Innovative development of surgical parallel robots

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Abstract — One of the pioneer fields for robots is their assimilation in surgery, especially in minimally invasive procedures which aim the treatment of a disease with minimum damage to healthy tissue and suffering for the patient. The paper presents a new parallel robot used as base module for surgical instruments positioning, which was developed on the customized demands of the Operating Room. The parallel mechanism structural synthesis, its geometric and kinematic models for speeds and accelerations are presented. Some simulation results are illustrated at the end of the paper.

Keywords: parallel robots, minimal invasive surgery, kinematics, surgical robots.

1. INTRODUCTION

Robotic systems have been developed in every field where a further progress was constricted due to the human limitations in terms of speed, precision, fatigue, repeatability, strength, etc.

Surgery is one of the fields where robots have been introduced due to their positioning accuracy which exceed the human capabilities.

The introduction of robots in the Operating Room has represented a two step process, conditioned by the progress in technology:

1. In the 80s the technique called “minimally invasive surgery” has been developed, when surgeons operated through small entry ports, using a video camera and small instruments in order to reduce to a minimum the damage of healthy tissue and the suffering of the patient;

2. In the late 90s the further progress in science, and above all the increased reliability of robotic systems, allowed companies to start the development of surgical robots which would assist the doctors in the Operating Room.

In [1] is presented the experimental comparison between the performance of a human assistant and a robotic one in manipulating a laparoscope. The results of this comparison emphasized the superiority of the robot in terms of motion steadiness. Several researchers invested efforts in assimilating the robot in the surgical arena [2].

A robotic telesurgical workstation for laparoscopy was developed by “Robotics and Intelligent Machines Laboratory of the University of California, Berkeley (UCB)” [3] and the “Department of Surgery of the University of California San Francisco (UCSF)”. The current design is a bimanual system with two 6 DOF manipulators instrumented with grippers, controlled by a pair of 6 DOF master manipulators.

Orthodoc and Robodoc are two systems for orthopaedic surgery (hip and knee implants). In 1997, they extended their field to neurosurgery with a system called NeuroMate used for biopsy and tumour removal [4, 5].

AESOP [4] robotic arm, used to guide a tiny camera inside the body, was the first robotic system used in surgery dated from 1993. It was produced by Computer Motion, which developed several such versions of AESOP until they created Zeus™ Robotic Surgical System with three robotic arms attached on the side of the operating table.

A competitor of Computer Motion, Intuitive Surgical, designed another revolutionary equipment, da Vinci™ Surgical System, which became the market competitor of Zeus until 2003 when the two companies merged. [4].

At the Helmholtz Institute there is under development the CRIGOS project, which deals with the development, integration and evaluation of a Compact Parallel Robot for Image Guided Orthopaedic Surgery [6].

Prof Moshe Shoham has been performed extensive studies regarding the performances of the surgeon in endoscopy, focused on the fulcrum effect [7] (the motion of the surgical instrument on the monitor is opposite to the one performed by the surgeon). By performing different tests on several ways of transmitting the motion there has been evaluated the performance of the doctor from both the precision and working speed points of view as well as his capability to adapt and learn to manipulate the robotic system. Another project which deserves to be pointed out, deals with the development of new miniaturized robots which can be mounted on the bones and a research regarding the different methods for...
scanning and surface recognition of bones before the surgical intervention [8]. Based on previous experience and on the data supplied by the doctors, at the Tehnion Institute there has been developed a new surgical robot, with parallel structure. The robot has a small volume, a low weight and its precision is much higher than the one achieved by manually handling the surgical instruments. This robot, of RSPR type, was used successfully in orthopaedic surgical procedures. The most recent research projects deal with the development of microrobots for navigation inside the human body and for endoscopies of the spinal cord [9].

As an obvious conclusion, in order to offer the best support for patients in the Operating Room, humans and robots must work together, the surgeon being the master (the decision maker) and the robot the slave – with excellent precision, untiring, without tremor and smaller than the human hand.

Most of the robots, which assist the surgeons, are serial robots [2]. Nowadays there have been designed hybrid robots, which combine a first serial module with an open kinematic chain with a second parallel one having a closed kinematic chain. The serial module generates a large workspace while the parallel module is steadier and offers a high accuracy during the surgical operation. In this case, there are used force control algorithms in order to ensure the safety behavior and the accepted accuracy.

