Proceedings in MANUFACTURING SYSTEMS Proceedings in Manufacturing Systems, Volume 12, Issue 1, 2017, 29–34 ISSN 2067-9238

LAPAROSCOPIC ROBOTIZED INSTRUMENT

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Abstract: *Robot-assisted surgery has many advantages over conventional surgery: greater spatial accuracy, dexterity and precision reliability, reproducibility and ultimately better patient outcomes. Investigations of current instruments for robot-assisted surgery such as daVinchi and ZEUS are indicated to have some technological deficiencies which must be overcome. The main objective of this work is focused on improving some technical deficiencies of existing robotized surgical instruments. For this reason we design a novel robotized instrument for laparoscopic surgery with better mechanical characteristics. In contrast to EndoWrist technology by Intuitive Surgical* Incorporation *– USA for daVinchi instruments (three orthogonal rotations) we offer other decision of the construction. The laparoscopic robotized instrument that was designed provides a kinematic structure with* $R \perp R \parallel R$*, which avoids additional rolls. As a consequence of the limitations by the operating environment - the manipulation is performed in a narrow working space inside the patient's body through small surgical instruments, the motors are situated in the base of the instrument, which is disposed outside of the troacar, respectively, outside the human body. The model allows obtaining the optimal working area of this instrument and force feedback control. By developing of a novel type of specialized instrument for robots we have created more compact, simple, cheaper and easier robotic instruments than before. The paper includes a structure of a laparoscopic robotized instrument and describes the basic movements in the wanted working area. A kinematic-structural analysis of a novel construction with autonomous and dependent movement will be presented. Transfer functions are determined through a control system which provides control by the operator movements. In this case we have also developed a simulation program that outlines the workspace and the possible actions there. This program is not an object of present paper.*

Key words: *mechatronics, robotics, surgical robots, robot-assisted surgery, instruments, laparoscopy.*

1. INTRODUCTION

The development of laparoscopic techniques and instruments has dated since the sixties of last century [1] but is not practically applicable. It is due to insufficient development of equipment and instruments. Nowadays laparoscopic surgery is a very popular surgical intervention to diagnose and repair many gynecological and abdominal problems such as gallbladder stones and carcinoma.

The basic laparoscopic instruments consist of a roll-pitch-yaw mechanism which covers three rotational movements to the execution links around three perpendicular axes. A wrist between the executive links and a shaft of the instrument rotates the pitch and the yaw. The shaft provides the roll rotation. As a consequence of this mechanical construction one degree of rotational movement is lost.

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The introduction of robots in the surgical area such as *daVinchi* [2] and *ZEUS* [3] considerably enhances the surgical skills, thereby preventing trauma to and infection of the abdominal area. Robotics can help and solve many problems in surgery.

Some problems which Robotics solves in surgery:

- precision of the tool position and orientation into pre- and intra-operative imaging;
- following of complex, accurate directions;
- elimination of the problem ,"hand-eye coordination";
- risk reduction;
- ergonomic position for the surgeon-less fatigue and errors during the interventions;
- eliminating the need for a third hand during the surgical procedure;
- intelligent robot control can filter hand tremor and increase accuracy by motion scaling.

Nevertheless, the investigation of the current instruments for robot-assisted surgical systems [4] shows that they have some technological deficiencies which must be overcome. Many robot instruments consist of basic mechanical components such as strings, rollers, gears, links, pivots, sliders, etc., which are common mechanical parts. Thereby the instruments are very complex with multiple interacting mechanical components. The *daVinchi* instruments are indicated to have some technological deficiencies the main of which is the different dimension of grasping force and the surgeon lacks tactile feedback. This problem can be solved by introducing small force sensors that enable force interaction to the surgeons. The mechanical structure creates problems with sterility. The strings are easily wearable and require constant replacement. Another important problem of robot instrument is that they are too expensive.

In daVinchi instruments *EndoWrist* technology by Intuitive Surgical Incorporation – USA is applied. The full range of the catalogue contains structures with four and seven degrees of freedom. *EndoWrist* with four degrees of freedom provides independent movement of the executive links. The disadvantage of this structure is three orthogonal rotations (R ⊥ R ⊥ R), which requires the application of additional rollers to drive the executive links.

