TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 64, Issue III, September, 2021

NEW APPROACH TO HYBRID ROBOTIC SYSTEM APLICATION IN SINGLE INCISION LAPAROSCOPIC SURGERY

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Abstract: *The paper presents a new approach concerning a new hybrid robotic system for Single Incision Laparoscopic Surgery (SILS). The main characteristics of the proposed robotic solution are defined based on a critical analysis of the current achievements in robotic surgery and the specific ergonomic limitations in SILS. The proposed hybrid solution has a master-slave architecture. The surgeon master console uses twin haptic devices for surgical instrument manipulation and Augmented Reality (AR) tools, whereas the slave hybrid robotic system uses a KUKA iiwa LBR collaborative robot in combination with independent orientation modules for the active instrument guidance. Several kinematic solutions are presented for the orientation module, together with their structural analysis. Furthermore, the integration of the hybrid solution in the Operation Room (OR) is also presented, highlighting its ergonomics.*

Keywords: *Robotic-assisted surgery, ergonomics, safety, parallel mechanism synthesis, collaborative robot.*

1. INTRODUCTION

SILS is a step forward in Minimally Invasive Surgery (MIS) evolution. In SILS, the surgical instruments are introduced into the operating field through a single port compared to MIS, where the surgical instruments are inserted through separate ports. The most significant benefits of SILS are the reduction of trauma to the patient and better cosmesis [1]. However, SILS also presents several challenges, such as handling instruments in a confined space and the ergonomics of the procedure, which can negatively affect patient safety [1].

The use of medical robots for SILS has been proposed to eliminate significant challenges of the manual procedure. The first robotic-assisted SILS procedures (e.g., for the abdominal area [2]) were performed with robotic systems for MIS (da Vinci platform [2]), highlighting the medical benefits despite ergonomics and operation time drawbacks. Thus, the need for dedicated robotic systems for SILS was demonstrated. However, the availability of robotic systems (nowadays) for SILS at the European and National level is limited.

The da Vinci SP is one of the earliest robotic solutions dedicated to SILS, used in various urologic and gynecologic procedures [3, 4]. It consists of a 3D camera and two active (bendable) instruments [3]. Da Vinci SP represents a module that is mounted on a single robotic arm of the da Vinci platform. SPORT [5] is another SILS robot with flexible instruments for grasping, cutting, etc. Other solutions were proposed in the literature (e.g., [6, 7]), but many authors acknowledge the limitations of the available SILS systems [7].

A new solution for robotic SILS for urology (in contrast to the available systems with bendable instruments) is proposed in this paper. The solution is based on a hybrid robotic system consisting of a serial manipulator (to position surgical instruments at the insertion port) and a parallel orientation module (to manipulate the surgical instruments independently). The hybrid system combines the architectural advantages of both serial and parallel manipulators leading towards a robotic system with large workspace, high dexterity and accurate positioning capability. The control of the hybrid system

Received: 25.07.21; **Similarities**: 23.05.21: **Reviewed**: 05.06.21: **Accepted**:13.06.21

follows a master-slave approach (the surgeon operates the robot from a control console).

Following the Introduction Section, the paper is structured as follows: Section 2 presents a comparison of various minimally invasive procedures, highlighting the poor ergonomics of SILS. Furthermore, Section 3 presents the current SILS robotic solutions for urology. A new approach for robotic SILS is presented in Section 4, and the integration of the robotic system in the OR is described in Section 5. Finally, the conclusions are drawn in Section 6.

2. CRITICAL ANALYSIS BETWEEN THE DIFFERENT MINIMALLY INVASIVE SURGICAL PROCEDURES

Minimally invasive procedures share a common characteristic, namely the reduction, to a minimum possible, of the damage to the healthy tissue. However, there are also some differences between classical MIS and SILS, which derive from the way the instruments are inserted inside the body, having, as consequence a direct influence on the workspace of the instruments and the ergonomics of the procedure. A surgical trainer is used to emphasize the main differences between the procedures.

Figure 1 illustrates a typical minimally invasive procedure, where the instruments are inserted inside the body through 3 separate incisions.