Parallel robots offer a higher stiffness and smaller mobile mass than serial robots, thus they allow faster and more precise manipulations. The problems concerning parallel structures kinematics are usually more complicated than for the serial structures. The drawbacks of serial robots, determined by their structural construction, motivate the research in the field of robot assisted surgery for a continuous search of task oriented robot architectures that best fit a specific group of medical applications. As an alternative for the serial structure, the parallel one seems promising because of its advantages that fit medical applications. Therefore, some investigators focused on exploring the capabilities of parallel robots in medical applications [12].

<table>
<thead>
<tr>
<th>Table 1. Human versus Robot in Surgery [2]</th>
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<tbody>
<tr>
<td><strong>Humans</strong></td>
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<tr>
<td><strong>Strengths</strong></td>
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<tr>
<td>Strong hand-eye coordination</td>
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<tr>
<td>Dexterous (at human scale)</td>
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<tr>
<td>Flexible and adaptable</td>
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<tr>
<td>Can integrate extensive and diverse information</td>
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<tr>
<td>Able to use qualitative information</td>
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<tr>
<td>Good judgment</td>
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<tr>
<td>Easy to instruct and debrief</td>
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<tr>
<td><strong>Limitations</strong></td>
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<tr>
<td>Limited dexterity outside natural scale</td>
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<tr>
<td>Prone to tremor and fatigue</td>
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<tr>
<td>Limited geometric accuracy</td>
</tr>
<tr>
<td>Limited ability to use quantitative information</td>
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<tr>
<td>Large operating room space requirement</td>
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<td>Limited sterility and susceptible to radiation and infection</td>
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To a robotic system for minimally invasive surgery, the research studies have shown that the parallel and hybrid structures are more adequate than serial ones in this field, and they represent a boost in robotic surgery in terms of increased performances and safety and lower costs.

The paper presents the structural synthesis, geometric and kinematic model of a new innovative parallel structure for the manipulation of surgical instruments in minimally invasive surgery. The parallel architecture has been chosen for its superiority in precision, repeatability, stiffness and occupied volume. The equations, which model the geometric and kinematic models, are pointed out for this robot based on its mathematically determined functional parameters.

The low-cost structure will allow a wider spread or the robot in the operation room an easier acceptance and a better feedback for further improvements. Some simulation results have been presented.

2. DESCRIPTION OF THE PARAMIS-PARALLEL ROBOT

In the figure 1 is presented the kinematic scheme of the new parallel structure – PARAMIS, which will be used...
for surgical instruments positioning. The structure has three degrees of freedom in space and it consists of three active joints (two of them are prismatic and one rotational one). The passive joints are two cylindrical joints, one prismatic joint and one Cardan joint.

The robot must position the end of the laparoscope, namely the video camera in any point of the operational field to offer the surgeon the best possible details of the surgical field. The particularity of this motion is the fact that the endoscope will move around a fixed point in space, which is the entrance point of the trocar in the abdominal wall of the patient. The presence of the passive Cardan joint before the laparoscope will allow the motion around the fixed point of the abdominal wall. The trocar, the abdominal entrance point and the endoscope can be seen as a virtual joint with four degrees of freedom, which allow the camera the rotation around the three axis and a translation parallel with the axis of the trocar. Thus, the endoscope can be positioned in any point of the abdominal area using the three degrees of freedom of the robot.

The developed parallel robot mechanism contains mechanisms of different families:
\[ F = 4, \quad F = 3, \quad F = 0 \]  

For each family corresponds a different computing formula, thus the number of degrees of freedom can not be computed with an unique formula.

We consider that the driving mechanism of the A point is considered as a joint of class \( C_3 \).

It yields:
\[ F = 0; \quad N = 2; \quad C_4 = 1; \quad C_3 = 1; \quad C_2 = 1 \]  

The mobility degree of the parallel mechanism will be:
\[ M = 6N - 5C_4 - 4C_3 - 3C_1 - 2C_2 - C_1 \]
\[ M = 3 \]  

4. KINEMATICS

The geometrical parameters of the parallel robot are represented by \( b, \ d, \ h; X_B, Y_B, Z_B \) (figure 1).

