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WORKSPACE ANALYSIS OF TWO INNOVATIVE PARALLEL ROBOTS FOR SINGLE INCISION LAPAROSCOPIC SURGERY

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Abstract: *Robotic assisted for Single Incision Laparoscopic Surgery (SILS) represents a viable alternative for most minimally invasive procedures providing shorter recovery time, reduced hospitalization time, and better esthetic results. The paper presents a family of innovative parallel robots designed for SILS, for which a detailed analysis of the workspace was performed in accordance with the medical task established by the specialists. Different types of workspaces were investigated in order to validate the robotic systems for the SILS medical task.*
Keywords: *Parallel robot, workspace analysis, robotic-assisted SILS, kinematics, simulation.*

1. INTRODUCTION

Technological development frequently complements the medical advancements, to provide better care for patients. The 20th century is recognized for the significant advances in these fields, one of the most important discoveries for the medical sector being Single Incision Laparoscopic Surgery (SILS).

Evolving from classical Laparoscopic Surgery described for the first time in 1922 [1], SILS presents an important improvement, considering the fact that SILS involves just a single incision through which active instruments and the laparoscopic camera are inserted.

This procedure provides many advantages such as faster recovery, less hospitalization time, and reduced scars post-operative. However, despite the obvious advantages, SILS procedure presents some challenges for the surgeon, especially caused by the manipulation of instruments in s small operating field. In order to help the doctor and increase patient safety [2], robotic-assisted SILS systems were developed.

The history of robotic-assisted SILS begin in 1985 when Kwoh et al. developed PUMA (Programmable Universal Machine for Assembly; Westinghouse Electric, Pittsburgh, PA), the first documented robot in this area [3].

However, this technique met a major advance just in the last two decades, due to da Vinci system, developed in December 1998, which received FDA approval for application in laparoscopic surgery in 2000. In 2018, da Vinci SP was developed, being the first robot dedicated to SILS [3]. An articulating camera and three robotic instruments can be positioned simultaneously through a single 25-mm SP multichannel connection in this system. Another commercial robot for SILS with FDA approval is Senhance, developed in 2012, this one provides a complex system that includes: eye tracking, haptic interaction, and a high level; of flexibility due to arm independencies [4].

Although all robots presented above have a serial structure, there are also parallel robots used in SILS.

In [5] the author presents a family of two different parallel robots designed to be used for this procedure, each structure having 6-DOF results by applying the formula presented in [6].

The aim of the study is to analyze the two robotic systems from [7] and [8], with respect to their workspaces. The result of the study will lead to the most optimal workspace[18-20].

There are different types of workspaces, that can be analyzed for parallel robots [9, 17, 21], each of them being suitable for a particular task.

This paper aims to analyze the constant orientation workspace and the orientation workspace of the studied robots. To illustrate the workspace, numerical methods where used.

Following the Introduction section, the paper is structured as follows: Section II presents the innovative parallel robots, Section III illustrates the 3D models for each parallel robot, and this section is followed by Section IV where is presented a detailed analysis of the workspace. Section V shows the results of generated workspaces, and Section VI contains several conclusions regarding the developed work.

2. MEDICAL TASK'S PROTOCOL

The starting point in the development of these innovative parallel structures is based on the definition of the medical task established together with the specialists in robotic-assisted SILS surgery. The medical task includes the following steps:

- **Step 1 (Preplanning):**

Verification of the patient's medical history and defining a therapeutic conduit, using innovative parallel robotics, approximating the patient's position on the operating table, and defining the RCM [10] point (insertion point), using AR and AI systems in generating an optimal solution for successful medical performance.

- **Step 2 (Preparation):**

Preparing the patient for the medical act by positioning him on the operating table, inserting the trocar into the patient's body, infusing CO_2 in the abdominal cavity, fixing the active instruments and the laparoscopic camera on the robot platform, testing the functionality of the robotic system using the master console [11], testing instruments active and visualization of the image generated by the laparoscopic camera, fixing, and sending the robot to the home position.