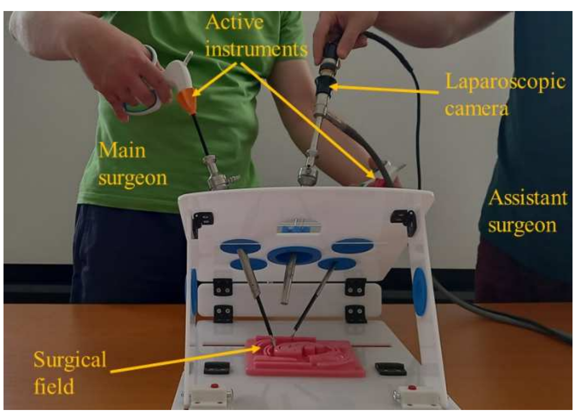

Fig.1 Instruments and surgeons' position in MIS

The procedure is performed by two surgeons in classical MIS, whereas the main surgeon manipulates the active instruments, using his left and right hand, while the assistant surgeon positions the laparoscopic camera based on the requests of the main surgeon. In order to interact with the surgical field, the main surgeon keeps his hands apart having a wide motion volume which reflects in high dexterity at the level of the instrument's tips.

SILS is a type of minimally invasive surgery performed through a single incision in the patient's body. When compared to standard multiple-incision laparoscopic surgery, while SILS presents itself to be similar in terms of complication rates, completion rates and post-operative pain scores, it does present significantly less scarring to the patient's body, especially if the procedure is done through the umbilicus [2]. SILS can be achieved with either classical MIS straight instruments, (figure 2) or with dedicated curved instruments (figure 3).

When SILS is performed with straight instruments, it can be observed that the hands of both surgeons are very close together, limiting the motions and reach of the active instruments with respect to the surgical field. Furthermore, the use of straight instruments, imposes their crossing (called the X position) inside the body which determines a counter-intuitive motion at the level of the surgeon hands.

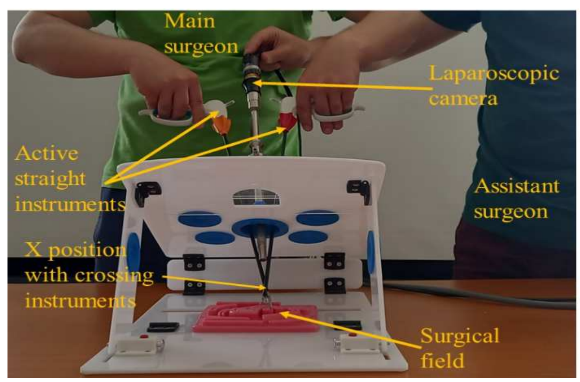

Fig.2 Instruments and surgeons' position in SILS performed with straight instruments

To increase the ergonomics in SILS, special curved instruments have been developed (figure 3). They allow access to the surgical field without the crossing of the instruments (called the Y position) which enables the surgeon to perform the motions intuitively as in MIS, however in a much smaller volume. The curvature of the instruments is limited to allow their insertion through the entry port inside the patient body.

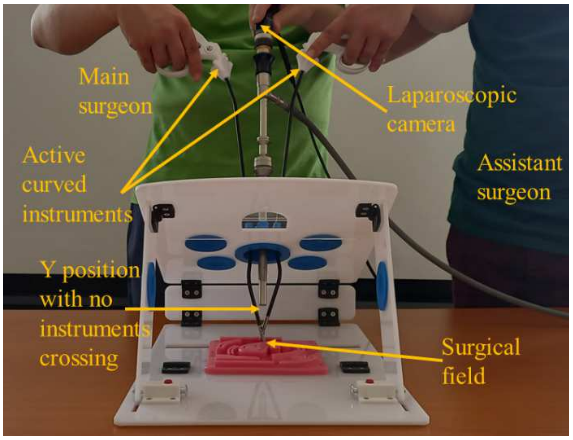

Fig.3 Instruments and surgeons' position in SILS performed with curved instruments

A critical analysis between MIS and SILS concludes that the invasiveness of SILS is lower with the cost of ergonomics on the surgeon's side.

