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THE CONCEPTUAL DESIGN OF A PARALLEL MECHANISM WITH 3 DEGREES OF FREEDOM FOR ROBOTIC ASSISTED MINIMALLY INVASIVE SURGERY

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Abstract: *The paper presents an innovative parallel mechanism with 3 degrees of freedom for minimally invasive surgery. Starting from a known architecture, with an architecturally constrained Remote Center of Motion, a new concept is proposed, according to the most important technical characteristics which must be fulfilled by surgical robot. The paper focuses on the development of the CAD design for the proposed concept. A Finite Element Analysis of some of the most important parts of the CAD model is performed, which further validates the overall design. Kinematic and dynamic simulations are performed in Siemens NX, thus validating the design in virtual environment.*

***Key words*:** parallel mechanism, Remote Center of Motion, mechanical design, surgery, analysis

1. INTRODUCTION

Cancer represents a significant global health concern, ranked as a leading cause of premature mortality worldwide. According to the data from World Health Organization's 2019, cancer represents the first or the second leading cause of death before age 70 in 61% of countries surveyed, and among the top four causes in an additional 13% [1]. Minimally Invasive Surgery (MIS) emerged as a revolutionary surgical approach in the early 1980s and represents a significant advancement in cancer surgery. This technique utilizes small incisions to introduce specialized instruments, allowing surgeons to perform precise interventions [2]. MIS offers advantages suck: lower infection risk, a faster recovery and improved outcomes after the surgery. This has enhanced innovations in specialized instruments, platforms, imaging technologies and robotic assistance [3]. Robotic-assisted MIS (RA-MIS) has gained particular attention, enhanced surgical precision, dexterity, and ergonomics while reduced surgeon fatigue [4-6]. This approach prioritizes patient well-being by minimizing trauma, pain, and recovery time, aligning with patient-centred care principles [7-8]. The Remote Center of Motion (RCM) represents a crucial aspect in minimally invasive surgical procedures. It represents a fixed point about which surgical instruments or robotic devices pivot during the surgical procedure, allowing for accurate and controlled movements inside the patient's body. The RCM in robotic systems for minimally invasive surgery can be achieved and maintained using various methods [9]. Several RA-MIS robotic systems have been developed to assist surgeons during the medical procedure. The Versius Surgical System represents an advanced surgical robotic system. It features four modular bedside units supporting instruments or cameras, controlled via an open console. This system comprises four robots, each robot supports an instrument or endoscopic camera. The design of the robotic surgical systems mimics the human arm articulation enhancing the surgical flexibility [10].

Stryker's Mako Robotic-Arm Assisted Surgery represents a robotic system used in hip and knee arthroplasty [11].

The Senhance Surgical System developed Asensus Surgical represents a robotic system used in laparoscopic surgery. Some key

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components of the robotic system are represented by an ergonomic console with eye-tracking technology, robotic arms with haptic feedback and a high-definition 3D vision system [12].

This paper presents the design of a novel robotic architecture for the RA-MIS procedures with architecturally constrained RCM. The rest of the paper is structured as follows: section 2 consists of the analysis of the most important technical characteristics and requirements to be fulfilled by a surgical robot, section 3 describes the robotic architecture for RA-MIS, section 4 presents the design and some simulations using the CAD model.

2. TECHNICAL REQUIREMENTS ANALYSIS FOR RA-MIS

This section presents the analysis of the most important technical requirements for RA-MIS.

Safety is an essential characteristic for the mechanism to be efficient during use, ensuring there is no danger to the patient or the operator. Additionally, the structural integrity of the machine must be maintained using high-strength materials. Additional safety functions, which sometimes means to overload the protection systems and clear user interfaces further enhance safety by preventing operational errors and overuse. It is mandatory for these functions to include singularity avoidance and anti-collision algorithms [13].

Fixed Remote Center of Motion (RCM) is an important concept in robotics and mechanical engineering, particularly in applications like surgical robots. Mechanically, it consists of the insertion point into the patient's body, and it ensures that the surgical instruments move around it. Various mechanisms have an architecturally constrained (e.g. the parallelogram mechanism) or an arbitrary chosen and programmed RCM within the mechanism workspace [14].