- **Step 3 (Go to insertion point):**

Positioning and orienting the robotic system platform above the insertion point (RCM) and manually inserting the active instruments and the laparoscopic camera inside a trocar or multi-lumen port described in [12].

- **Step 4 (Mobile platform positioning and orientation):**

Positioning and orienting the mobile platform around the insertion point after the active instruments and the laparoscopic camera have been inserted inside the patient, locking the mobile platform, and compensating the movements of the active instruments using the existing orientation mechanisms on the robot platform.

- **Step 5 (Surgical task):**

Performing the medical task by manipulating the active instruments by the surgeon and removing the diseased tissue from the operating field (patient's abdomen).

- **Step 6 (Procedure finalizing):**

Withdrawing active instruments from the patient's body by returning them to their original position (according to Step 4), removing the instruments from the mobile platform and sterilizing them, withdrawing the mobile platform to the home position, releasing CO_2 from the patient's body, and removing the trocar/ multi-lumen port followed by suturing.

3. THE INNOVATIVE PARALLEL ROBOTS

A family of 6-DOF parallel robots was developed (patent pending [5]) and described in [7]. Each robotic system is capable of positioning and orienting a mobile platform on which the medical instruments are mounted (active instruments and the laparoscopic camera). The main difference between the parallel structures of the robot family [5] is the way in which the kinematic chains of the robots are mounted on the fixed platform of the robots; the first robot [7] uses a triangular frame for the kinematic chains whereas, the second one [8] uses a rectangular frame for the kinematic chains mounting.

3.1 The 3-R-PRR-PRS parallel robotic structure with a triangular frame

Figure 1. illustrates the structure of the parallel robot which is part of the family of robots described in [7] with the components fixed on a triangular frame. The mobile platform that compensates for the movement of active

instruments and the parallel robots are also illustrated in Figure 2. The robot has three identical kinematics chains (denoted KC_1, KC_2, KC_3), positioned in a horizontal plane, on an equilateral triangle placed at the base of the robot, and a mobile platform (denoted MP). Each kinematic chain is actuated by two prismatic joints (denoted q_1, q_2 for KC_1; q_3, q_4 for KC_2; q_5, q_6 for KC_3) and one passive spherical joint (denoted S_1 for KC_1; S_2 for KC_2 respectively S_3 for KC_3). All prismatic joints execute a horizontal movement. The connection between the MP and the kinematics chains is made through spherical joints S_1, S_1, and S_1.