In contrast to *EndoWrist* technology by Intuitive Surgical Incorporation – USA for *daVinchi* instruments (three orthogonal rotations) we offer other decision of the construction. The laparoscopic robotized instrument that was designed provides a kinematic structure with R ⊥ R ‖ R, which avoids additional rolls. In *EndoWrist* technology the motors are located at the base, which makes the movement after the first degree of freedom. In the discussed scheme of the designed instrument the dependent movements are received at the third and fourth degrees of freedom only when bending the wrist. In this paper a driven system of the end-effectors is presented. According to end-effectors forms, manipulations such as grasping, holding, moving, cutting, etc. of irregular geometrical shape objects, preferably of elastic tissues, organs, blood vessels, that are not healthy tissues, can be performed.

Presently, a lot of surgical instruments are designed by several research groups, but only some of them have really found a place in clinical practice Several research efforts proposed instruments which have been developed either with rotating joints at the tip [5] or with a flexible tip [6, 7]. There are some research papers that [8-10] focused on flexible robotic end-effectors and can reach to any deep point of the work area significantly increased manoeuvrability, thereby increasing the quality of execution of the procedure itself. The main problems are a difficult control and coordination of movements, time delay, which is undesirable for surgery.

Prior papers have focused on some problems during the design process of laparoscopic robotized instruments with rigid links and elastic elements which are incorporated into their constructions as well as the design of the laparoscopic robotized tools with elastic end –effectors [11, 12].

The main objective of this work is focused on improving some technical deficiencies of existing robotized surgical instruments. For this reason we design a novel original construction of a robotized instrument for laparoscopic surgery with better mechanical characteristics. The model allows obtaining the optimal working area of this instrument and force feedback control. By developing a novel type of specialized instrument for robots we have created more compact, simple, cheaper and easier robotic instruments than before.

The possibilities for an incorporation of force sensors in the different places of the construction for receiving of reliable information for tool-tissues interactions will be examined with proposed mechatronic device [13].

The following section describes the structure of laparoscopic robotized instrument (main elements of the proposed mechanical construction), its end-effectors and fibre driving of the end-effectors of the laparoscopic robotized instrument.

2. STRUCTURE OF THE LAPAROSCOPIC ROBOTIZED INSTRUMENT

Precision, stability and safety are the decisive criteria when are designed laparoscopic instruments. At the same time the sensitive and easy control of the instrument is also a basic requirement for successful patient outcomes.

A laparoscopic robotized instrument includes the structure further described. The instrument is designed for grasping, holding, and moving of the objects with irregular geometric shape in the field of minimally invasive surgery, mainly elastic such as tissues, organs, blood vessels) [14] or rigid such as gallbladder stones. The general appearance of the instrument is shown on Figure 1, where 1 is the basis, 4 is a hollow tubular body, 13 is the wrist of the laparoscopic robotized instrument, 18 and 23 are the executive links of the proposed instrument or jaws.

The main elements involved in the mechanical structure of the laparoscopic robotized instrument are the basis (1) where electrical motors are fixed there, hollow tubular body (4) for transmitting motion and two execution links (jaws) (18) and (23).

One of the electrical motors through the hollow tubular body is driving the end-effectors of the designed instrument. The rest of the electrical motors are connected to the hollow tubular body and via transmitting mechanisms are driving the wrist of the laparoscopic robotized instrument.

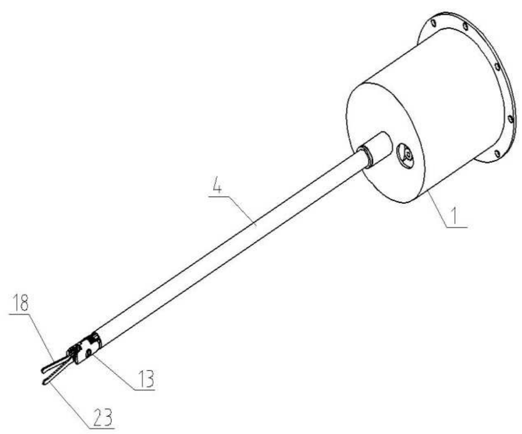

Fig. 1. A general appearance of the Laparoscopic Robotized Instrument.

