Tracking system for the position of the patient of the surgical robotic complex

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Abstract. The paper examines the design of the control system of the surgical robotic complex that is used for transurethral operations with resectoscopes. The proposed system consists of a subsystem for the motion control of the instrument (resectoscope) working part and a subsystem for tracking and stabilizing the patient's position. The patient’s position tracking system eliminates a patient's injury when he displaced relative to the initial position. The article describes the design of the patient’s position tracking system. The description of the principle of operation of the tracking system is also presented.

1. Introduction
Today, robotic systems for surgical operations have become quite widespread. There are ready-made solutions that have been applied in practice for a long time [1-6]. In addition to ready-made solutions, there is a fairly large number of design solutions and patents [6-10]. A characteristic feature of surgical robots is the ability to perform minimally invasive operations. For this, specially designed tools are used. In most cases, minimally invasive surgery (MIS) involves the invasion of instruments through a small incision. When performing such operations manually, the positioning of the working part of the instrument is performed by the surgeon, and the possible displacement of the patient is compensated for in a natural way. In the case of MIS robots, a rather complicated task of positioning the instrument in automatic mode arises. Rigid attachment of the instrument to the robot can lead to the patient injury if the wrong instrument movements are selected and if the patient moves from the initial position. To solve this problem, manufacturers of robotic systems offer various technical solutions based on the use of strain sensors and others. This situation arises because the majority of robotic surgeons are based on several kinematic schemes of multi-link manipulators that replace a human hand [11]. In this case, a rather complex control problem arises.

In this work, we propose a solution of the problem of tracking the position of the patient in the surgical robotic complex during urological operations using a resectoscope. The subsequent part of the article is structured as follows: Section 2 contains the formulation of the position tracking problem, Section 3 describes the system for tracking the position of the patient, and the conclusions are given in Section 4.
2. The position tracking problem statement

The control system of a considered robotic complex is used to perform surgical operations using resectoscopes and consists of two main parts: a subsystem for the motion control of the instrument (resectoscope) working part and a subsystem for tracking and stabilizing the patient's position. The implementation of the system in the form of two parallel subsystems is possible if the kinematic diagram of the robotic complex can be considered in the form of two independent circuits. In our case, the design is made in such a way that the control of instrument movements does not depend on the action of the positioning drives of the system relative to the zero position.

The zero position in this work is understood as the position of the patient relative to the robot, in which the point of intersection of the main axes of rotation coincides with the point of rotation of the working instrument. Compliance with this condition is critical for dividing the control system into two subsystems.

The instrument motion control system should solve the problem of moving the working part of the resectoscope in space in accordance with the image in Figure 1. The instrument performs movements relative to the membranous section, which in this case acts as a natural point of rotation.

The main movements are: "back and forth" along the longitudinal axis of the instrument – $X_1$; rotational movement "right-left" around the vertical axis – $\beta$; "up-and-down" rotational movement around the horizontal axis – $\alpha$. And additional movements are: rotation of the tool around its longitudinal axis – $\gamma$; and the translational movement of the resectoscope cutting loop – $X_2$. To implement each of the movements, three motors are required, which are responsible for the main movements in space, and two additional motors, which are responsible for the rotation of the instrument and the movement of the cutting loop of the resectoscope. The motors are selected in such a way that the movement of each of them changes only one of the coordinates of the instrument, this allows them to work in parallel. If it is necessary to move the instrument along one of the axes, one drive is used.

Figure 2 shows the proposed design of the robot. The development of the motion control system is simplified due to this design and does not require the development of a geometric spatial equation system for recalculating the change in the angles of rotation of the motors into the current spatial coordinate of the working part of the instrument.
We noted earlier that such a simple control system can be implemented provided that the stabilization system works in parallel with it [12]. The stabilization system is responsible for ensuring that the entire structure is correctly positioned in relation to the patient. Changing the position of the structure is performed by three drives in three spatial coordinates: "forward-backward", "right-left", "up-down". Let us denote the axes along which the coordinates change by each of the drives, respectively X, Y, Z. For movement along the Z axis, the structure is equipped with a lifting column, movement along the X, Y axes is performed by two motors in the horizontal plane. The motors and the lifting column change the corresponding coordinates of the robotic complex: $x_0, y_0, z_0$.