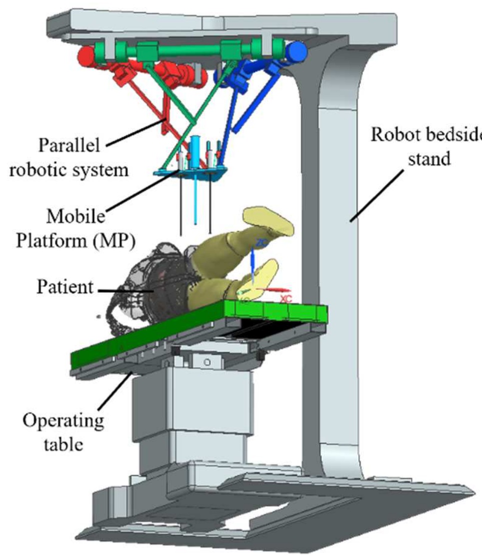


Fig. 1. Robotic integration in the operating room

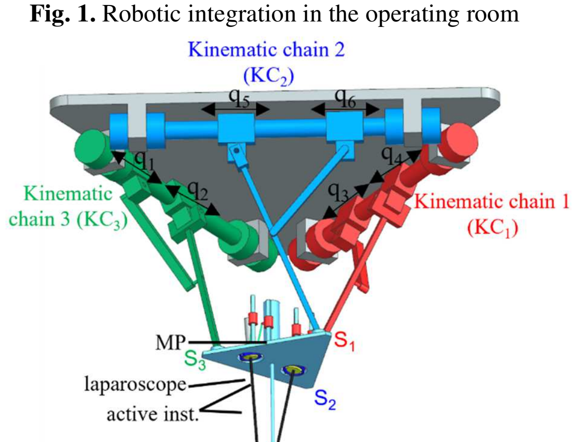


Fig. 2. The 3-R-PRR-PRS parallel robotic structure with a triangular frame

3.2 The 3-R-PRR-PRS parallel robotic structure with a rectangular frame

The robot presented in [8] has also three identical kinematics chains (denoted KC_1, KC_2, KC_3). Figure 3. illustrates the integration into the operating room of the parallel robot structure described in.

The kinematic scheme of the parallel robot with a rectangular frame is shown in figure 4. Each kinematic chain is actuated by two prismatic joints (denoted q_1, q_2 for KC_1; q_3, q_4 for KC_2; q_5, q_6 for KC_3) and one passive spherical joint (denoted S_1 for KC_1; S_2 for KC_2 respectively S_3 for KC_3). Placed on a rectangular frame, with an R-PRR-PRS configuration, the active couple q_1, q_2, and q_5, q_6 produces a vertical movement by simultaneous actuation, while q_3 and q_4 produce a vertical movement. The connection between the MP and the kinematics chains is made through spherical joints S_1, S_1, and S_1.

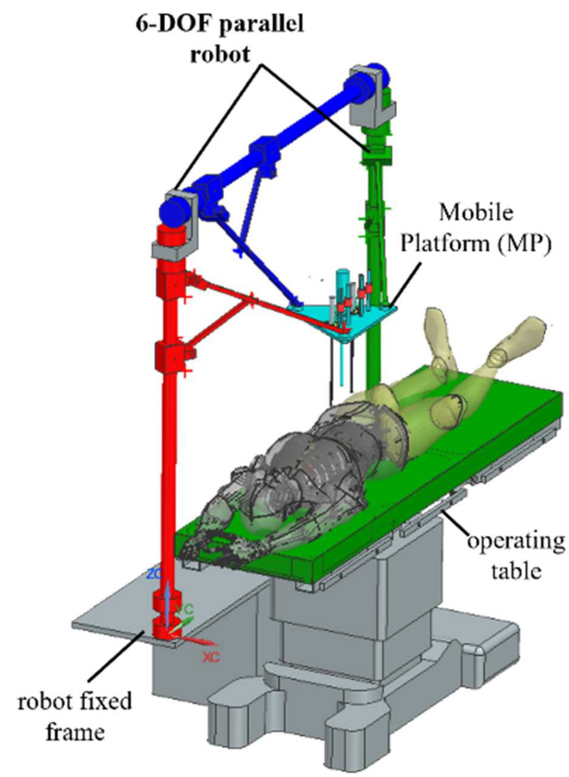


Fig. 3. Robotic integration in the operating room

Figure 5 illustrates the mobile platform with the instruments necessary for the medical act (two active instruments with 4-DOF and the laparoscopic camera) to which are added two mechanisms with 3-DOF that have the role of supplementing the movement of the active instruments mounted on the platform.