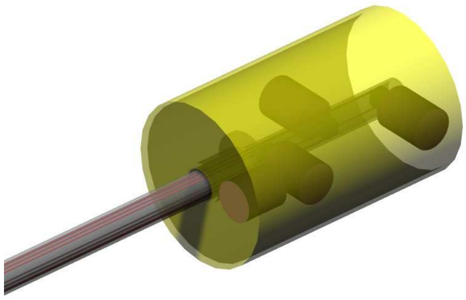

Fig. 2. Position of the motors into the base of the laparoscopic robotized instrument.

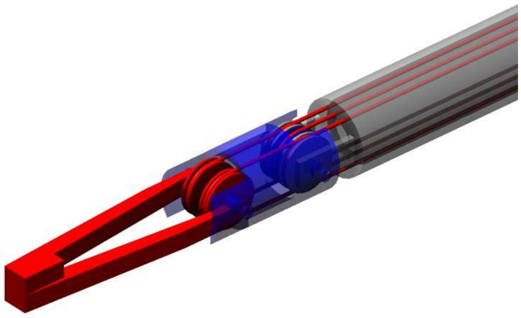

Fig. 3. End –effectors of the robotized laparoscopic instrument.

Axes Dy1, Dy2 and Dy3 of the electrical motors are parallel to each other and to the axis rotation Y1 and Y2. The axis of Dx1 motor is perpendicular to them and parallel to the axis a hollow tubular body (4). (The axes of the electrical motors are shown in the section "Working area at the initial, open and closed position").

On Fig. 2 the position of the electrical motors into the base of the laparoscopic robotized instrument is shown. As a consequence of the limitations imposed by the operating environment (the manipulation is performed in a narrow working space in the patient body) motors are situated at the base of the instrument, which is situated outside of the troacar, respectively, outside of the human body. This provides free working space for the instrument. The diameter of the hollow tubular body is 8 mm, since the diameter of the troacar, where the instrument is inserted is the standard size of 10–12 mm. The length is inserted is also standard 68 mm. Due to the limitations imposed by the environment and the human body according to the specificity of the intervention the instrument moves forward and back are limited to 100 mm.

The end-effectors with fibers (wires) of the laparoscopic robotized instrument are shown in Fig. 3.One primer of fiber driving of the end – effectors of the laparoscopic instrument is shown in Fig. 4.

3. WORKING AREA AT THE INITIAL, OPEN AND CLOSED POSITION

This section describes the working area of the designed laparoscopic robotized instrument at the initial, open and closed positions. Different open positions of the links are shown.

Working area of the designed laparoscopic robotized instrument at the initial, open and closed positions are shown in Fig. 5.

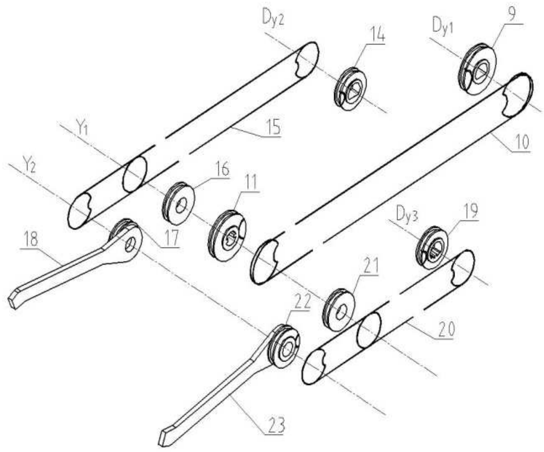

Fig. 4. Fibre driving of the end – effectors of the laparoscopic robotized instrument**.**

The possible movements of the laparoscopic robotized instrument in the working area are two. The angle of rotation, around the axis of the tool is 360 degrees. This movement is realized by one of the motors (D2) and transmission mechanism towards motor D2 (Fig. 5). The hollow tubular body (4) length is 68 mm.

The jaws (two execution links) of the instrument are fully open at the rotation angle of 120 degrees depending on the position. It allows moving only one of the links. The movement of the jaws (18) and (23) is implemented by the motors and the wiring mechanisms. The length of the end -effectors is 6–8 mm by the limitations and specifics of the working area, respectively, the human body.

