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GEOMETRIC MODEL AND DESIGN OF A NEW PARALLEL ROBOT USED IN MINIMALLY INVASIVE SURGERY

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Abstract: *Robotic assisted surgery allows surgeons to operate through infinitely smaller incisions, resulting in significantly less pain, scarring and recovery time for patients and for doctors providing benefits such as reduction in hand tremor, navigation, and workspace scaling. A new parallel architecture is proposed in this paper, the geometric model of this new structure is determined and the design of the robot is presented.* ***Key words:*** *parallel robot, geometric model, design, minimally invasive surgery*

1. INTRODUCTION

Robots are useful tools in minimally invasive surgery (MIS), providing benefits such as reduction in hand tremor, navigation, and workspace scaling. The advantages and the disadvantages of using the robotic systems for surgical applications are presented in [1]. This study lays the bases of a world competition for development of robotized structures for surgery. The requirements for minimally invasive robotic assisted surgery are given in [2].

The AESOP robotic arm was the first robotic laparoscope manipulator used in MIS dating since 1993 [3]. This robotic arm was initially activated by a foot pedal, and later by voice commands [4], [5]. After AESOP, Computer Motion created Zeus™ Surgical Robot with three robotic arms attached to the side of the operating table [6]. LARS, one of the first laparoscope holders with 7 DOF, was clinically successful, but limited by security concerns [7]. Another endoscopic device that ended up as a market product is Naviot [8]. It consists in one-touch parallel manipulator with 2 DOF, and an automatic micro-zoom function used in cardio-vascular and thoracic surgery. ARTEMIS [9] is a fully-developed robot deviced for a variety of MIS applications. It consists of two master-slave units guiding the surgical instruments and a remotely controlled endoscope guiding system.

Another robotic system with 4 DOF is the EndoAssist® [10], which is a console positioned alongside the patient, controlled by an association of foot-head activation through infrared technology, being commercially available. A highly articulated robot for MIS, threading through tightly packed volumes without disturbing the surrounding organs or tissues, is presented in [11]. It is actually a snake-like robot which was primarily used for cardiac surgery. Another compact laparoscopic assistant robot is KaLar [12]. It has 3 DOF mechanism composed of 2 DOF for bending motion in the patient's abdomen, and 1 DOF for in-out motions of the laparoscope outside the patient's abdomen. CURES is a surgical robot developed by BioRobotics Laboratory at the University of Washington [13].

LAPMAN® is a laparoscope holder with 3 DOF, guided by a joystick clipped onto the laparoscopic instruments under the operator's index finger [14]. The most complex and efficient robot in use is the da Vinci surgical system released in 1997 by the Intuitive Surgical Inc. Currently, it is at the second generation of robot called da Vinci Si HD Surgical System [15], being the most common robotic system, approved for medical use, namely in general surgery and urology.

The first steps in this field of research were achieved at the Technical University of Cluj-Napoca in 2005, and the first experimental model of a laparoscopic holder with 3 DOF, named PARAMIS was achieved in 2008 [16, 17, 18]. Thought as a part of a multiarm surgical system, PARAMIS takes fully benefits from the architectural advantages of parallel structures.

Most of the robots, which assist the surgeons, are serial robots. The serial robots generate a large operational workspace, while the parallel robots are steadier and offer a high accuracy during the surgical operation. Parallel robots [19] offer higher stiffness and smaller mobile mass than serial robots, thus allowing faster and more precise manipulations.

2. THE PARALLEL ROBOT

Starting from the parallel structure presented in [20], a schematic representation of the new parallel robot used in minimally invasive surgery, which can handle both a laparoscope and an active instrument is shown in Figure 1. The robot task is to position the tip of the laparoscopic camera or an active surgical instrument (point G) within the surgical field based on the surgeon's commands. The parallel robot has five active joints: two translations: q_1, q_2 and three rotations: q_3, q_4, q_5. The robot also has several passive joints: three rotational joints: K, L, M; three Cardan joints: N, P, C and two spherical joints: R, Q (fig. 2). The geometrical parameters of the robot are b, l and h. Point B, representing the entrance point of the instrument into the abdominal cavity, is always a fixed point in space and its position is known. The first two active coordinates (q_1, q_2) achieve a translation along the OZ axis, the active coordinate q_3 achieves a rotation around the OZ axis, while active coordinates q_4, q_5 achieve rotations around the CY_1^* and Cx* axes, as seen in figure 1. The orientation parallel module with the active joints q_4, q_5 is presented in the figure 2. Another rotation around the Y axis with β angle in point A is achieved by relative motion of q_1 and q_2. Lastly, a translation along the axis Z with l is required in order to reach the point G (the tip of the endoscope).

