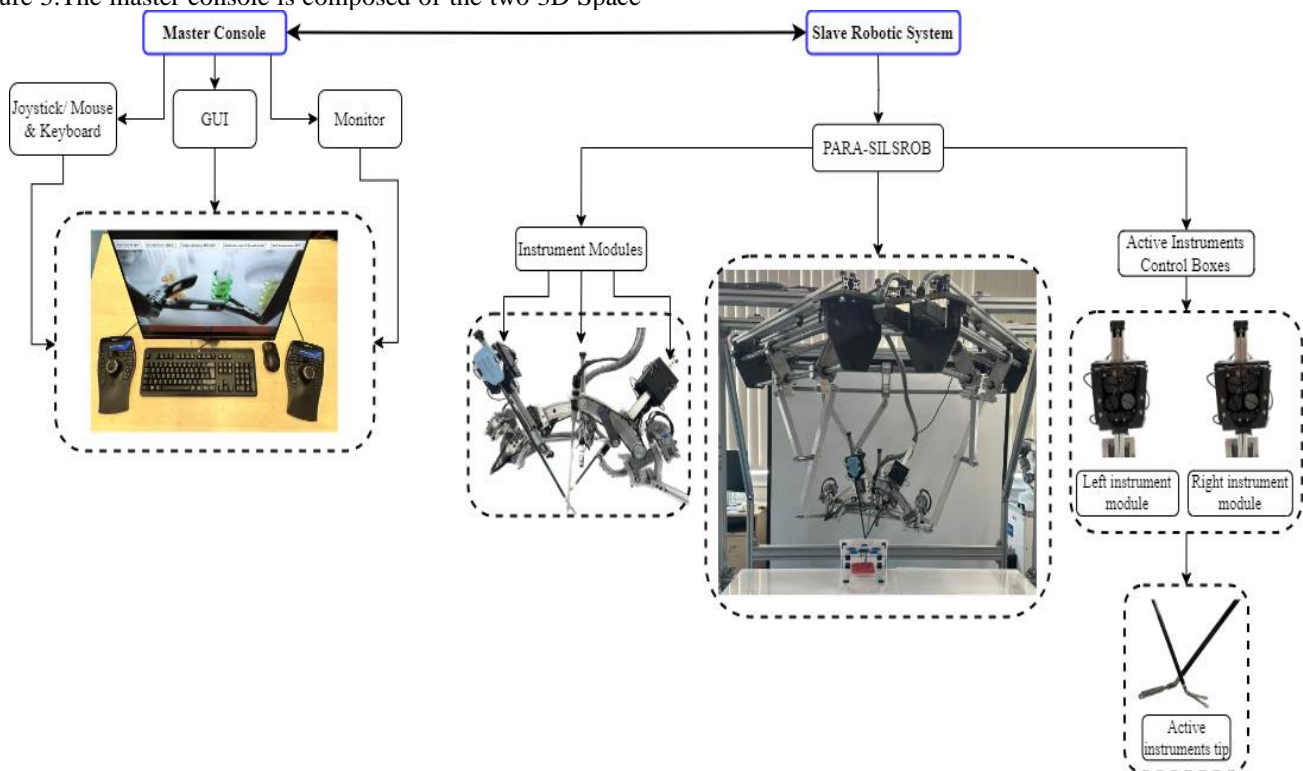


Fig. 5. The master-slave architecture of the PARA-SILSROB

III. RESULTS

Figure 6 presents the mobile platform trajectory, targeting the laparoscope positioning and orientation towards the surgical field. The plots present the end-effector position and orientation, as well as the velocity and acceleration of the six controlled coordinates. The motion has three parts:

- Laparoscope motion towards the insertion point into the SILS port (the patient's abdominal cavity);
- Laparoscope insertion, using a vertical position;
- Laparoscope orientation within the surgical field.