The technological advancements enabled the development of robotic systems which aimed to enhance the efficiency of the surgeons by adding new features and functionalities impossible to implement in a manual setup. The use of robots in surgery is strictly regulated through the IEC 80601-2-77:2019 which defines their basic safety and performance indicators along with the statement that a surgical robot has zero autonomy. This means that any surgical robot must be developed based on the master-slave concept and teleoperation, which means that the surgeon uses a master console from where, through appropriate joysticks, transmits the motion to the slave robotic system.

A short overview of the use of robotic systems in MIS and SILS is performed to evaluate, based on clinical results, their advantages and limitations.

Robotic assisted surgery (RAS) has gained increasing popularity among surgeons and patients in recent times, which lead to 3 times increase in RAS procedures over the past decades [8].

In general, the improved dexterity and precision provided by robotic systems has allowed minimally invasive procedures to be more feasible, which led to benefits compared to conventional open surgery such as less postoperative pain, reduced blood loss, shorter hospital stays and recovery times [1,7, 9, 10].

As a drawback, the lead surgeon is separated from the rest of the team, imposing changes in communication, coordination and teamwork, a cited cause for procedural errors and surgical injury [8]. The increased operation time of RAS is another commonly referred disadvantage, due to difficulties in port-placement, instrument changes, docking, robot arms collisions, etc.

Robotic SILS started to be used as an alternative to MIS recently, and there are few studies comparing the characteristics of the different approaches. Elli et. al. [11] published a study detailing the long- and short-term results of 409 laparoscopic and robotic sleeve gastrectomy procedures. The robotic approach recorded longer operative time, but its reduced invasiveness led to very few hiatal hernia repairs (7.6% of the cases compared to 45.7% for the manual therapy) and no complications. Hagen et.al. published in 2017 [12] a study detailing a comparison between robotic SILS and multiport laparoscopic cholecystectomy performed on 99 patients. Several complications were registered in the case of robotic SILS which also had higher hospitalization costs. However, robotic SILS treated 31% of the cases as outpatient procedures (not requiring hospitalization).

Corrado et. al. published in 2016 a study [13] comparing Robotic SILS hysterectomy in early endometrial cancer to robotic multi-port hysterectomy. The single-port surgery lead to less intraoperatory blood loss and shorter hospitalization days.

Lopez et. al. [14] published an article comparing Robotic SILS to SILS for benign hysterectomies over 100 cases. Robotic SILS recorded longer operative times but three times less complications and a shorter learning curve.

Based on the performed review, it concludes that robotic assisted SILS is a promising new technique but requires the development of dedicated equipment to increase the safety and ergonomics of the procedure its specific drawbacks.

3. ROBOTIC-ASSISTED SILS IN UROLOGY

Concerning robotics in urology SILS is performed since 2008, when Kaouk et. al. reported the first cases of robotic laparo-endoscopic single site surgery, concluding that using a robotic platform presented better dissection and suturing compared to classical laparoscopic surgery [15].

Bowen et.al. [16] presented in 2018 a study regarding the use of robotics in pediatric urology, presenting advantages such as tremor control and increased maneuverability of the wrist which is not possible during conventional surgery due to the limitations of non-articulated instruments that are used. In specific procedures, as pyeloplasty (the reconstruction of the renal pelvis) robotic assisted procedures imposed themselves as gold standard due to the very high success rate [17]. Similar efficiency was also reported in ureteral reimplantation [16].

Several studies have presented clinical results with the da Vinci SP system in ureteroneocystostomy, ureteral reimplantation, radical prostatectomy and radical cystectomy [18]. The studies reported similar outcomes to conventional multi-port procedures. Further studies of the feasibility of this system are still necessary [19].

As a conclusion, in urology, due to the smaller volume of the surgical field robotic assisted SILS procedures are preferred due to the reduced trauma and better cosmetic results.

4. A NEW HYBRID ROBOTIC SYSTEM FOR SILS IN UROLOGY

The main drawback of SILS (considering the manual procedure) is the poor ergonomics (which may negatively affect patient safety) due to the limited volume in which the instruments are manipulated outside the patients' body. Most available and proposed robotic solutions use (continuum) flexible active instruments, which according to medical experts (with experience in robotic-assisted urologic surgery), can sometimes lack the necessary force (due to the bending mechanism) for, e.g., grasping, suturing.