A set of criteria has been defined by a team of surgeons, consisting in a set of conditions that the robot should respect in [21]: workspace - 200/200/200 mm; the arm support a laparoscope of 5 or 10 mm; maximum displacement speed 10 mm/s; motion accuracy 1 mm; left, right, up, down

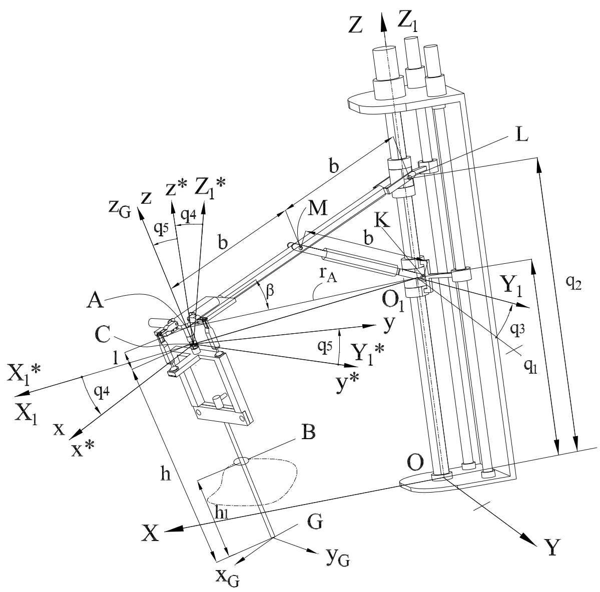

Fig. 1. The kinematic scheme of the parallel robot

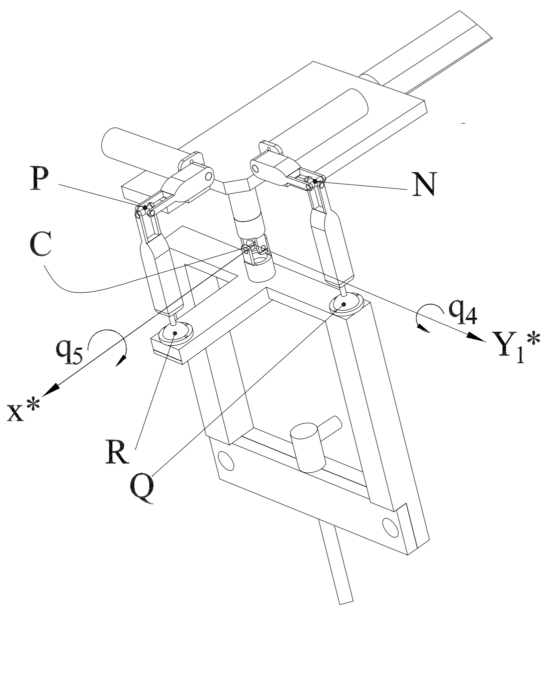

Fig. 2. The parallel module

with 60 degrees with respect to the central axis and the entrance point in the patient; displacement along the laparoscope axis on its full length; efficient speed and force control in the entire workspace; safety systems in accordance with the surgical procedure.

3. KINEMATIC MODELING

3.1 The inverse geometric model

In the case of the inverse geometric model, the end-effector coordinates $G(X_G, Y_G, Z_G)$, the angles ψ and θ, the geometric parameters b, h and l are known. The generalized active coordinates q_1, q_2, q_3, q_4, q_5 are to be determined.