4.1. Direct geometrical model

In this case the \( X_E, Y_E, Z_E \) end effector coordinates are computed with respect to the \( q_1, q_2, q_3 \) driving coordinates. The inverse geometric model delivers also the angles \( \phi, \theta \) (figure 2).

\[ r_a = b + \sqrt{d^2 - (q_2 - q_1)^2} \]  

\[ X_a = r_a \cos q_3 = \left[ b + \sqrt{d^2 - (q_2 - q_1)^2} \right] \cos q_3 \]
\[ Y_a = r_a \sin q_3 = \left[ b + \sqrt{d^2 - (q_2 - q_1)^2} \right] \sin q_3 \]
\[ Z_a = q_1 \]

Geometrically we can have two cases:
1. If \( X_a \neq X_b \), \( Y_a \neq Y_b \)

\[
e = \sqrt{(X_a - X_b)^2 + (Y_a - Y_b)^2}
\]

\[
\varphi = \alpha \tan 2 \left( \frac{\sqrt{e^2 - (Z_a - Z_b)^2}}{e}, \frac{Z_a - Z_b}{e} \right)
\]

\[
\tan \theta = \frac{Y_a - Y_b}{X_a - X_b}
\]

\[
X_E = X_a - h \sin \varphi \cos \theta
\]

\[
Y_E = Y_a - h \sin \varphi \sin \theta
\]

\[
Z_E = Z_a - h \cos \varphi
\]

2. If \( X_a = X_b \), \( Y_a = Y_b \)

\[
\begin{align*}
X_a &= X_E + h \sin \varphi \cos \theta \\
Y_a &= Y_E + h \sin \varphi \sin \theta \\
Z_a &= Z_a + h \cos \varphi
\end{align*}
\]

4.2. Inverse geometrical model

In this case the end effector coordinates \( X_E, Y_E, Z_E \) are given and the driving coordinates \( q_1, q_2, q_3 \) are computed.

\[
h_i = \sqrt{(X_E - X_b)^2 + (Y_E - Y_b)^2 + (Z_E - Z_b)^2}
\]

\[
\cos \varphi = \frac{Z_b - Z_E}{h_i}, \quad \sin \varphi = \sqrt{1 - \left( \frac{Z_b - Z_E}{h_i} \right)^2}
\]

\[
\tan \theta = \frac{Y_b - Y_E}{X_b - X_E}
\]

Geometrically we can have two cases:

1. If \( X_a \neq X_b \), \( Y_a \neq Y_b \)

\[
\begin{align*}
X_a &= X_E + h \sin \varphi \cos \theta \\
Y_a &= Y_E + h \sin \varphi \sin \theta \\
Z_a &= Z_a + h \cos \varphi
\end{align*}
\]

2. If \( X_a = X_b \), \( Y_a = Y_b \)

\[
\begin{align*}
X_a &= X_E \\
Y_a &= Y_E \\
Z_a &= Z_E + h
\end{align*}
\]

Then in both cases, the relations are obtained:

\[
r_a = \sqrt{X_a^2 + Y_a^2}
\]

\[
q_1 = Z_a
\]

\[
q_2 = q_1 + \sqrt{d^2 - (r_a - r_b)^2}
\]

\[
q_3 = \alpha \tan 2(Y_a, X_a)
\]

4.3. Direct kinematic model

For solving the kinematic models we use the implicit functions:

\[
\begin{align*}
f_1(X_E, q_1, q_2, q_3) = X_E - \left[ b + \sqrt{d^2 - (q_2 - q_1)^2} \right] \cos q_3 = 0 \\
f_2(Y_E, q_1, q_2, q_3) = Y_E - \left[ b + \sqrt{d^2 - (q_2 - q_1)^2} \right] \sin q_3 = 0 \\
f_3(Z_E, q_1) = Z_E - q_1 = 0
\end{align*}
\]

With the notations:

\[
A = \begin{bmatrix}
\frac{\partial f_1}{\partial X_E} & \frac{\partial f_1}{\partial Y_E} & \frac{\partial f_1}{\partial Z_E} \\
\frac{\partial f_2}{\partial X_E} & \frac{\partial f_2}{\partial Y_E} & \frac{\partial f_2}{\partial Z_E} \\
\frac{\partial f_3}{\partial X_E} & \frac{\partial f_3}{\partial Y_E} & \frac{\partial f_3}{\partial Z_E}
\end{bmatrix},
B = \begin{bmatrix}
\frac{\partial f_1}{\partial q_1} & \frac{\partial f_1}{\partial q_2} & \frac{\partial f_1}{\partial q_3} \\
\frac{\partial f_2}{\partial q_1} & \frac{\partial f_2}{\partial q_2} & \frac{\partial f_2}{\partial q_3} \\
\frac{\partial f_3}{\partial q_1} & \frac{\partial f_3}{\partial q_2} & \frac{\partial f_3}{\partial q_3}
\end{bmatrix}
\]