Thus, the laparoscope (and the mobile platform) begins the motion from an initial position and orientation provided by the end-effector coordinates, the laparoscope tip: $X_E = -25mm$; $Y_E = 10mm$; $Z_E = -200mm$, and the two angles $\psi = 40^\circ$, $\theta = 20^\circ$, and $\varphi = -40^\circ$. The motion parameters are $v_{max} = 10mm/s$, $a_{max} = 5mm/s^2$, these being the maximum allowed values for the laparoscope tip velocity and acceleration. Within the first motion part, the laparoscope is oriented towards a vertical position (when $\psi = 0^\circ$, $\theta = 0^\circ$, while the angle

$\varphi = -60^\circ$, representing the rotation angle of the laparoscope around its symmetry axis. From this position, the laparoscope is inserted using its current orientation on a vertical axis (only the Z_E coordinate changes during this motion). Finally, after an insertion of 100mm , the laparoscope is positioned towards a

laboratory simulated surgical field, when its motion is completed. Figure 7 presents the time history diagram of active joints positions, velocity, and acceleration for the proposed motion trajectory. It proves that the robot can perform the orientation and positioning of the laparoscope, given a specific surgical field.

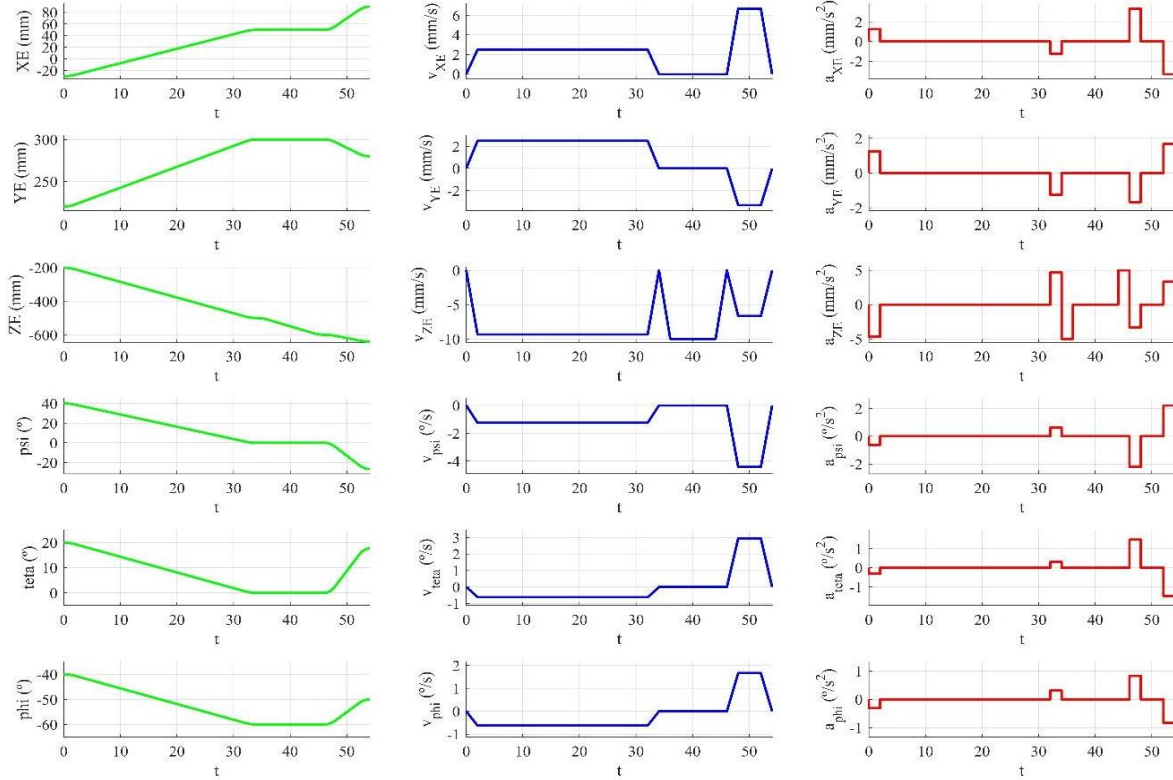


Fig. 6. Motion trajectory generated at the tip of the laparoscopic camera using the PARA-SILS ROB robot