One important aspect to be mentioned is that before inserting the surgical instrument into the abdominal cavity, the angles ψ and θ are required, but once the surgical instrument is inside the abdominal cavity, and consequently point $B(X_B, Y_B, Z_B)$ is known, ψ and θ are computed (figure 3). The values of the angles can be determined using the relations (1) and (2):

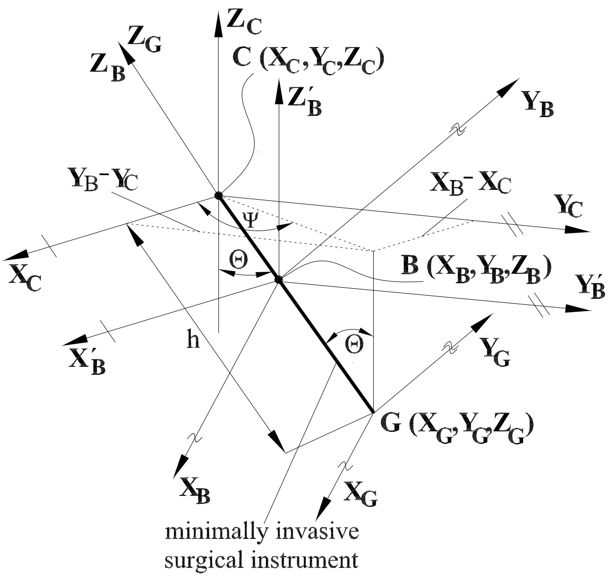

Fig. 3. The angles ψ and θ

$$\psi = a\tan 2(Y_G - Y_B, X_G - X_B) \quad (1)$$

$$\theta = a\tan 2\left(\sqrt{(X_G - X_B)^2 + (Y_G - Y_B)^2}, Z_B - Z_G\right) \quad (2)$$

From Figure 3, the coordinates of point $C(X_C, Y_C, Z_C)$ are determined. There are two cases:

a) if $X_G = X_B$ and $Y_G = Y_B$ (the surgical instrument is parallel with OZ axis), one can obtain:

$$\begin{cases} X_C = X_G \\ Y_C = Y_B \\ Z_C = Z_G + h \\ \psi = 0 \\ \theta = 0 \end{cases} \quad (3)$$

b) if $X_G \neq X_B$ and $Y_G \neq Y_B$ (the surgical instrument is in ordinary position), one can obtain:

$$\begin{cases} X_C = X_G - h \cdot \cos(\psi) \cdot \sin(\theta) \\ Y_C = Y_G - h \cdot \sin(\psi) \cdot \sin(\theta) \\ Z_C = Z_G + h \cdot \cos(\theta) \\ \psi = a\tan 2(Y_G - Y_B, X_G - X_B) \\ \theta = a\tan 2\left(\sqrt{(X_G - X_B)^2 + (Y_G - Y_B)^2}, Z_B - Z_G\right) \\ rC = \sqrt{X_C^{\,2} + Y_C^{\,2}} \\ q_3 = a\tan 2(Y_C, X_C) \\ q_2 = \sqrt{(2 \cdot b)^2 + l^2 - rC^2} + Z_C \\ \beta_1 = a\tan 2(rC, q_2 - Z_C) \\ \beta_2 = a\tan 2(l, 2 \cdot b) \\ \beta = \pi / 2 - (\beta_1 + \beta_2) \\ q_1 = q_2 - 2 \cdot b \cdot \sin(\beta) \\ q_4 = a\tan 2(-\sin(\theta) \cdot \cos(\psi - q_3), \cos(\theta)) - \beta \\ q_5 = a\tan 2(\sin(\psi - q_3) \cdot \sin(\beta + q_4), -\cos(\psi - q_3)) \end{cases} \quad (4)$$