Through derivation of the relations (21) it yields:

\[
A \dot{X} + B \dot{q} = 0
\]

\[
A \ddot{X} + A \ddot{X} + B \ddot{q} + B \dot{q} = 0
\]

Thus, the direct kinematic model for speeds, respectively for accelerations is obtained:

\[
\dot{X} = A^{-1}B \dot{q}
\]

\[
\ddot{X} = A^{-1} \left[ B \ddot{q} + A \ddot{X} + B \ddot{q} \right]
\]

4.4. Inverse kinematic model

From the relations (28) and (29) the inverse kinematic model for speeds, respectively for accelerations is obtained:
\[
\dot{q} = -B^{-1}AX
\]
\[
\dot{q} = -B^{-1} \left( AX + \dot{A}X + B\dot{q} \right)
\]

5. SIMULATION RESULTS

A complex simulation program was developed in order to study the geometric, kinematic and dynamic characteristics of parallel robots with different degrees of freedom [15, 16, 17].

For the graphical modeling of the parallel structures it was used Solid Edge™, one of the most advanced software for computer aided design, available on the market [18]. This program was selected especially for its outstanding performances in terms of stability and user-friendly interface, and even more for its total compatibility with Visual Basic.

The geometric parameters of the parallel structure can be modified within the 3D modeling software (Solid Edge Assembly) influencing the simulation environment. The assembly relations between parts, between subassemblies or between parts and subassemblies can be also modified [19].

These facilities of the simulation software enable the possibility to develop a complex study about the kinematics and dynamics in order to optimize the parallel structure. The program has the possibility to select the parallel structure from a list in accordance with the class of the mechanism and its degree of freedom.

Depending on the desired graphical quality, the representation could be wire frame or a realistic photo image. If the image is more complicated and the representation algorithms are more complex, it requires a longer computing time.

The simulator determinates the next robot state, independent of the input mode. If an error appears, the user is informed through an error message with its type and elimination way. If any errors are encountered, the next command is executed.

The simulator is interactively achieved such as the user could influence the simulation parameters and could be informed about the possible errors during the simulation process.

The data exchange between simulation system modules is achieved through data files, which allow future module integration in the existing system and makes easy the data exchange with another off-line programming systems.

For the graphical simulation, a parallel mechanism with the following geometric parameters is considered: 
\[
b = 304 \text{ mm}, \quad d = 545 \text{ mm}, \quad h = 270 \text{ mm};
\]
\[
X_B = 650 \text{ mm}, \quad Y_B = 84 \text{ mm}, \quad Z_B = 411 \text{ mm}
\]

Figure 3. Simulation of the PARAMIS parallel structure

In the figure 3 is presented the graphical interface for graphical modeling for different parallel structures.

The kinematic algorithms have been implemented in the kinematical module (Kinematics). In the simulation is included the parallel robot with the instrument and the virtual human body.

Figure 4 presents the virtual laparoscope which has been modeled based on a real one. Figure 5 shows the Cardan passive joint which allow the laparoscope to move around a fixed point.

Figure 4. The laparoscope

Figure 5. The Cardan passive joint

Figure 6 represents a virtual model of the human abdomen, inflated and ready for the laparoscopic procedure having also a schematic representation of the internal organs.

The simulations were performed using the hybrid robot presented in figure 7 which manipulates the laparoscope in the virtual human model.
Figure 6. The virtual human body

Figure 7. The robotic system

The results obtained are useful for the designers not only to understand the distribution of characteristics of the workspaces for various geometrical parameters of parallel structures, but also to optimize the parallel robots.

6. CONCLUSIONS

Robotic surgery is an on growing research field and new solutions are needed to allow average patients to benefit of them.

In the paper the PARAMIS new parallel robot is presented. Its structural synthesis, geometric models and kinematic models are described. All the obtained models have compact analytical solutions.

The simulations results obtained with the developed simulation system for parallel robots allow a structure verification before a parallel robot is built.

7. ACKNOWLEDGMENTS

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8. REFERENCES


[18] www.solidejde.com