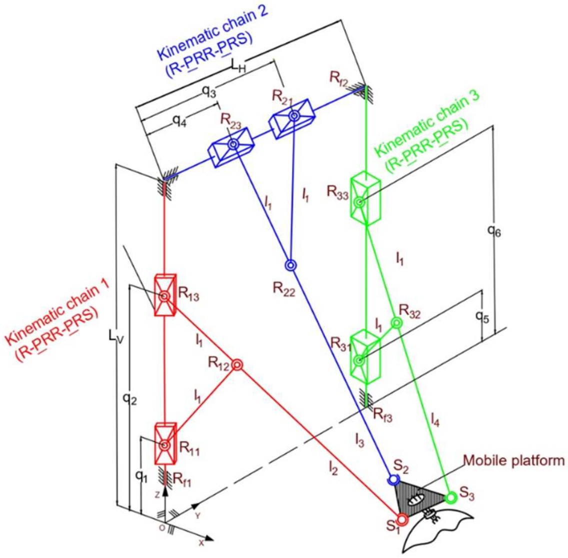


Fig. 4 The kinematic scheme of 3-R-PRR-PRS

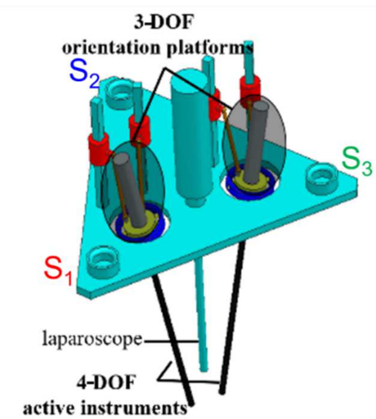


Fig. 5. Mobile platform with instruments

4. WORKSPACE ANALYSIS

The workspace for the innovative parallel robots was generated starting with the inverse kinematic model, where we know the coordinates of the laparoscopic camera namely E (X_E, Y_E, Z_E), the orientation of the laparoscopic camera (ψ, θ, φ), and the coordinates of the insertion point (RCM) noted with B (X_B, Y_B, Z_B).

Figure 6 illustrates the position of the patient's body on the operating table according to the expert surgeon performing the surgery. In this case, the surgery is made with the introduction of the trocar in the intercostal area, the trocar port representing the RCM point for active instruments, and the laparoscopic camera.

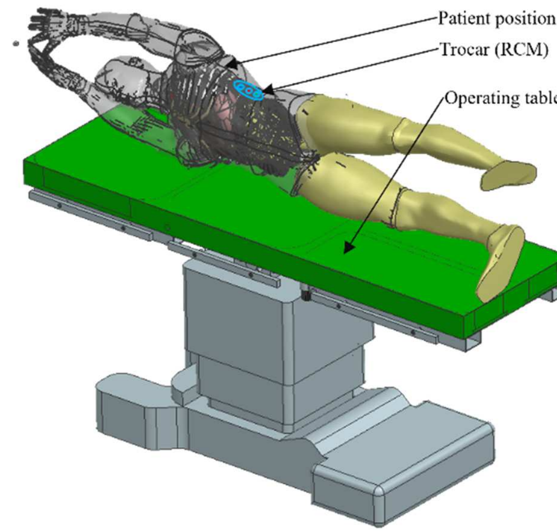


Fig. 6. The patient's position on the operating table

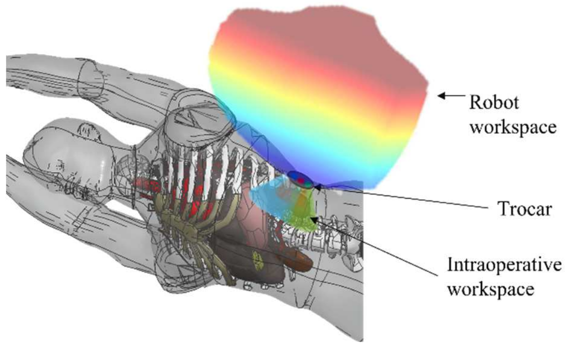
By varying the angles ψ, θ, and φ according to the medical task or obtaining a series of configurations specific to each robotic system described above. The process of generating workspace based on inverse kinematics has several specific steps.

Constant orientation workspace:

- Define the numerical values for ψ, θ, φ
- Define numerical intervals for X, Y, Z coordinates, and indentation step
- Define the geometric parameters and active joints limits
- Compute the inverse kinematic model for each E_i [X_i Y_i Z_i], and verify if the q_i (i=1...6) is real
- If q_i is real plot E_i.