Stiffness represents a fundamental characteristic to ensure the safety and effectiveness of the RCM mechanism, it refers to the ability of the mechanism to resist deformation under the load, maintaining its shape and functionality under various operational stresses, it is highly related to the accuracy of the robot [13].

Minimal Invasiveness targets the limitation of the number and the size of the incisions needed to perform surgical procedures. Generally, the existence and the compliance of the robot's RCM should be enough to ensure that the approach is minimally invasive, with minimum impact on the healthy tissue of the patient [15].

Ergonomics represents a key factor in robotic assisted surgical procedures. Some criteria that should be considered are optimized control design, intuitive controls and visualization systems. These criteria aim to improve precision, reduce operator fatigue and maintain surgeon comfort during the surgical procedure [16].

Accuracy in mechanical systems, refers to the degree to which a system's output aligns with the intended or desired value. High accuracy is essential for ensuring that surgical robotic system performs the tasks with precision, reliability, and minimal deviation. In laparoscopic procedures, the pose (position and accuracy) of the instruments tips is visually confirmed (using the endoscopic camera), which means that, although generally critical, the accuracy of the RA-MIS devices can be compensated, and the instruments position corrected. Motion scalability is required for accurate control of the instruments [17-18].

Manual Override refers to the direct operation of the robot by a human operator, using physical controls rather than automated systems. There are situations when such a control may be required for an easier and faster instruments position within the surgical field or during their removal. It adds flexibility and improved control in specific situations [13].

Degrees of Freedom (DoF) refer to the number of independent movements or parameters that define the motion of a body or mechanism. Within RA-MIS, keeping a low number of DoFs is preferable, since these systems are rather complex, sometimes with many actuators. Even so, redundancy is sometimes required, to increase the workspace and versatility [19].

Load distribution refers to how forces and weights are spread across a structure or system. Proper load distribution is crucial for ensuring the stability, safety, and efficiency of the RA-MIS systems. This characteristic can significantly impact the mechanical architecture and actuators' rigidity and finally the accuracy [13].

Compact design, which means that the system should be closely packed or arranged to occupy minimal space is desired in the case of RA-MIS. This is also due to the large number of medical devices required during the surgical procedure, all placed in the close vicinity of the patient.

Versatility, being the ability of a system, to perform a wide range of functions or adapt to various conditions and requirements, is also a characteristic of considerable importance in RA-MIS. Versatile designs are highly valued because they offer flexibility and adaptability various surgical interventions and an increased overall workspace [13].

Modular design requires that the RA-MIS devices are built using interchangeable and independent components or modules. Each module can be developed, tested, and maintained separately while contributing to the overall functionality of the system. It further leads to increased flexibility, scalability, and ease of modification [13, 20].

Workspace of robotic surgery represents the operative volume within the robot arm and the instrument cand perform the surgical procedure. The space is defined mainly by the mechanical constrains.

These characteristics have been analysed and prioritized using the Analytical Hierarchy Process in Qualica [13, 21, 22], where each criterion's importance is assessed in relation to the others, assigning values between 4 and 1/3 (4 representing the value for the most important characteristic and 1/3 for the least important characteristic) to select the most important characteristics within the RA-MIS device design. The result show that the most important characteristic of the mechanism is safety, with a percent of 18%, followed by fixed (architecturally constrained) remote center of motion with a percentage of 14%, while the third most important characteristic is represented by manual override with a percentage of 12%. These criteria primarily emphasize the robotic system's operational safety during the surgery, the precision and stability offered by a fixed remote center of motion and the ability to shift to manual control. At the bottom of the ranking are Modular Design and Ergonomics, each with 4% followed by Compact and Versatility, each with 3%.

- more important (>1),
- equally important(1), or
- less important (<1)

compared to the row item?

Fill the lower triangular matrix, starting from the diagonal. Fill the items directly under the diagonal first. Then work your way down to the lower left corner.