Our vision is to develop a hybrid robotic system with the following main components:
1. A single serial robot, which is used to perform the positioning of an orientation module for the SILS instruments at the insertion point;
2. The orientation module, which guides the active surgical instruments in achieving their independent control;
3. The active surgical instruments for SILS, which have multiple degrees of freedom (DOF) to increase the dexterity of the distal instrument head.

The above characteristics aim to:

- increase the procedure ergonomics (having a single serial manipulator at the surgical field);
- ensure optimum dexterity for the surgical instruments (through a combination of the orientation module and the surgical instruments DOF);
- ensure optimum manipulating force, e.g., the distal instrument head grasps a suturing needle, whereas the orientation module provides optimum force to move the needle in the suturing process.

4.1. THE CONCEPT OF REMOTE CENTER OF MOTION

In minimally invasive procedures, the motion of the surgical instruments is achieved with respect to a fixed point in space – the entry point in the body. This point acts as a class 2 joint [20] was defined as the Remote Center of Motion (RCM) by R. Taylor in 1995 [21]. Maintaining the position of the RCM is important to ensure the patient safety during the medical procedure.

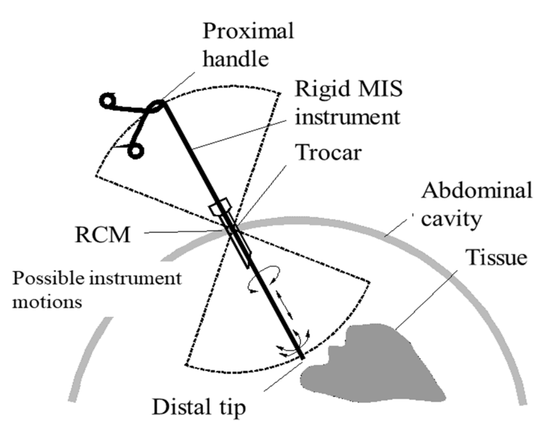

Fig. 4. Possible instrument motions constrained by the RCM [25]

A surgical instrument (with respect to RCM) should have 4 DOF, which may be characterized in two ways. In spherical coordinates, the distal head of the instrument has 3 rotations and 1 translation along the longitudinal axis of the instrument. On the other hand, in Cartesian coordinates, the distal head has 3 translations and 1 rotation around the longitudinal instrument axis (figure 4). The RCM can be achieved in three ways [22] (each having specific advantages and disadvantages), as illustrated in Table 1.

Table 1. Types of RCM

RCM type	Characteristics	
Passive	Simple mechanism	Low accuracy
Mechanically Constrained	Complex mechanism	Good accuracy
Architecturally Constrained	Simple Mechanism	Good accuracy

4.2. THE SERIAL ROBOT FOR ORIENTATION MODULE POSITIONING

A viable solution for the serial robot (for the orientation module positioning) is the KUKA iiwa LBR redundant 7 DOF collaborative robot. It allows the surgeons to manually position the orientation module in-situ (to comply with the procedure needs). Furthermore, the redundant robot's null-space motion [23] allows its positional reconfiguration without changing the position of the mounted orientation module (which can reduce the robot footprint in the OR). Consequently, KUKA iiwa LBR provides good ergonomics of the medical procedure, ensuring patient safety. In addition, the capability to work together with human operators, the force/torque sensors located in every joint, and a layer of safety functions makes the KUKA iiwa LBR robot suitable for medical applications [24].

Having the redundant DOF, KUKA iiwa LBR can generate the RCM while ensuring also the necessary DOF required by a rigid instrument as demonstrated in Figure 5 using a human phantom (in three snapshots). KUKA iiwa LBR allows an optimum RCM manipulation in a large proportion of the robot workspace (improving the ergonomics of the procedure).