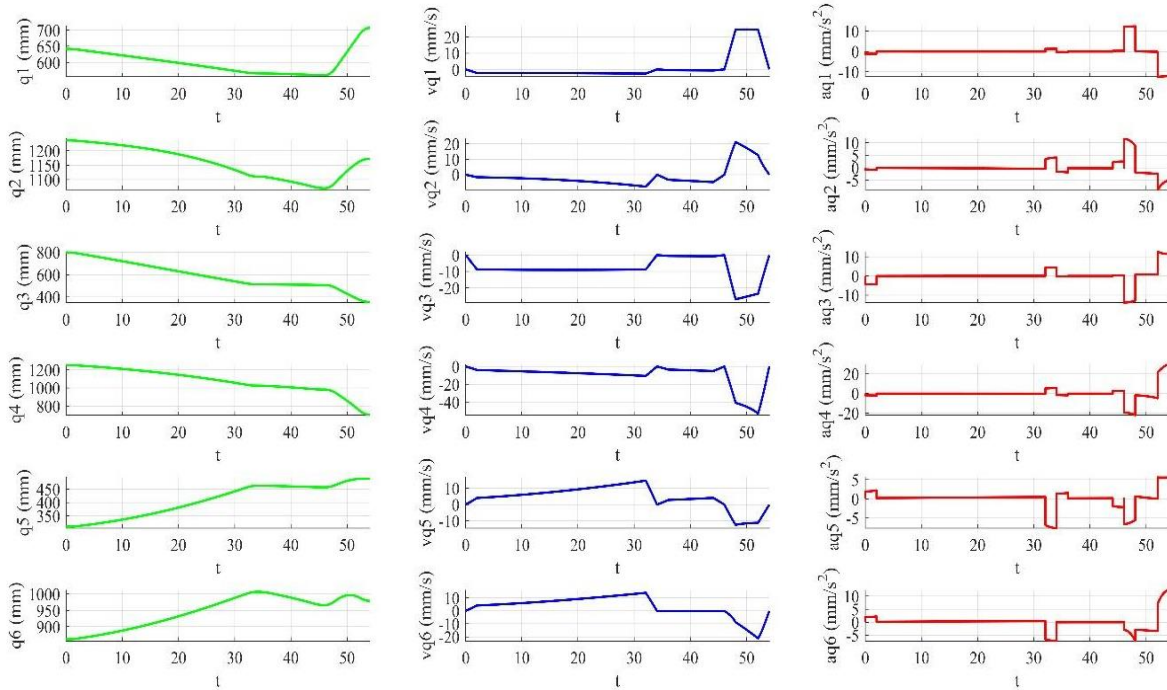


Fig. 7. Displacement, velocity, and acceleration of the PARA-SILS ROB active joints

IV. CONCLUSIONS

This paper showcases an experimental model of the innovative parallel robot, known as PARA-SILSROB, purpose-built for Single Incision Laparoscopic Surgery (SILS). The development of PARA-SILSROB adheres rigorously to established medical protocols and surgeon specifications.

The control architecture for PARA-SILSROB has been meticulously designed, leveraging the B&R Automation X20 family of industrial components. This choice ensures heightened reliability and stability without compromising the system's responsiveness.

The paper also presents an in-depth analysis of the robot's trajectory during laparoscope positioning and orientation. Furthermore, it includes comprehensive diagrams depicting the instantaneous position, velocity, and acceleration of the active joints (motors).

Future endeavors are geared towards experimental testing within controlled laboratory settings to evaluate the practicality of the proposed architecture for SILS procedures.

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