In Figs. 6 and 7 different open positions of the links of the laparoscopic robotized instrument are shown.

4. KINEMATICAL ANALISYS OF THE PROPOSED SCHEME

The desirable working area of the designed laparoscopic robotized instrument depends on the linear sizes (l_1, l_2, l_3) and limitations of the joints (angles of rotations)

$$q_1 \min \le q_1 \le q_1 \max, q_2 \min \le q_2 \le q_2 \max).$$

The values of q_3 and q_4 depend on the type of intervention (gripping, moving, cutting, clamping), which is often symmetrical to the two execution links and because of this, the kinematic chains are identical but with autonomous drive.

Solving the direct kinematical problem of the proposed scheme is done by a simulation program the way the wanted working area is outlining. Moving at the working area is realized by the motors. The transmitting mechanisms corresponded with the motors and end - effectors. This relation can be written by Equation 1:

$$\bar{\varphi} = J \bar{q}\,, \tag{1}$$

where $\bar{\varphi}$ is angular position vector of the electrical motors; J – matrix of Jacobs; q – angular position vector of the end-effectors.

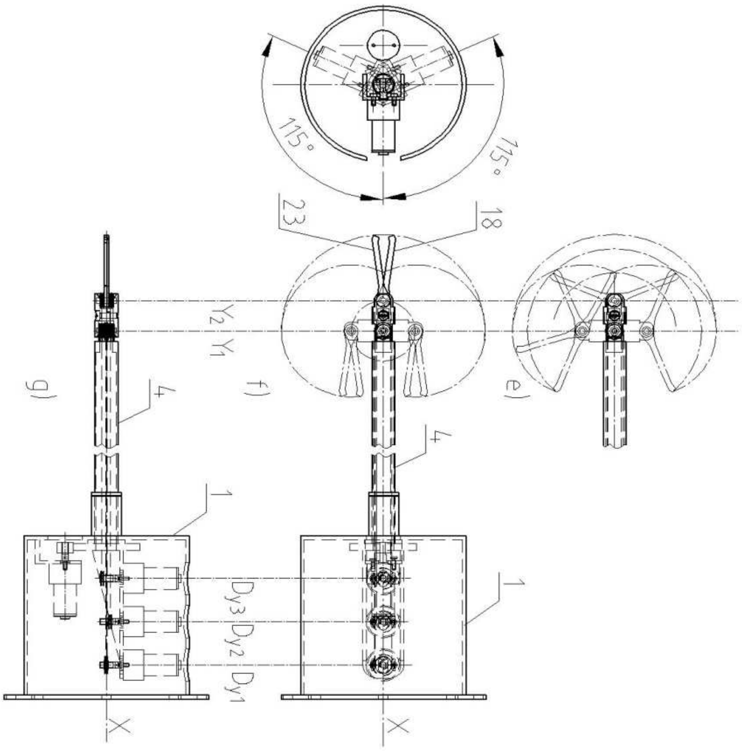

Fig. 5. Working area of the instrument at the initial, open and closed position.

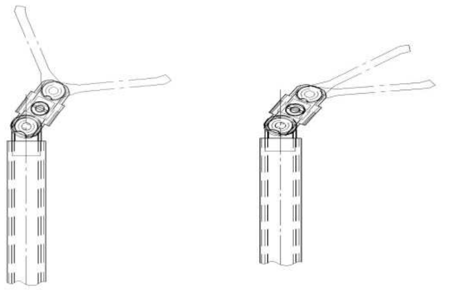

Fig. 6. Different open positions of the links of the laparoscopic robotized instrument.

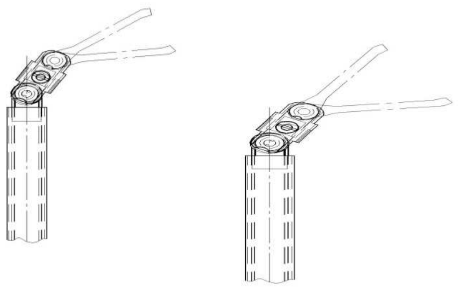

Fig. 7. Different open positions of the links of the laparoscopic robotized instrument.