	Safety	Fixed Remote Center of Motion	Manual Override	Minimal Invasiveness	Stiffness	Load Distribution	Accuracy	Degrees of Freedom	Modular Design	Ergonomics	Compact Design	Versatility	Importance in Group
Safety	1	1/2	1/2	1/2	1/2	1/3	1/2	1/3	1/5	1/3	1/5	1/5	18%
Fixed Remote Center of Motion	2	1	1/2	2	1	1/2	1/2	1/3	1/5	1/3	1/5	1/5	14%
Manual Override	2	2	1	1/3	1/2	1	1/3	1/2	1/2	1/3	1/2	1/3	12%
Minimal Invasiveness	2	1/2	3	1	1	1/2	1	1	1/5	1/2	1/5	1/2	11%
Stiffness	2	1	2	1	1	1	1/2	1	1/3	1/3	1/3	1/2	9%
Load Distribution	3	2	1	2	1	1	2	1/2	1/3	1/2	1/3	1/2	8%
Accuracy	2	2	3	1	2	1/2	1	1	1/2	1/2	1/2	1/2	7%
Degrees of Freedom	3	3	2	1	1	2	1	1	1/2	1/3	1/3	1/2	7%
Modular Design	5	5	2	5	3	3	2	2	1	1/3	1/3	1/2	4%
Ergonomics	3	3	3	2	3	2	2	3	3	1	2	1/2	4%
Compact Design	5	5	2	5	3	3	2	3	3	1/2	1	1/2	3%
Versatility	5	5	3	2	2	2	2	2	2	2	2	1	3%
Consistency (Lamda - N):	1.03												

Fig.1. Technical characteristics using the AHP matrix

3. DESIGN OF THE NOVEL ROBOTIC ARCHITECTURE FOR RA-MIS

Two robotic architectures for RA-MIS have been proposed and analyzed. The first one presented in Figure 2, is a five-bar spherical parallel (decoupled) mechanism with 3 DoFs, as in [15]. This architecture consists of five revolute joints, namely R1', R2', R3' and q1', q2', the last two being active. Thus, the mechanism can perform the instrument orientation in the surgical field, fulfilling the RCM constraint, which is placed in the center of the spherical mechanism. An additional prismatic joint q3'has been added to perform the surgical instrument insertion. Starting from the architecture presented in Figure 2, an innovative parallel robotic architecture has been designed and presented in Figure 3. It consists of two parallel modules: the five bar spherical mechanism, but this time only with passive revolute joints which is used to constraint the RCM position in the center of the sphere, and a parallel robot with 3 DoFs, namely: two prismatic joints (q_1 and q_2) which performs the translation along the OX axis if both joints are actuated in the same direction, and the translation along the OZ axis, if the joints are actuated in opposite directions, with the same quantity; a revolute joint (q_3) which performs the surgical instrument insertion along its axis. The module also has 7 passive revolute joints (R_{1P}- R_{7P}), three passive prismatic joints (P_{1P}- P_{3P}) and three passive spherical joints (S_{1P}- S_{3P}).

Based on the two previously presented concepts, a PUGH analysis was conducted to determine which of the two concepts better satisfies the functional criteria. Following the PUGH analysis, Concept 2 (The innovative parallel mechanism for RA-MIS) was chosen based on the score illustrated in Figure 4. This concept was 3D designed and is presented in the following section