Orientation workspace:

- Define the (RCM) insertion point I [X_I Y_I Z_I]
- Define the numerical intervals for X, Y, Z, ψ, θ, φ
- Define the geometric parameters and active joints limits
- Compute the inverse kinematic model for each E_i [X_i Y_i Z_i], and verify if the q_i (i=1...6) is real
- If q_i is real plot E_i.
- Fig 7 shows the workspace of parallel robots and the intraoperative workspace (active instruments and laparoscopic camera).



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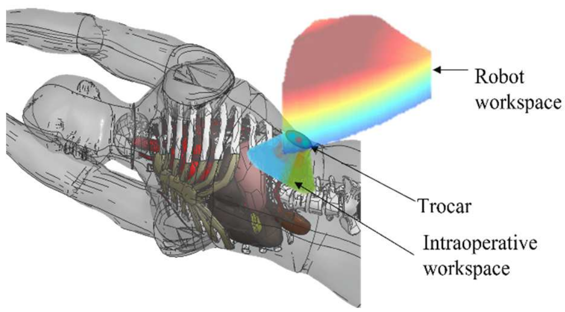
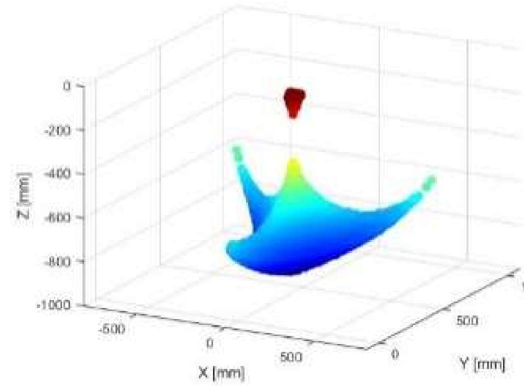


b.

Fig. 7. Workspace and intraoperative workspace for each parallel robot



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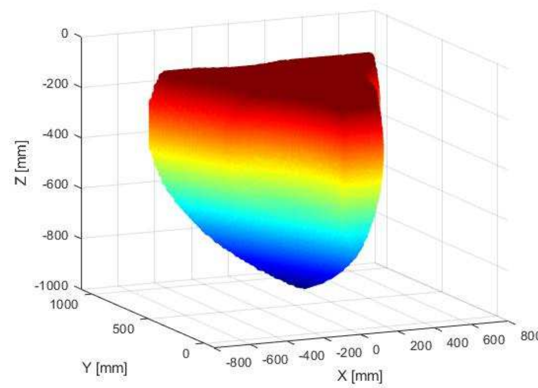


c.

Fig. 8. Robot workspace analysis for a). ψ=0°, θ=0°, φ=0°; b). ψ=0°, θ=0°, φ=60° and c). ψ=0°, θ=0°, φ=-60°

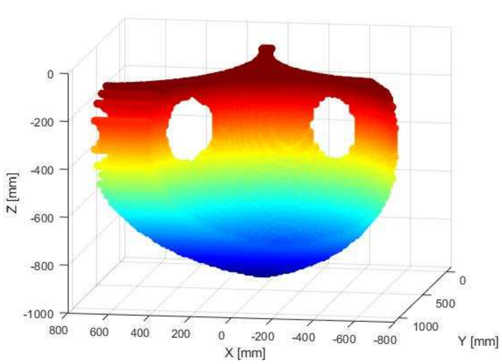
5. RESULTS

5.1 Workspace for parallel robotic structure with a triangular frame

5.1.1 Constant orientation workspace

For the robotic system described in figure 1, in accordance with the medical task, the ψ and θ angles of the robot platform should not exceed ±30° and the φ angle can be varied in intervals of ±60° [8].

Figure 8 shows the mobile platform in different configurations of the angle φ, the most favorable angle in terms of the working space being φ=-60°. Since the angle φ=-60° generates the best workspace configuration, this angle will be kept and the angles ψ and θ will be varied to find the area with the largest workspace.