3.2 The direct geometric model

The active generalized coordinates (q_1, q_2, q_3, q_4, q_5) are known and the position of the tip of the end-effector ($G(X_G, Y_G, Z_G)$) and its orientation (ψ and θ) are to be found. If the incision point into the abdominal cavity $B(X_B, Y_B, Z_B)$ is known, firstly, the coordinates of point $A(X_A, Y_A, Z_A)$ are computed:

$$\begin{cases} X_A = \sqrt{(2 \cdot b)^2 - (q_2 - q_1)^2} \cdot \cos(q_3) \\ Y_A = \sqrt{(2 \cdot b)^2 - (q_2 - q_1)^2} \cdot \sin(q_3) \\ Z_A = q_1 \end{cases} \quad (5)$$

$$\begin{cases} rA = \sqrt{(2 \cdot b)^2 - (q_2 - q_1)^2} \\ \beta = a\tan 2((q_2 - q_1), rA) \end{cases} \quad (6)$$

$$\begin{cases} X_C = X_A - l \cdot \sin(\beta) \cdot \cos(q_3) \\ Y_C = Y_A - l \cdot \sin(\beta) \cdot \sin(q_3) \\ Z_C = Z_A - l \cdot \cos(\beta) \end{cases} \quad (7)$$

$$\begin{cases} \psi = a\tan2(Y_B - Y_C, X_B - X_C) \\ \theta = a\tan2(\sqrt{(X_B - X_C)^2 + (Y_B - Y_C)^2}, Z_C - Z_B) \end{cases} \quad (8)$$

$$\begin{cases} X_G = X_C + h \cdot \cos(\psi) \cdot \sin(\theta) \\ Y_G = Y_C + h \cdot \sin(\psi) \cdot \sin(\theta) \\ Z_G = Z_C - h \cdot \cos(\theta) \end{cases} \quad (9)$$

The following conclusion can be draw from (1)-(9): for both the inverse and direct geometric model, analytical solutions are obtained, with important implications in the control of the robot.

4 DESIGN OF THE PARALLEL ROBOT

Figure 4 represents the CAD model of the parallel module of orientation and in the figure 5 and figure 6 is showed the design of the parallel robot use in surgical applications.
All motors of the 5-DOF robot are rotation motors from MAXON [22]. The translation motion is obtained by using two ball-screw mechanisms. The three motors in the robot base have 60W and the gear planetary transmissions has a ratio of 1:26 for the motors that actuate the ball-screw mechanisms and 1:936 for the other motor, which makes the rotation around the Z axis. For the orientation mechanism, the motors have 6W and a planetary gear ratio of 1:4592. The overall dimensions of the robot are: 1000 mm x 1000 mm x 300 mm.

