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DESIGN AND STRUCTURAL ANALYSIS OF PARASURG-9M PARALLEL HYBRID SURGICAL ROBOTIC SYSTEM

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Abstract: *In the paper the parallel hybrid surgical robotic system PARASURG-9M is presented. The structure contains two modules: a robotic arm PARASURG 5M with five degrees of freedom (DOF), and an active robotized surgical instrument PARASIM with four DOF. The paper begins with a brief introduction in the approached field and continues with the description of the CAD model of the surgical PARASURG-9M hybrid robot. The structural analysis of the robot, and design considerations are also presented.*
Key words: *Parallel Hybrid Robot, Design, Structural Analysis, Surgical Robotic System, Active Robotized Instrument, Minimally Invasive Surgery (MIS).*

1. INTRODUCTION

The problem addressed in this paper is the design and structural analysis of a parallel hybrid surgical robotic system: PARASURG-9M. This robot is the research result in the field of robot-assisted minimally invasive surgery.

As stated before by other authors [1-3], robotic surgery primarily provides: accurate dissections, less blood loss, quick recovery of patient; being more efficient compared to classical surgery techniques. However this technology is still out of reach for many hospitals and healthcare institutions due to the high purchasing cost, maintenance and consumables. For this reason a new low-cost efficient surgical robotic system is developed: PARASURG-9M [4]. The PARASURG-9M robot consists of two major models: a hybrid parallel robotic arm with five DOF, PARASURG-5M [5-8] and PARASIM, a four DOF surgical active parallel robotized.

Considering some advantages of parallel robotic structures over serial ones, important from the surgeon's point of view in a surgical procedure, there are: improved dynamic behavior, high stiffness and higher precision of positioning [9]. So, the resulting robot presented in this paper PARASURG-9M is a successful combination of parallel and serial structures.

The paper is organized as follows: After a short introduction in section 1, section 2 is dedicated to the presentation of the CAD model of the parallel hybrid surgical robot PARASURG-9M. Section 3 deals with the structural analysis of the robot. Section 4 describes the kinematic consideration of the surgical robot PARASURG-9M used in MIS. In Section 5, the design of PARASIM active surgical instrument is described, followed by the conclusions at the final part of the paper.

2. CAD MODEL OF PARASURG-9M PARALLEL HYBRID ROBOT

The parallel hybrid surgical robotic system, PARASURG 9M is presented in figure 1. The robot is composed of PARASURG 5M which was extensively discussed in [5 - 8], and the active robotized surgical instrument PARASIM.

The surgical system was conceived so that the connection of PARASURG-5M (which performs the positioning in the surgical field) and PARASIM (which performs the orientation of the end-effector) is possible. From the kinematic point of view, the robotic arm