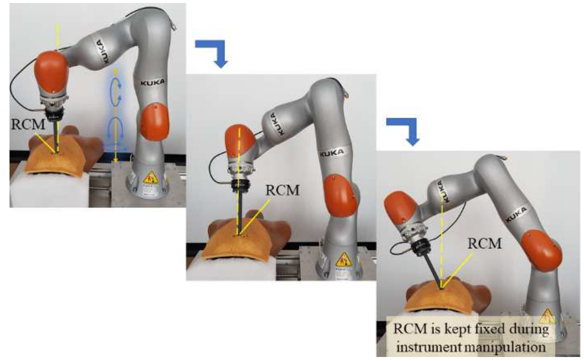

Fig. 5. KUKA robot manipulates an instrument using a RCM control

One solution for the orientation module (attached to the serial manipulator flange) is to design an innovative module for all the surgical instruments required in SILS. The design must ensure that the endoscopic camera is coincident with the last rotation axis (to ensure intuitive control) of the robot while the active instruments are positioned on the left and right. A conceptual design of a SILS robotic system is illustrated in Figure 6. The robot generates the RCM, which is used to position the camera, while the instruments require independent positioning control.

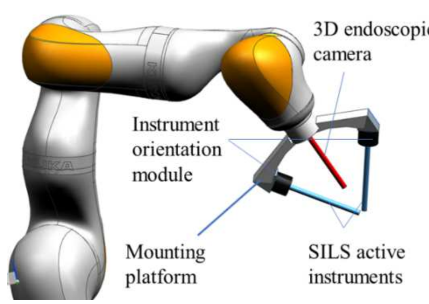

Fig. 6. Conceptual design of a SILS hybrid robotic system

4.3. ORIENTATION MODULES FOR SURGICAL INSTRUMENTS

This section presents four possible options for the instrument orientation modules, which ensure the RCM motion for the surgical instruments.

4.3.1. A serial RR orientation module

Figure 7 presents the kinematic scheme and the CAD model of a serial RR orientation module with two rotation axes perpendicular to each other.

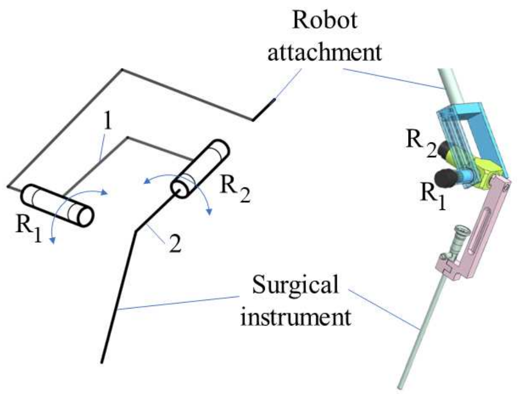

Fig. 7. A serial RR orientation module.

To describe the mechanism mobility, the formula proposed by Plitea [20] is used:

$$M = (6-F)\cdot N - \sum_{i=1..5}(i-F)\cdot C_i \qquad (1)$$

where:

M – the mobility degree of the mechanism;

F – the mechanism family (the number of common constraints among all the mobile elements);

N – the number of mobile elements;

C_i – number of joint of class "i" (**i** represents the number of constraints of one joint, e.g., a rotational joint is class 5).

The RR orientation module (fig. x) has 2 mobile elements (1,2) and two revolute joints (R_1, R_2) and family $F=4$. Based on Eq. (1) it yields:

$$M = (6-F)\cdot N - (5-F)\cdot C_5 = 2 \qquad (2)$$

4.3.2 A P-CYL-RRU parallel orientation module

Figure 8 shows the kinematic scheme and the CAD model of a P-CYL-RRU parallel orientation module with 2 actuated joints (due to P_1 and the rotation axis of the cylindrical joint CYL_1). Due to the common translation between P_1 and CYL_1, P_1 is not considered in the mechanism synthesis. Furthermore, CYL_1 and U_1 share a rotation axis, therefore, U_1 is considered a class 5 joint. Consequently, the parallel module has 3 mobile elements (1..3), three class 5 joints (R_1, R_2, U_1^*) and one class 4 joint (CYL_1) and the family is $F=3$. It yields:

$$M = (6-F)\cdot N - (5-F)\cdot C_5 - (4-F)\cdot C_4 \qquad (3)$$
$$M = 2$$

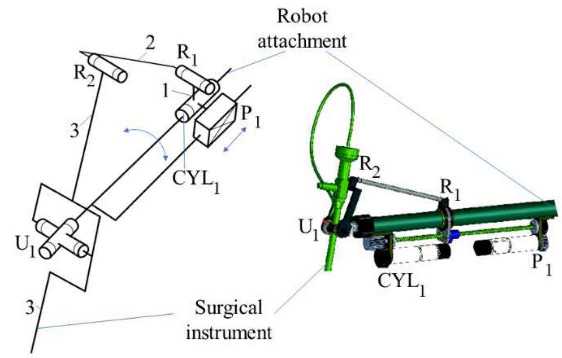

Fig. 8. A parallel P-CYL-RRU orientation module for surgical instruments.