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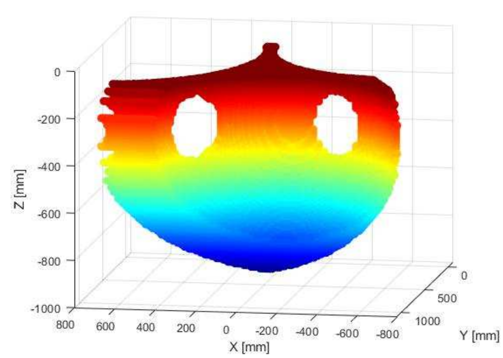

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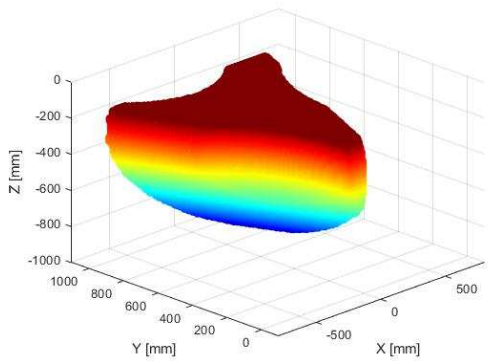

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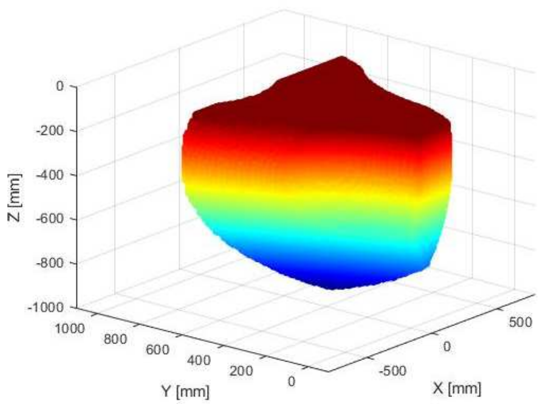


c.

Fig. 9. Robot workspace analysis for a). ψ=0°, θ=0°, φ=0°; b). ψ=25°, θ=25°, φ=-60° and c). ψ=-30°, θ=30°, φ=-60°

Figure 9 shows a variation of the angles ψ and θ keeping the angle φ=-60° resulting in the largest workspace at the values ψ=-10°, θ=-10°, φ=-60°, and the small workspace result at the value ψ=25°, θ=25°, φ=-60°.

5.1.2 Orientation workspace

The orientation workspace for the robot described in [7] was generated using MATLAB software by varying the angles θ and φ in the range [-30°, 30°], and keeping the angle ψ= 0° according to the figure 10.

Figure 11 illustrates the working space of the robot with the rectangular frame where the largest working space is if the angles are: ψ=30°, θ =30°, φ=0°, and the most unfavorable case is: ψ=-30°, θ=-30°, φ=0°.

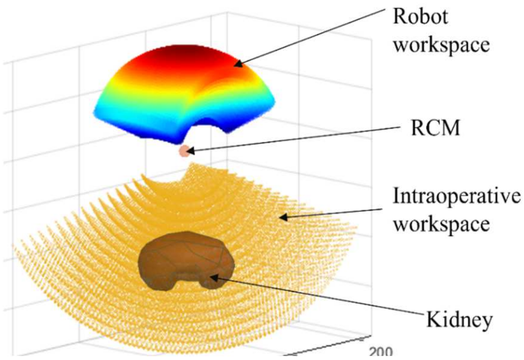
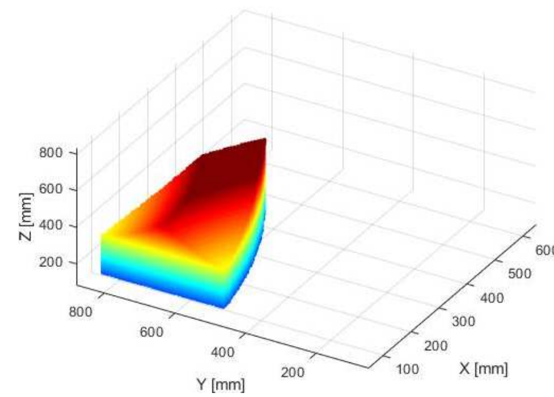


Fig. 10. Orientation workspace with kidney

5.2 Workspace for parallel robotic structure with a rectangular frame

5.2.1 Constant orientation workspace

In the parallel robotic system described in figure 3, in accordance with the medical task and the medical experts the ψ, θ, and φ angles of the robot platform should not exceed ±30.