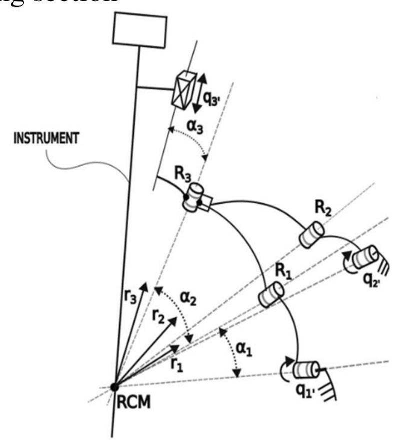

Fig.2. The five-bar spherical parallel mechanism

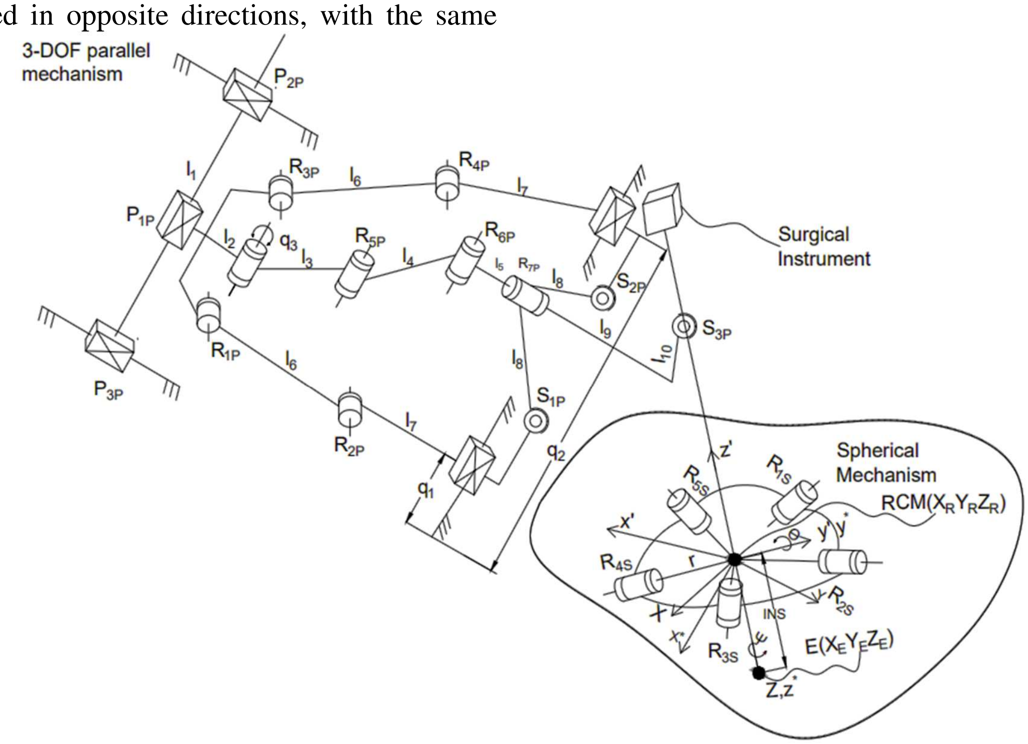

Fig.3. The innovative parallel mechanism for RA-MIS

4. MECHANICAL DESIGN

Based on the PUGH analysis result, the 3D model of the innovative parallel mechanism for RA-MIS was generated using Siemens NX.
In Figure 5 the mechanical design of the proposal innovative parallel mechanism for RA-MIS is presented. This mechanism has 3 DoF and the main components are:

1.Motors.
2-3. Screw nut mechanism.
4. Spherical coupling.
5. Spherical mechanism.
6.Runner blocks.
7.Printing part

To validate the detailed 3D model of the mechanism, Finite Element Analysis (FEA) was performed on the most stressed components. The FEA was conducted using Siemens NX, with the most significant results presented in
OZ) and the material selected for the components subjected to FEA is ABS.

Figures 6-8. These figures show the maximum displacements and von Mises stresses generated by applying a force between 20 and 30 N (this force was applied on all three axes *OX, OY,* and *OZ.*
The most important results are:

- For the link part: 0.0561 mm displacement and 1.16 MPa von Mises stress.
- For the support: 0.0809 mm displacement and 2.4 MPa von Mises stress.
- For the link of the spherical mechanism: 0.06 mm displacement and 0.85 MPa von Mises stress. at analysis is Siemens NX.

The FEA results demonstrate that the designed elements are mechanically robust. Therefore, during the system's operation, there will be no deformations that could cause elasticity in the mechanism, reduce accuracy, or pose any safety issues.