4.3.3 A 2RUS-U parallel orientation mechanism

Figure 9 illustrates the kinematic scheme and the CAD model of a 2RUS-U parallel mechanism for surgical instruments orientation.

The mechanism contains two identical RUS kinematic chains connected to the mobile platform (5). Furthermore, a third kinematic chain connects the fixed platform (robot attachment) with the mobile one (5) through the universal joint U_3. Consequently, we can pursue the mechanism synthesis in two steps. Firstly, we compute the M mobility degree of the mobile platform only based on the two RUS chains.

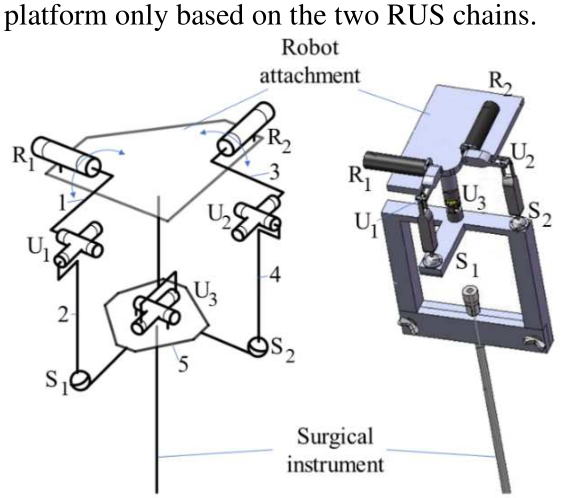

Fig. 9. A parallel 2RUS-U orientation module for surgical instruments.

In this case, we have: $N=5$ mobile elements, two class 5 joints (R_1, R_2), two class 4 joints

(U_1, U_2) and two class 3 joints (S_1, S_2), the family of the mechanism $F = 0$. Thus:

$$M = (6-F)\cdot N - (5-F)\cdot C_5 - (4-F)\cdot C_4 \\ -(3-F)\cdot C_3, M = 6 \quad (4)$$

By adding the U_3 joint between the fixed platform and the mobile one, we eliminate 4 DOF, the three Cartesian motions, and 1 rotation (around a vertical axis). Thus the mobility of the parallel mechanism is $M = 2$.

4.3.4 A 2PSS-RR orientation module

Figure 10 shows the kinematic scheme and the CAD model of a 2PSS-RR parallel module for surgical instruments orientation.

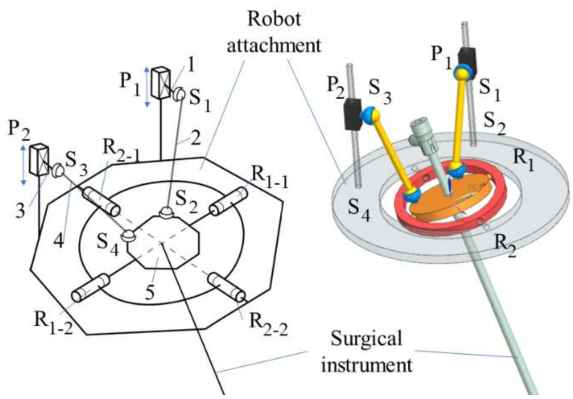

Fig. 10. A parallel 2PUS-RR orientation module for surgical instruments.