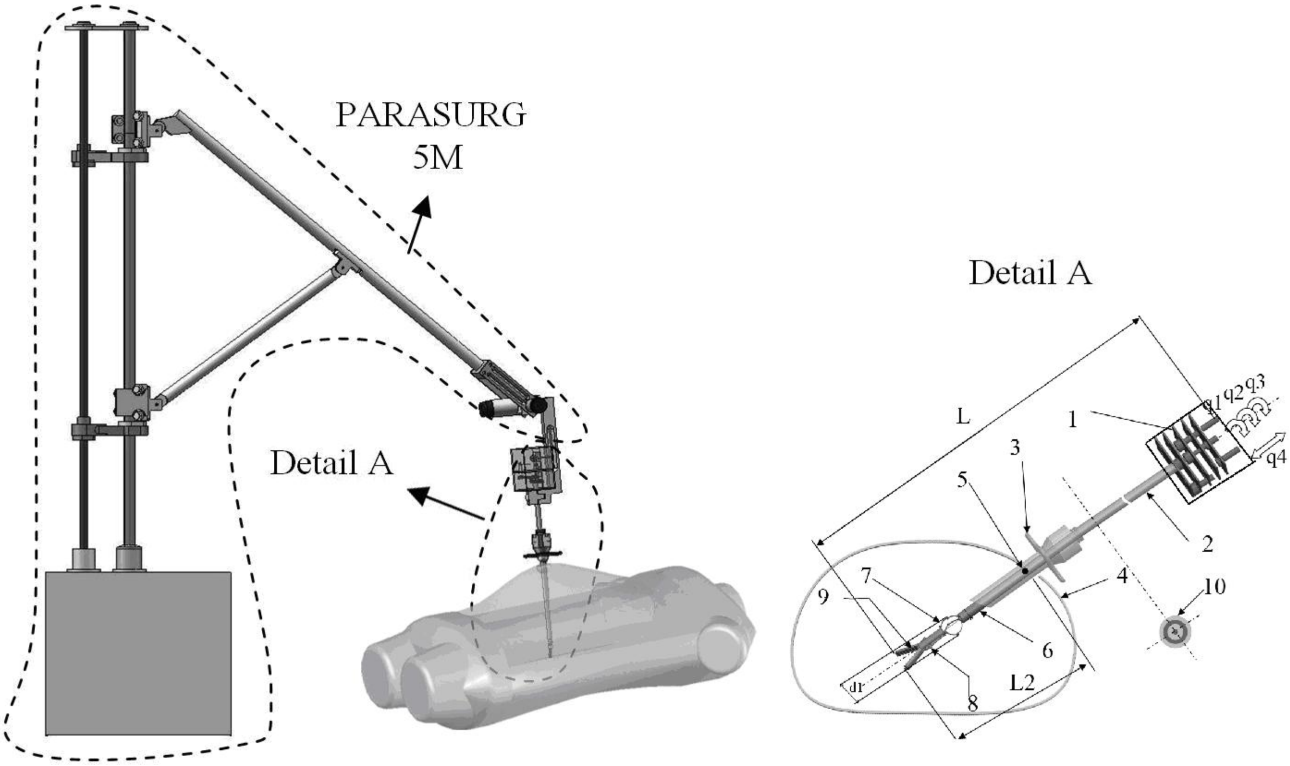

Fig. 1. a) The surgical robot PARASURG 9M, b) detail A: the active parallel robotic instrument PARASIM

PARASURG 5M has three DOF given by a module with parallel kinematics, for instrument positioning in the surgical field, and two DOF given by a module based on a serial chain for its orientation with respect to the fixed point B (the insertion point in the abdominal wall, component no. 5 in Fig. 1b)), aiming to eliminate any pressure upon the patients abdominal wall.

Regarding the active robotized instrument PARASIM which has 4 DOF, its main component is the orientation module consisting of the spherical parallel mechanism (SPM) (component no. 7 in Fig.1b)) with three identical closed kinematic chains.

The actuators of the instrument (component no. 1 in Fig. 1b)) are mounted on the base platform contained in a box.

In terms of geometric parameters used for the CAD model of the instrument, the most important are: L_2 =80 mm, representing the length of the instrument inside the surgical field; d_1=10 mm, the diameter of the SPM; and L=400 mm the length of the PARASIM active surgical instrument.

3. STRUCTURAL ANALYSIS OF PARASURG-9M

A structural analysis of PARASURG-9M, can be made using the relation [9]:

$$M = (6-F)\cdot N - (5-F)\cdot C_5 - (4-F)\cdot C_4 - (3-F)\cdot C_3 - (2-F)\cdot C_2 - (1-F)\cdot C_1 \quad (1)$$

Where the symbols are: M = mobility degree of the structure; F = mechanism's family; N = Number of mobile elements; C_i – Number of "i" class joints.