	A	B	C	D
1	-- 0.00 Unacceptable - 2.50 Borderline O 5.00 Almost meets requirement + 7.50 Meets requirement ++ 10.00 Exceeds requirement	Importance	1 Concept 1	2 Concept 2
2	Functional Requirements			
3	Safety	16.00%	+	+
4	Fixed Remote Center of Motion	14.00%	+	++
5	Manual Override	12.00%	O	+
6	Minimal Invasiveness	11.00%	+	+
7	Stiffness	9.00%	++	+
8	Load Distribution	8.00%	+	+
9	Degrees of Freedom	7.00%	+	++
10	Accuracy	7.00%	+	++
11	Modular Design	4.00%	-	+
12	Ergonomics	4.00%	-	+
13	Compact Design	3.00%	+	+
14	Versatility	3.00%	+	+
15				
16	Weighted Score (0 ..10)		7.0	8.2

Fig 4. PUGH analysis

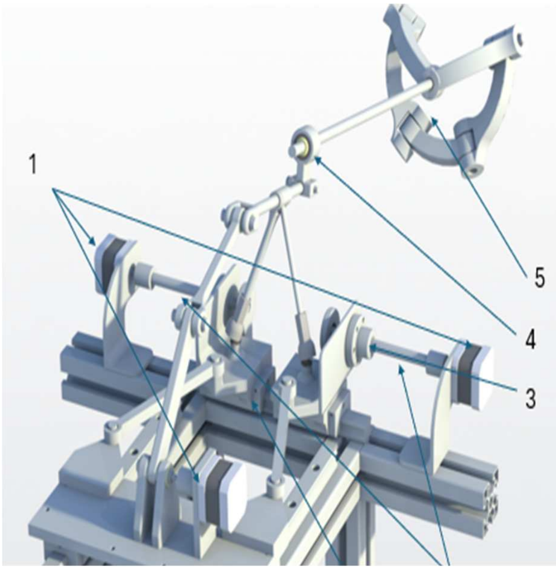

Fig 5. The mechanical design of the Concept 2

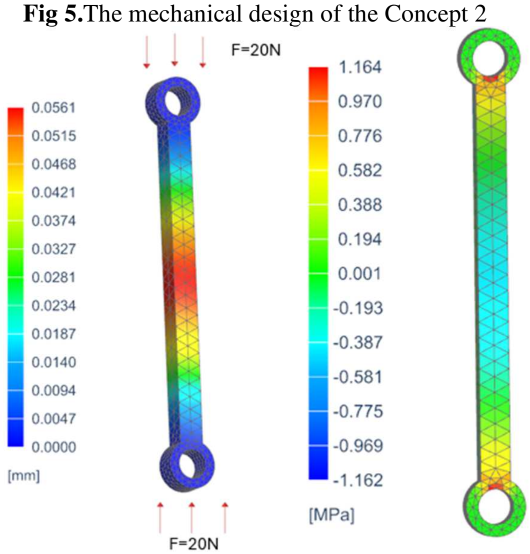

Fig.6. Displacement and von Mises stress of the link part

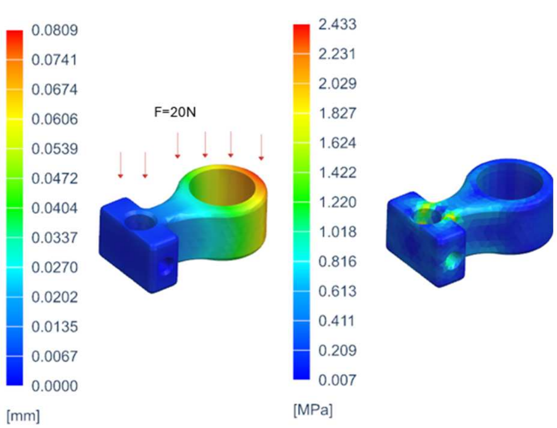

Fig.7. Displacement and von Mises stress of the support

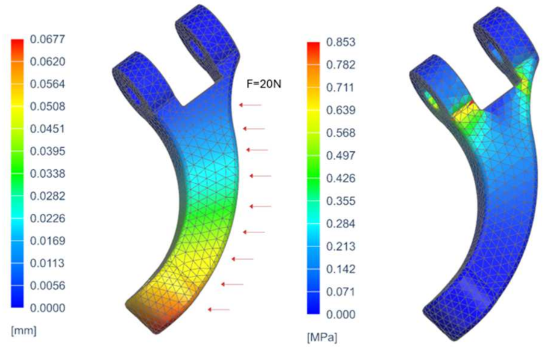

Fig.8. Displacement and von Mises stress of the link for spherical mechanism

5. SIMULATIONS

The CAD model in Figure 5 has been used to simulate a real trajectory in the surgical field to re-position and re-orient the surgical instrument. The simulation recorded the displacements, velocities, accelerations and forces/torques of the three active joints of the proposed design. For the moment the two prismatic joints (q_1 and q_2) have been considered as linear actuators.
The simulated motion is a re-position of the surgical instrument on the mobile OZ axis and an orientation around the OY axis, which is why the displacements for q_1 and q_2 are mirrored. The results of the simulation are presented in Figure 9. The dynamic simulation [23, 24] provides information regarding the actuator's requirements for their proper selection, while validating the functionality and usability of the proposed design.

6. CONCLUSIONS