The mechanism contains two PSS kinematic chains which connect the fixed platform (robot attachment) with the mobile one (5). The mobile platform is linked with the fixed one via two revolute joints (R_1, R_2) with perpendicular axes. Just like in the previous case (the 2RUS-U mechanism), the analysis is performed in two steps. First, the mechanism consisting of (only) the two PSS chains yields: the number of mobile elements $N = 5$, two class 5 joints (P_1, P_2), four class 3 joints ($S_1 \mathrm{K}\, S_4$), the family of the mechanism $F = 0$. Using Eq. (1), it yields:

$$M = (6-F)\cdot N - (5-F)\cdot C_5 - (3-F)\cdot C_3 \\ M = 8 \quad (5)$$

Analyzing the mechanism in Figure 10 shows that links 2 and 4 have self-motion around their longitudinal axis, adding 2 DOF. Consequently, the mobility of the 2PSS mechanism is $M = 6$. Since the fixed platform is linked with the mobile one via the RR chain, 4 DOF are eliminated (3 Cartesian motions and one rotation). Thus the mobility of the 2PSS-RR parallel mechanism is $M = 2$.

4.4. BENDING INSTRUMENT FOR SILS

The proposed active SILS instrument also has 3 DOF: 2 rotations due to a dual bend that changes its configuration from a straight to an angled position 25], and a grasping DOF for the distal instrument head. Figure 11 illustrates one example of such an instrument with 90° and 45° bends, respectively. Due to the orientation module, the distal instrument head (the grasper) has a total of 6 DOF.

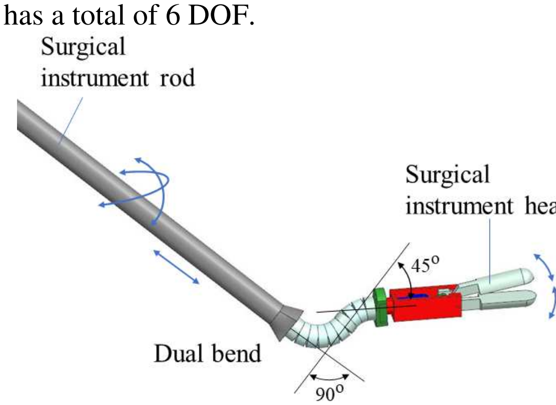

Fig. 11. SILS instrument with dual bend and grasper.

5. INTEGRATION OF THE ROBOTIC SYSTEM IN THE OPERATING ROOM

Figure 12 presents the typical setup of the operating room (OR).

Fig.12 OR setup and main equipment

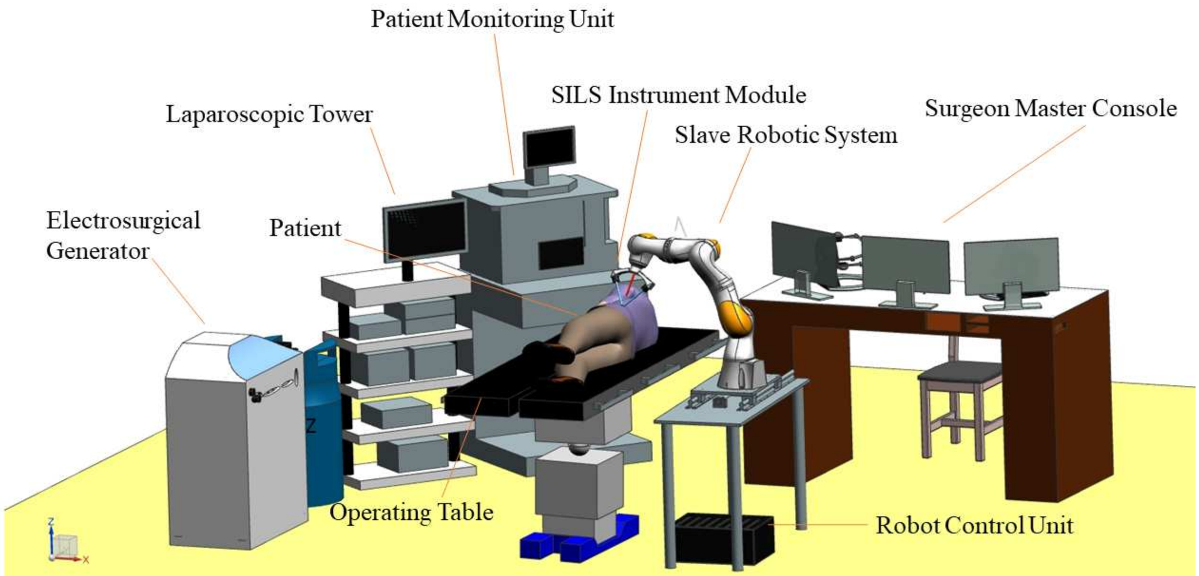

Fig. 13. Integration of the innovative SILS robotic system in the virtual operating room with the patient positioned in lateral decubitus for renal cyst decortication by retroperitoneal approach.