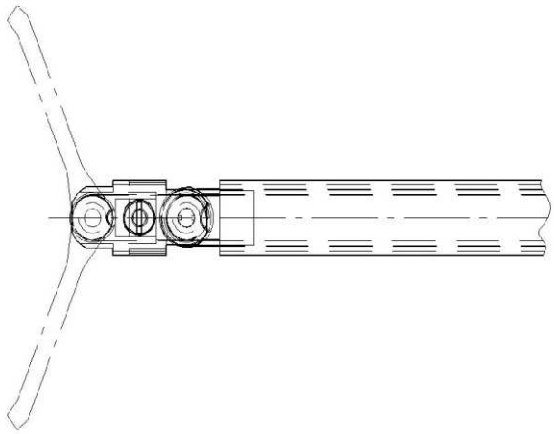

Fig. 8. Fully open position of the laparoscopic robotized instrument.

Figure 8 shows fully open position of the proposed instrument.

For the concrete example, Eq. (1) can be written as:

$$\begin{vmatrix}\varphi_1\\ \varphi_2\\ \varphi_3\\ \varphi_4\end{vmatrix} = \begin{bmatrix} \frac{\partial\varphi_1}{\partial q_1} & 0 & 0 & 0 \\ 0 & \frac{\partial\varphi_2}{\partial q_2} & \frac{\partial\varphi_2}{\partial q_3} & \frac{\partial\varphi_2}{\partial q_4} \\ 0 & 0 & \frac{\partial\varphi_3}{\partial q_3} & 0 \\ 0 & 0 & 0 & \frac{\partial\varphi_4}{\partial q_4} \end{bmatrix} \cdot \begin{bmatrix} q_1\\ q_2\\ q_3\\ q_4 \end{bmatrix}, \qquad (2)$$

Transmitting functions at the major diagonal $\frac{\partial\varphi_i}{\partial q_i}$, where i_{pi} $(i = 1, 2, 3, 4)$ has a similar structure:

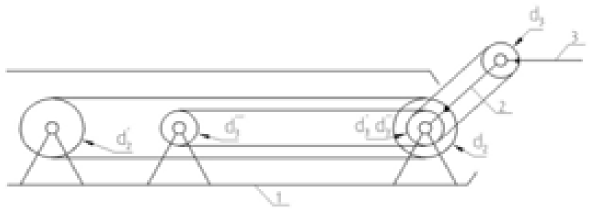

Fig. 9. Kinematic scheme of the proposed model of the laparoscopic robotized instrument.

$$\frac{\partial \varphi_i}{\partial qi} = i_{pi} \cdot i_{ni} \quad , (i = 1, 2, 3, 4)\,, \tag{3}$$

where i_{pi} $(i = 1, 2, 3, 4)$ is the value of the gear reduction ratio of the respective chain (often and in this case they are identical) i_{ni} $(i = 1, 2, 3, 4)$ and is the value of the gear transmission ratio of the wire. For the determination of i_{pi} we have applied the following kinematic scheme of the proposed model of the laparoscopic robotized instrument, which is shown in Fig. 9.

The kinematic chains of the links 2 and 3 are only shown thereby kinematic chain to the link 4 as well 3.

The value of component (3) i_{pi} is obtained from Equation 4:

$$i_{pi} = \frac{\varphi_i}{\psi_i} = a_i\,, (i = 1, 2, 3, 4)\,. \tag{4}$$

The gear transmission ratio of the wires i_{ni} is written by Eqs. 5–8.

$$i_{p1} = \frac{\psi_1}{q_1} = \frac{d_1}{d_1^{'}}\,, \tag{5}$$

$$i_{p2} = \frac{\psi_2}{q_2} = \frac{d_2}{d_2^{'}}\,, \tag{6}$$

$$i_{p3} = \frac{\psi_3}{q_3} = \frac{d_3}{d_3^{'}}\,, \tag{7}$$

$$i_{p4} = \frac{\psi_4}{q_4} = \frac{d_4}{d_4^{'}}\,. \tag{8}$$

The construction scheme and Equation 2 show that movement of links 3 and 4 is result from controlled movement of the link 2. This movement must be appropriately controlled. For that reason it is necessary to determine the transfer functions $\frac{\partial \varphi_2}{\partial q_3}$ and $\frac{\partial \varphi_2}{\partial q_4}$, respectively, which are obtained from Eq. (9):

$$\frac{\partial \varphi_2}{\partial q_i} = i_{21}^{di} = \frac{1}{1 - \frac{d_i}{d_i^{'}}} = \frac{d_i^{'}}{d_i^{'} - d_i};(i = 3, 4), \tag{9}$$