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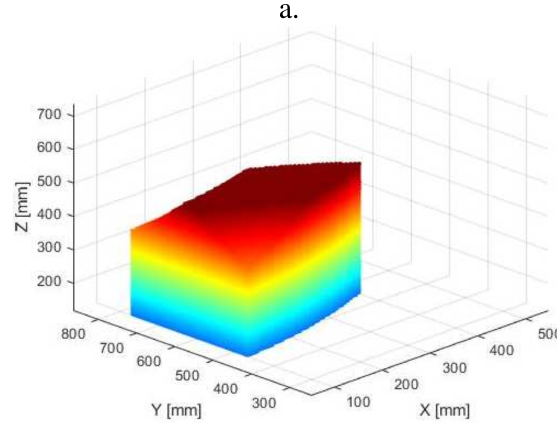

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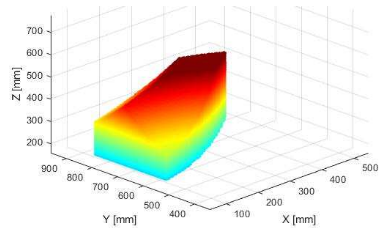

c.

Fig. 11. Robot workspace analysis for a). ψ=0°, θ=0°, φ=0°; b). ψ=30°, θ=30°, φ=0° and c). ψ=-30°, θ=-30°, φ=0°

5.2.2 Orientation workspace

The orientation workspace for the robot described in [8] was generated using MATLAB software by varying the angles θ and φ in the range [-30°, 30°], and keeping the angle ψ= 0° according to the figure 12.

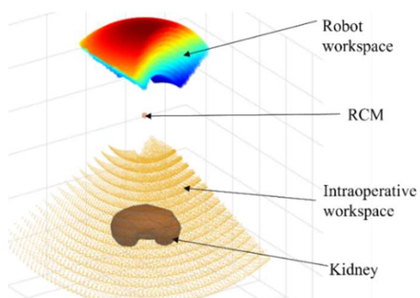

Fig. 12. Orientation workspace with kidney

6. CONCLUSIONS

The paper presents two parallel robotic systems for SILS with 6-DOF, having the same kinematic chains but with different frames, subjected to an extensive analysis of the workspace. The workspace analysis was generated starting from the inverse kinematic model, which generated an analytical solution. The extensive study of the workspace was generated by maintaining a constant orientation of the mobile platform and by varying the angles ψ, θ, and φ around the RCM (insertion point).

Following these analyzes, it is found that both structures validate the medical task, thus consolidating the continuation of studies for the development of these systems.

Future work will focus on the dimensional optimization of these systems and on finding the singularities of this robotic system.

ACKNOWLEDGMENTS

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ANALIZA SPAȚIULUI DE LUCRU PENTRU DOI ROBOȚI PARALELI INOVATIVI UTILIZAȚI ÎN CHIRURGIA UNIPORT

Chirurgia uniport (SILS) asistată robotic reprezintă o alternativă viabilă pentru procedurile minim invazive, având avantajele unui timp redus de recuperare, de spitalizarea, obținându-se în același timp rezultate estetice superioare față de procedura clasică. Lucrarea prezintă o familie de roboți paraleli inovativi dedicați chirurgiei uniport (SILS) pentru care s-a realizat o analiză detaliată a spațiului de lucru în conformitate cu protocolul medical stabilit de medicii specialiști. Pentru validarea acestor sisteme robotice s-a obținut o analiză extinsă asupra spațiului de lucru, corelata cu procedura medicală, aferent fiecărei structuri robotice.

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