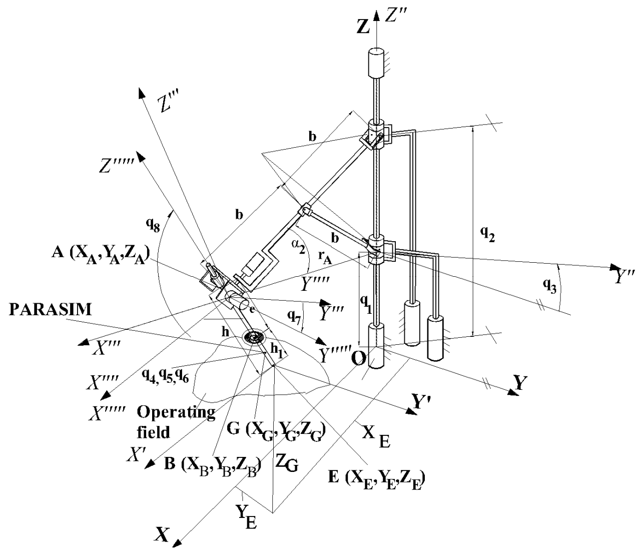

Fig. 2. Structural construction of PARASURG-9M

In order to determine the total number of DOF of PARASURG-9M (figure 2), the number of DOF of the two modules: PARASURG 5M and PARASIM are calculated next.

For PARASURG 5M:

$$F = 0; \quad N = 2; \quad C_4 = 1; \quad C_3 = 1. \qquad (2)$$

The number of DOF for PARASURG 5M is:

$$M = 6 \cdot N - 4 \cdot C_4 - 3 \cdot C_3 = 5 \qquad (3)$$

For PARASIM :

$$F = 3; \quad N = 7; \quad C_5 = 9. \qquad (4)$$

It yields:

$$M = 3 \cdot N - 2 \cdot C_5 = 3 \qquad (5)$$

The fourth DOF of PARASIM, the active function (cutting, grasping, etc.) of the instrument PARASIM is achieved by the fourth motor (component 1 from figure 1b)) which transmits the motion through a wire to the gripping actuation mechanism (component 8 from figure 1b).

Finally, the number of DOF of PARASIM is:

$$M = 4 \qquad (6)$$

Using (3) and (6), the total number of DOF for PARASURG-9M results:

$$M = 9 \qquad (7)$$

4. KINEMATIC CONSIDERATION OF PARASURG-9M USED FOR MIS

From the design point of view, the robot has nine actuated joints (three prismatic and six rotation ones, Figure 3). The following passive joints are introduced: two cylindrical joints (between links (1) and (3), respectively between links (2) and (3)), two prismatic joints (between links (4) and (3), respectively (5) and (3), three rotary joints (between links (4) and (6), (5) and (7) respectively (6) and (7). At the end of the element (12) there is mounted the element (8), representing the PARASIM instrument.

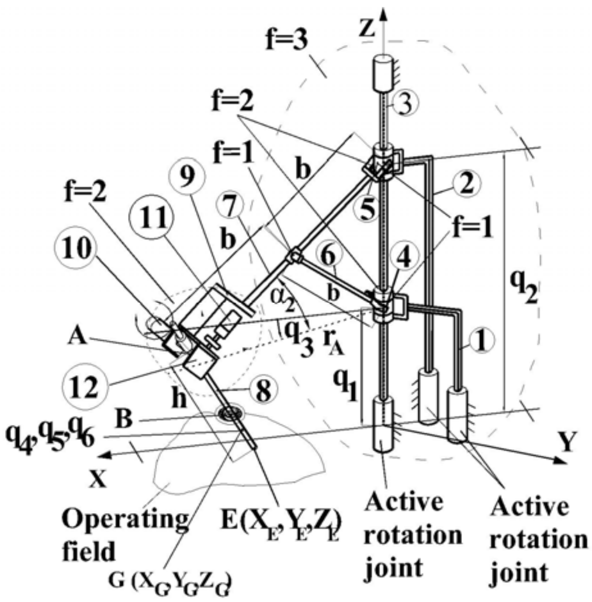

Fig. 3. The kinematic scheme of hybrid parallel robot

For a better view, the components of the instrument PARASIM can be noticed in Fig. 1 b): 1-actuation system of PARASIM included in a box, which is mounted on the mobile plate of PARASURG 5M; 2-the instrument outside surgical field; 3-the trocar; 4- surgical field; 5-the insertion point on patient (point B); 6- the instrument inside the patient; 7-the spherical parallel mechanism (SPM), which for a better observation is scaled 1.5:1; 8-gripper actuation mechanism; 9-the end-effector; 10-section view through the instrument.