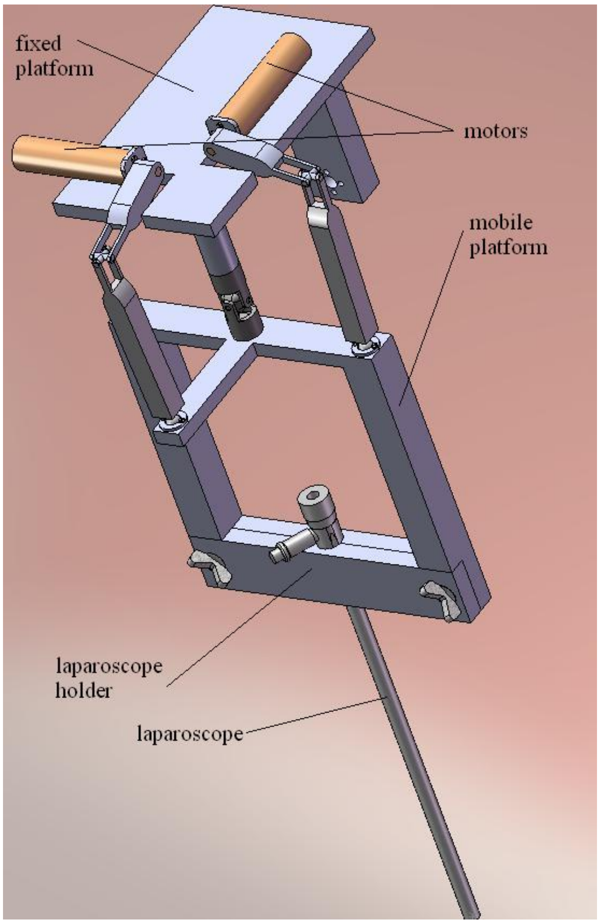

Fig. 4. The parallel module

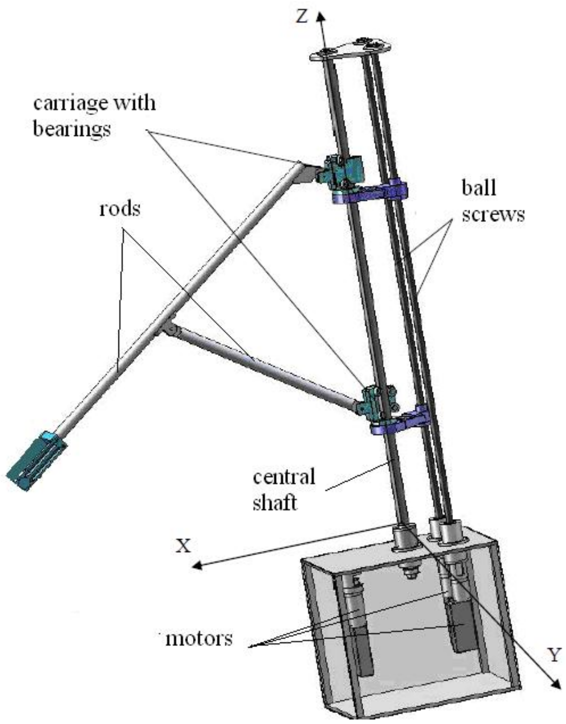

Fig. 5. The parallel robot without the orientation parallel module

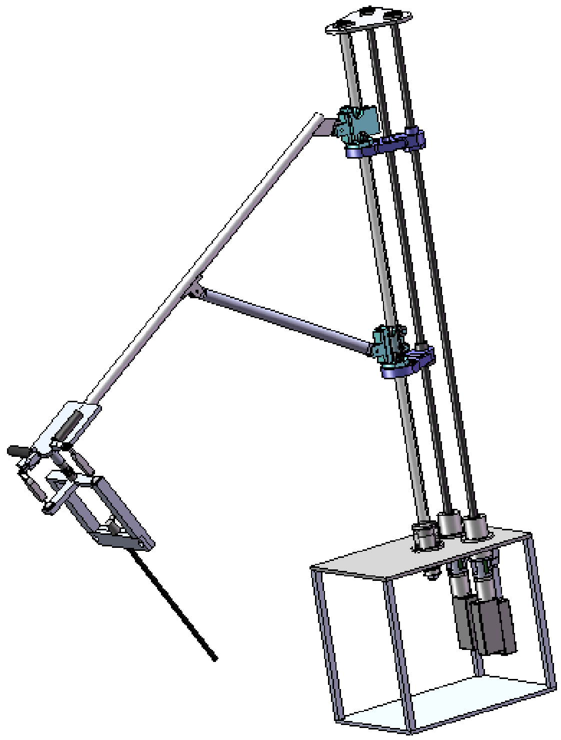

Fig. 6. The parallel structure used in minimally invasive surgery

5. CONCLUSION

The contribution of this paper consists in the development of a new, simple, parallel structure for minimally invasive surgery. This structure reduces the pressure on the abdominal wall and can handle both a laparoscope and an active instrument for different operations such as cutting, suturing, grasping. The advantage of this new parallel structure from the kinematic point of view is that its both direct and inverse geometric models have been obtained through an analytical approach. However, the results obtained from geometric model of the robot can be successfully implemented into a real-time control algorithm. The design of the parallel robot is also presented.

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MODELUL GEOMETRIC ŞI DESIGN-UL UNUI NOU ROBOT PARALEL FOLOSIT ÎN CHIRURGIA MINIM INVAZIVĂ

Rezumat: *Chirurgia robotic-asistată permite chirurgilor să opereze prin incizii foarte mici, rezultând semnificativ în mai puțină durere, cicatrizare şi timp de revenire pentru pacienți, şi pentru chirurgi oferindu-le beneficii ca şi reducerea în tremurarea mâinii, navigarea şi scalarea spațiului de lucru. O nouă structură paralelă este propusă în această lucrare, modelul geometric al acestei structurii este determinat şi design-ul robotului este prezentat.*

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