The paper presents the initial design of a robot for minimally invasive surgery. Starting from a set of technical requirements, carefully hierarchized using the AHP (Analytic Hierarchy Process) analysis, an innovative concept has been proposed. The PUGH method has been used to compare the innovative design with a known robot architecture, also suitable for MIS, which indicated that for the proposed medical task, the new design offers certain advantages. The stress analysis for the assembly components showed that the parts withstand the forces with very little deformation.

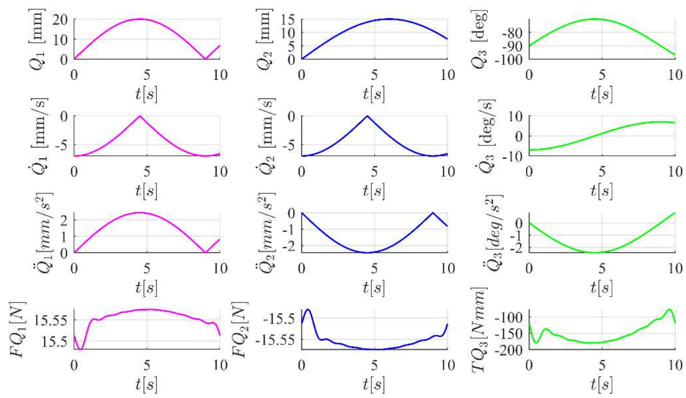

Fig.9. Time history diagram for displacements, velocities, accelerations and forces/torques for the proposed mechanism

The proposed architecture has several advantages over the five-bar spherical mechanism, among which: higher dynamic properties, being able to withstand surgical instruments with larger weights and smaller motors; the possibility of removing the parallel mechanism (with 4 DoFs) and keeping only the unactuated spherical mechanism, when the surgical instrument can be manually guided through a pre-set RCM; higher accuracy, due to the use of prismatic joints.

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Proiectarea conceptuală a unui mecanism paralel cu trei grade de libertate destinate intervențiilor chirurgicale minim invasive

Lucrarea prezintă un mecanism paralel inovator cu 3 grade de libertate pentru chirurgia minim invazivă. Plecând de la o arhitectură cunoscută, cu un Remote Center of Motion constrâns din punct de vedere arhitectural, se propune un nou concept, conform celor mai importante caracteristici tehnice pe care trebuie să le îndeplinească robotul chirurgical. Lucrarea se concentrează pe dezvoltarea modelului CAD pentru conceptul propus. Este efectuată o analiză cu element finit a celor mai importante componente ale modelului CAD în vederea validării conceptuale. Simulările cinematice și dinamice sunt efectuate în Siemens NX, validând astfel conceptul în mediu virtual.
Cuvinte cheie: mecanism paralel, centru de mișcare la distanță, proiectare mecanică, chirurgie, analiză

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