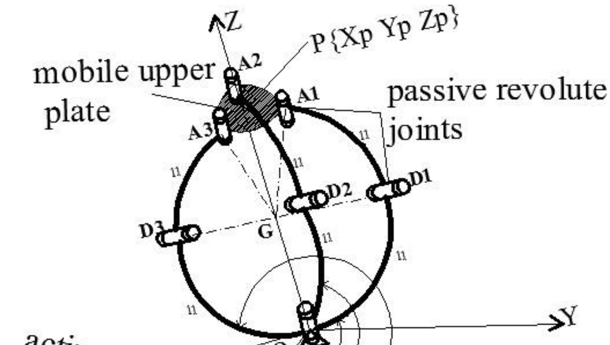

Fig. 4. The kinematic scheme of the SPM

The design of the instrument PARASIM is structurally dependent on the SPM (Fig. 4), which consists of three identical, closed-loop kinematic chains. Each "i" kinematic chain (i=1, 2, 3) (Fig. 2 b) has an active joint q_i, the proximal link which is the active element (the first one from the base up), a passive revolute joint located in D_i, a distal link which is the passive element and the passive joint located in A_i on the mobile platform. The mechanism is to maintain all its joints on a sphere while in movement.

The actuation of the SPM and the orientation of the end-effector are achieved through three concentric bores, component 10 in Fig. 1. b), that start from the connection system (component no. 1 in Fig. 1) and travel the entire length of the instrument, until they reach the SPM where each bore actuates one of the three kinematic chains: q_4, q_5, q_6, giving the desired orientation of the instrument in the surgical field.

5. DESIGN OF PARASIM ACTIVE SURGICAL INSTRUMENT

In order to achieve an experimental model, a design is necessary.

During the design process of the surgical instrument PARASIM, some requirements had to be considered: high precision; compactness in size and low weight; diameter of maximum 10 mm; modular and interchangeable construction.

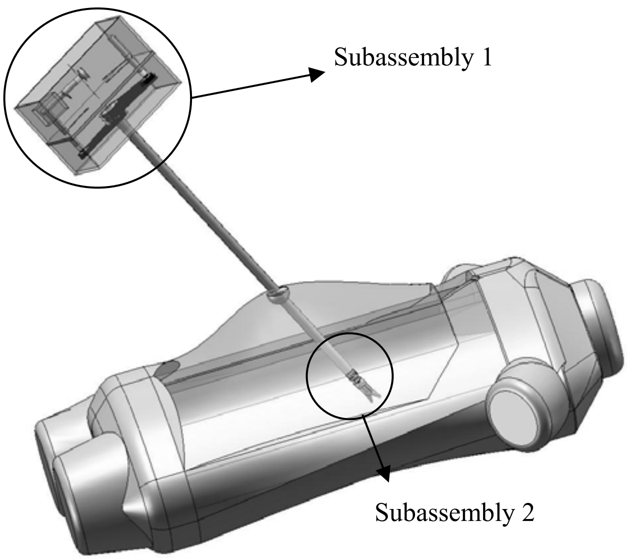

Fig. 5. PARASIM active surgical instrument

Figure 5 presents the active surgical instrument PARASIM designed in the UGS NX software [10].

Next the functioning and design considerations of PARASIM are presented and explained.

