Design and modeling of robotic surgical system for transurethral operations

A A Kabanov¹, D A Tokarev¹, V A Kramar¹

¹ Sevastopol State University, 33, Universitetskaya str., Sevastopol, 299053, Russia

E-mail: kabanovaleksey@gmail.com

Abstract. The paper examines the design and modeling of the robotic surgical system that is used for transurethral operations with resectoscopes. The proposed system consists of a robot-manipulator and a control system for a surgeon. A design feature of the robot-manipulator is the presence of free rotation units that ensure the mobility of the instrument together with the holder unit. This design eliminates a patient injury when one is displaced relative to the initial position. Another important feature of the proposed surgical robotic system is the ability to use an existing surgical instrument (resectoscope). The article describes the design, as well as the results of the modeling of the robot in the V-rep system. The parameters of the forces and torques of the executive system of the robot are obtained by simulation.

1. Introduction

Minimally invasive surgery (MIS) operations, in some cases, require significant physical training from surgeons and support staff. An example of such operations is transurethral operations using a resectoscope. During these operations, the surgeon is forced to be in an uncomfortable position for a long time. Such situation leads to fatigue and poor performance. One of the solutions to this problem is the use of special medical robotic tools. The capabilities of robotic systems can improve the quality of operations up to the automation of some typical movements of surgeons.

Today, a large number of researchers and companies are engaged in the development of robotic surgery. Advanced achievements in this field are regularly demonstrated at various scientific and technical exhibitions and conferences. Here is a list of robots considered in this research:

- Da Vinci Surgical System is designed by IntuitiveSurgical. It comprises three distinct subsystems [1]: the patient-side cart with manipulators; the surgeon control console; and the vision cart;
- MiroSurge surgical robot was originally developed at DLR (German Aerospace Center). It is made in the form of four manipulators mounted on a surgical table. It is controlled by special joysticks [2];
- Surgical robot manipulator – UPM – is developed by researchers of the High School of Industrial Engineers of the Universidad Politécnica de Madrid (UPM) and the Gliatech S.L Company[3];
- IGAR Robot developed by CSII. It is a programmable automatic robot; it can work without human intervention according to a predetermined program [4];
- Robotic surgical system Mazor Robotics manufactures Mazor Renaissance. It is a highly specialized medical instrument for performing operations on the spine and brain [5];
- Sensei X robotic catheter system is developed by Hansen Medical Inc. It is an open robotic platform for endovascular surgical procedures [6].
The list of considered medical robots is not complete and does not include assistant robots, which greatly facilitate the work of surgeons, but do not interact directly with patients. In addition to the presented industrial samples, attention should be paid to a large number of patents and articles in this field.

In [6-10], various designs of robots and systems that solve similar problems are described. It should be noted that most of the proposed solutions require additional safety control systems to prevent injuries to patients, require special tools for operations and, as a rule, do not have passive safety equipment.

An analysis of the existing surgical robotic systems shows that in most cases the robot operates with special tools and instruments. These instruments are an integral part of the robot and can only be used by this specific robot model. Each such instrument undergoes special clinical trials. Since this instrument and the method of their application are not widespread in medicine, special additional training of surgeons is required. A surgeon who has been trained to work on a specific robot model will not be able to control a robot of another model without additional training. This is also due to the fact that the workplace of the surgeon (robot operator) in complexity is not inferior to the complexity of the robot.

Another important issue in medical robotization is to evaluate the efforts of the surgical instrument applied to the patient. This problem arises from the faults in construction and restrictions on the robot movement. For this reason, a large number of patented developments require systems for measuring and evaluating the made efforts. In [11-13], a description of the system for measuring and correcting the applied forces is given. This system may be as a part of the robot design or be used as an add-on device.

This study describes the development of a robotic system for performing transurethral operations using resectoscopes. The proposed robotic system consists of two main parts: the robot-manipulator and the control system. The development of the robot-manipulator was carried out taking into account the analysis of existing surgical robots indicating their disadvantages and advantages. A control system for the robot manipulator was designed in the form of control circuits and programs.

2. The robot-manipulator design

Based on the considered requirements, a roboticsystem has been developed for use in MIS. The purpose of the robot is to perform endoscopic operations using existing surgical instruments (rectoscope, etc.). The robot is used for manipulation and positioning of the working element of the connected instrument in the patient’s body in a predetermined way to perform operation.

Figure 1 shows a sketch of the developed robot-manipulator system with a designation of the main elements and units. The described robotic system consists of a manipulator 102 to which a holder 101 is attached. The surgical instrument is held by the holder 101. The manipulator 102 moves the instrument by moving the holder 101, which in turn holds the instrument.