Considering all the medical equipment, the integration of the SILS robotic system in the OR is made by placing the Surgeon Master Console aside them and the Slave Robotic System on the side of the operating table, mounted on an adjustable table, based on the patient anthropometric characteristics and the targeted organ (figure 13). The robotic system is based on the Master-Slave architecture and uses a teleoperation control solution. To perform the SILS procedure, the surgeon sits at the Master console illustrated in detail in figure 14.

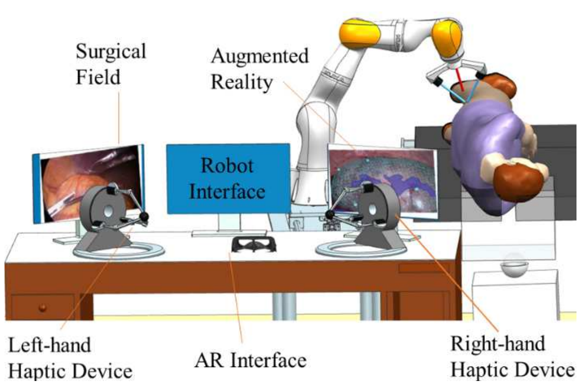

Fig. 14. The Concept of Surgeon Master Console

It integrates a pair of 7 DOF haptic devices used to manipulate the two active surgical instruments and a microphone to achieve the positioning of the endoscopic camera based on voice control as it was proposed already in [26]. A three-display setup is proposed, with one display showing the robot control interface, a central one presenting the intraoperatory real-time images and a third display where additional enhancements are integrated. Using Augmented Reality (AR) tools the surgeon can receive additional information such as internal organ structure or pre-planning strategies and Artificial Intelligence agents that will detect and report specific data: internal bleeding, major vessels clamping times, patient status, etc. These additional functionalities aim to increase the procedure safety and its outcome.

6. CONCLUSIONS

The critical analysis of the state-of-the-art illustrated the high potential of SILS together with its current limitations.

To improve the ergonomics the authors proposed a new hybrid robotic system, using a single, highly dexterous robotic arm, connected to a platform that holds all the instruments. For the independent positioning of the active instruments, multiple orientation modules were presented. All the mechanisms are viable solutions for the SILS instruments orientation module. The final selection will be further made based on a multi-criterion analysis (e.g., workspace, weight, size, and so on) to ensure an optimum design for the SILS robotic system. The use of additional bends in the active instruments improves the reachability of the distal head. In a Master-Slave configuration, the integration of the robotic system in the OR was presented along with the main components of the surgeon console.

Future work will focus on the modelling and kinematics of the orientation module and the detailed design of the active instruments.

7. ACKNOWLEDGEMENT

This work was supported by a grant of the Ministry of Research, Innovation and Digitization, CNCS/CCCDI – UEFISCDI, project number PCE171/2021 - Challenge within PNCDI III.

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O abordare nouă pentru implementarea unui sistem robotic in chirurgia uni-port

Rezumat: Lucrarea prezintă o abordare nouă privind un sistem robotic hibrid pentru chirurgia uni-port. Principalele caracteristici ale sistemului sunt definite pe baza unei analize critice a stadiului actual in chirurgia robotizată și a limitărilor ergonomice ale chirurgiei uni-port. Soluția hibridă propusă are la bază o arhitectură master-slave. Consola master utilizează un set de dispozitive haptice pentru manipularea instrumentelor și elemente de realitate augmentată iar sistemul slave integrează un manipulator KUKA iiwa LBR în combinație cu module de orientare independente pentru ghidarea instrumentelor active. Se prezintă mai multe soluții pentru modulele de orientare alături de sinteza lor structurală. Integrarea soluției hibride în sala de operație scoate în evidență ergonomia acesteia.

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