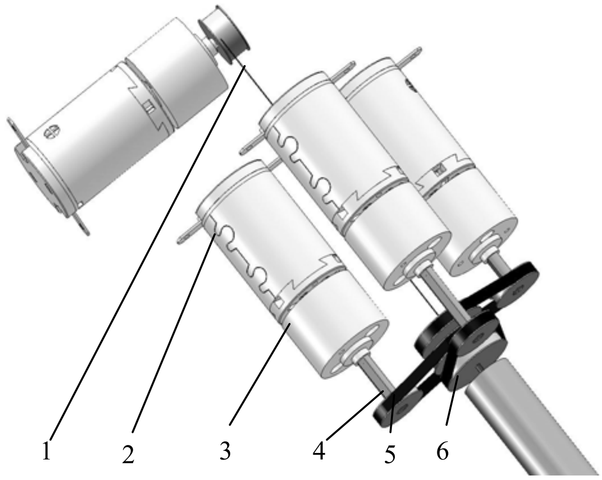

Fig. 6. Subassembly 1 of PARASIM active surgical instrument

Figure 6 contains the first subassembly of PARASIM represented by the actuation system that transmits motion to the end-effector of the active instrument. The actuation system is composed of four Maxon AG EC Ø6 mm, brushless DC motors (component no. 2 in fig. 6), equipped with encoders and planetary gearheads (component no. 3 in fig. 6) [11].

The transmission elements between the motors and the end-effector consist of a system of three belts (component no. 4 in fig 6) and six pulleys (component no. 5, 6 in fig 6), which respectively will rotate each of the three concentric bores (component no. 10 in fig. 1b)).

The active function (gripping) of the instrument is achieved by the flexible wire (component no. 1 in fig. 6) which also is driven by a pulley connected to the fourth electrical motor.

In figure 7 the second subassembly of PARASIM is presented. This contains the end-effector of the active instrument, with the following components: 1-gripper; 2, 3, 4-fixing bolts; 5-mobile rod; 6-housing; 7-compression spring; 8-flexible wire; 9- SPM mobile plate; 10- SPM.

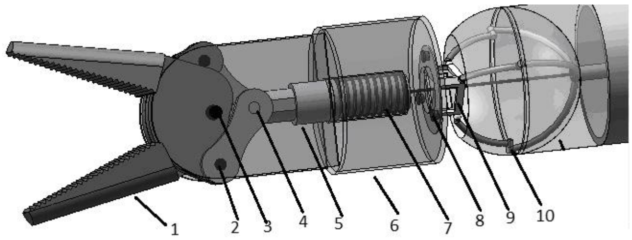

Fig. 7. Subassembly 2 of PARASIM active surgical instrument

The active element (gripper- component no. 1 in fig. 7), is set in motion by the mobile rod (5), which moves when the flexible wire (8) is pulled, and returns to its initial state due to the compression spring (7). Due to its interchangeable characteristics, the jaws of the gripper can be replaced by scissors, forceps, electrocautery devices and staplers.

6. CONCLUSIONS

PARASURG-9M parallel hybrid surgical robotic system used in MIS was presented in this paper with its CAD model. The structural analysis of the robot, and design considerations were also described. Starting from the requirements of a surgical instrument, the design of the active surgical instrument PARASIM with the explanation of its functioning were also described in this paper. The design of PARASIM has shown that due to its small components, the experimental robot manufacturing requires special machining and materials in order to achieve the demanding accuracy. The future step in the research is the development of the dynamical model of the structure, and the experimental model with the adequate control of the robot.

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PROIECTAREA CONSTRUCTIVA SI ANALIZA STRUCTURALA A SISTEMULUI ROBOTIC CHIRURGICAL PARALEL HIBRID PARASURG-9M

In lucrare este prezentat sistemul chirurgical robotic paralel hibrid PARASURG-9M. Structura este formata din doua module: un brat robotic PARASURG 5M cu cinci grade de libertate, si un instrument chirurgical activ PARASIM cu patru grade de libertate. Lucrarea incepe cu o scurta introducere in domeniul abordat, şi se continuã cu descrierea modelului CAD a robotului chirurgical paralel hibrid PARASURG-9M. Analiza structurala a robotului, si aspecte de proiectare constructive sunt de asemenea prezentate.

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