The manipulator 102 provides rotational movement of the instrument relative to the axes 1 and 2 and translational movement about the axis passing through points 301 and the instrument entry point. The specified movements are implemented by actuators that rotating the links 204 and 205. Link 205 is equipped with a mechanism that moves the holder 101 relative to the axis passing through points 301 and the entry point. The manipulator 102 ensures the correct movement of the working element provided that the intersection points of the axes 1 and 2 coincide with the entry point. To enable alignment of these points, the manipulator 102 is equipped with a mechanism for longitudinal displacement in the three coordinates. The longitudinal displacement mechanism is implemented by the links 201, 202, 203 of the manipulator 102. Each of the links provides movement along one of the mutually perpendicular axes.

The holder 101 is necessary to hold the surgical instrument with the possibility of controlled movement of the working element along the instrument longitudinal axis (it passes through points 301 and 302) with the possibility of rotation.

The holder 101 is attached to the structure 102 through revolute joints 206 and 207. The rotation
axes of these joints are mutually perpendicular and intersect at point 302. The revolute joints 206 and 207 provide mobility of the holder 101 with the connected instrument in case the patient moves during surgery operation. This eliminates damage to the patient with the instrument and increases the safety of operations. Mismatch of the point of intersection of axes 1 and 2 with the entry point leads to a change of rotational angles of the revolute joints 206 and 207. This situation is possible with the initial positioning of the instrument at the beginning of the operation and in case of the undesirable patient movement. In both cases, the compensation of the mismatch of the points of intersection of the axes 1 and 2 with the entry point is carried out by the longitudinal displacement mechanism implemented by the links 201, 202, 203.

Figure 1. The view of the developed robot-manipulator
3. Modelling of the robot-manipulator

The design of the robot-manipulator was made using Autodesk Inventor. To identify errors and check the adequacy of the robot before manufacturing, it is necessary to simulate the system.

For the developed robotic system, a kinematic model was obtained in the standard notation of Denavit-Hartenberg (D-H) using the V-Rep system [14]. The result of system modeling is shown in figure 2. The link parameters are shown on the left side of the figure, and the 3D model is on the right side. Changing the parameters of the links leads to editing of the 3D robot model. The model can display the set and measured rotation angles of the links joints. The difference between the measurements occurs under the influence of external factors and with incorrect selection of drive capacities. Based on the simulation results, forces and torques were obtained at which the robot performs movements with a given accuracy for a given time according to the technical specifications.

![V-Rep Simulator with the model of robot-manipulator](image)

Table 1 shows the results of the selection of forces and torques for the robot drives, the maximum speed of translational and rotational motions. The selection of efforts was carried out taking into account the materials for manufacturing the parts of the robot.

| Symbolic notation | Type of pairing | Required Force / Torque | Maximum speed of translation / rotation |
|-------------------|----------------|-------------------------|----------------------------------------|
| z₀                | translation   | 450 N                   | 0.1 m/s                                |
| y₀                | translation   | 50 N                    | 0.1 m/s                                |
| x₀                | translation   | 50 N                    | 0.1 m/s                                |
| α                 | rotation      | 39 Nm                   | 60 °/s                                 |
| β                 | rotation      | 13 Nm                   | 120 °/s                                |
| X₁                | translation   | 15 N                    | 0.1 m/s                                |
| β₀                | rotation      | 0                       | Passive element                        |
| α₀                | rotation      | 0                       | Passive element                        |
| γ                 | rotation      | 5 Nm                    | 180 °/s                                |
| X₂                | translation   | 5 N                     | 25 mm/s                                |
Designations in table 1 correspond to the full kinematic diagram of the robot (figure 3). The diagram consists of 12 links. The first 11 are related to the design of the robot and the 12th link is necessary for modeling and is implemented as a supporting element. The symbols in figure 3 correspond to the symbolic notation in table 1.

Figure 3. Full kinematic diagram of the robot-manipulator

The simulation system during operation can respond to external commands from the master via a local area network using standard data transfer protocols. For testing, a translator program was developed, which is installed on a computer with a joystick. When you press the joystick buttons or analog sticks, the program generates control codes and sends them to the computer in the robot simulation system. This approach allows us to debug the control system of the robot without using the physical sample of the robot.

4. Conclusion
The development of a robotic system for performing transurethral operations using resectoscopes is presented in the paper. Important design features of the proposed robotic system are:

- the presence of free rotation units that ensure the mobility of the instrument together with the holder unit. This ensures the mobility of the patient and eliminates one’s injury when one is displaced relative to the zero position (when the axis of rotation of the main engines coincides with the entry point). When the patient moves, the attitude of the holder unit changes. The nonzero angles of the holder unit relative attitude mean that the patient is offset from the zero position and correction is required;
- the balancing of the robot, due to which turning off the power of the robot does not lead to spontaneous movement of the resectoscope, thereby increasing the safety of the patient;
- the ability to use an existing surgical instrument (resectoscope).

Future research and design will be aimed at creating a convenient control interface for a surgeon and developing algorithms for the motion automation of the robot-manipulator.
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