Angles of rotations of the execution links q_i $(i = 1, 2, 3, 4)$ when the angles of motors rotations φ_i $(i = 1, 2, 3, 4)$ are obtained from Eq. 10:

$$q_1 = a_1 \times \frac{d_1}{d_1^{'}} \times \varphi_1\,,$$

$$q_2 = a_2 \times \frac{d_2}{d_2^{'}} \times \varphi_2\,,$$

$$q_3 = a_3 \cdot \frac{d_3}{d_3'} \cdot \frac{d''}{d_3'''} \cdot \varphi_3 + a_2 \cdot \frac{d_2}{d_2'} \left(\frac{d_3'}{d_3' - d_3} \right) \cdot \varphi_2\,,$$

$$q_4 = a_4 \cdot \frac{d_4}{d_4'} \cdot \frac{d_4''}{d_4'''} \cdot \varphi_4 + a_2 \cdot \frac{d_2}{d_2'} \left(\frac{d_4}{d_4' - d_4} \right) \cdot \varphi_2\,. \tag{10}$$

Because of the specifics of the constructions and requirements of symmetry of the executive links 3 and 4 of the laparoscopic instrument, it is chosen:

$$d_3 = d_4\,;\; d_3' = d_4',\; d_3'' = d_4'',\; d_3''' = d_4''' \tag{10}$$

and $a_3 = a_4$.

Nevertheless, there are two kinematic chances and two driving motors, the last expressions of Eq. 10 are identical. If q_3 and q_4 are immovable, respectively, when the link 2 is moving ($\varphi_2 \neq 0$), then φ_3, and φ_4, respectively, can be written by Eq. 11:

$$\varphi_3 = a_2 \frac{d_2}{d_2'} \left(\frac{d_3'}{d_3' - d_3} \right) \cdot \frac{d_3'}{d_3} \cdot \frac{d_3'''}{d_3''} \cdot \frac{\varphi_2}{a_3}\,. \tag{11}$$

The sign (−) defines the direction of rotation of φ_3 and φ_4, which is opposite to φ_2.

5. CONCLUSIONS AND FUTURE WORK

There are many areas in surgery where mechatronics and robotics can make a difference for the better. In most cases, both the surgeon and patient benefit from it. This work described our efforts for improving some technical side and design of instruments for robotic laparoscopic surgery. It is presented an original construction of laparoscopic robotized instrument. The instrument is designed for manipulation (grasping, holding, moving) of objects with irregular geometric shape in the area of minimal-invasive surgery, mainly elastic (tissues, organs, blood vessels). As a result, the limitations by the operating environment-the manipulation is performed in a narrow working space in the human body, engines are situated in the base of the instrument, which in turn is disposed outside of the troacar or outside the human body, respectively. The designed laparoscopic instrument for robot includes four degrees of freedom. The model allows obtaining the optimal working area of this instrument and force feedback control. Solving a direct kinematical problem of the proposed scheme is done a simulation program which will be an object of next research. We intend to introduce modularity, hermetically and easy and convenient sterilization of the new developed instruments.

The developed robotized instrument could be applied in many areas of bloodless microsurgery. The expected results of novel instrument to robots are developing of instruments with better mechanical characteristic for reduction of trauma, preventing errors and improvement of the quality and efficiency of our healthcare.

Future work will include extensive kinematical and force research of proposed laparoscopic instrument constructions. The possibilities for incorporating of force sensors in the different places of the construction will be assessed. At the proposed scheme possible location for sensing construction on the laparoscopic robotized tool is on the instrument shaft outside the patient's body, or near or at the actuating mechanisms driving a joint. Wireless system for control of the sensors and actuators which will be incorporated into the design of the instrument is necessary to create too. A computer program with information about various models of tissue should be develop too. The information obtained from force sensors will be used to find the appropriate tissue model and submitting the necessary command to force interaction between instrument and tissue. Some experiments with different tissues will be provided by novel laparoscopic robotized instrument.

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