The problem statement is to control the robotic complex in an automated mode, taking into account the division of the control system into two subsystems: the instrument motion control and the patient's position stabilization. At the initial stage of the operation, the work with the robotic complex is carried out in manual mode in such a way that such positions of the drives are set at which there is a coincidence of the point of intersection of the main axes and the point of rotation of the instrument in the patient's body. With this implementation, the patient must be motionless, otherwise, due to displacement the calculated movements of the instrument will not coincide with the real ones. The coordinates of the working part of the instrument, obtained by solving the direct kinematical problem will give an erroneous result. In the case of software control, this will lead to incorrect operation of the system and may be unsafe for the patient. In the case of control through a joystick or other remote control device, such displacement will lead to the fact that the movements in the received coordinates will be distorted.

Taking into account the above, we believe that it will be correct to equip the robotic complex with an automatic tracking system for the patient's position. The system must solve three problems: positioning of the robotic complex before the operation, monitoring the change in the patient's position and correction during the operation. An additional function is to ensure safety by inhibiting movement in the event that a mismatch of the patient's position with the zero position is detected.
3. Description of the patient's position tracking system

Tracking the position of the patient is carried out using two sensors of rotation angles, spread out in the nodes of free rotation. In the zero position, the rotation angles measured by the sensors are also zero. The main problem is that there are two sensors and three drives that change the position in space. Figure 2 shows a General view of the robotic complex with an image of the intersection of the axes of rotation of the main drives.

Figures 3 and 4 show the movement of the complex relative to the rotation axes of the main drives: horizontal and vertical.

If the patient is displaced in the vertical plane, the working tool is also deflected in the vertical plane. The position of the tool shown in figure 2 is deflected along the vertical axis of rotation. Compensation for these changes is possible by moving the structure in a vertical plane. Figure 5 shows possible movements of the structure using a vertical column.
Figure 5. Moving the column in a vertical plane.

Figures 6 and 7 show the moves of the instrument in the case of patient movement with a change in the rotation angles of the sensors installed in the free rotation nodes.

Figure 6. Tool Movement when the patient is displaced in the vertical plane (side view).
Figure 7. Moving the tool if the patient is displaced in the horizontal plane (top view).

Draw schematically how the system works in the case of displacement of the patient in the vertical plane. Let's assume that the patient is above the required rotation point. Figure 8 shows such an offset, where A – the intersection point of the main axes of rotation of the robotic complex; B - the point through which the axis of the free rotation node passes; C-the point of entry of the instrument into the patient's body; $\alpha_0$ – the angle measured by the sensor-encoder installed in the free rotation node; the stroke indicates the new position of point B relative to the previous one.

Figure 8. Schematic representation of the vertical displacement compensation system. Before compensation (top). After compensation (bottom).
The operation of the stabilization system in the vertical plane is performed as follows. When detecting a non-zero angle value $\alpha_0$, the vertical drive is activated. Drives movements shown in figure 5. A positive angle value means that the patient is higher than necessary to compensate this robot is shifted up until the angle value becomes zero. If the angle $\alpha_0$ is negative, the patient is below the required position, and the structure moves down. The operation of the system, in this case, will be shown similarly to figure 8. The Implementation of the described control is a trivial task it can be performed as an independent control loop because the offset in the vertical plane does not affect the readings of the offset sensor in the horizontal plane.

Let's consider how the system works if the patient displaced in the horizontal plane. The patient can move back and forth along the axis of the instrument and to the right and left relative to the base of the robot. The movement to the right and left are compensated similarly to the vertical displacement of the patient. Figure 9 shows the patient shifting to the right relative to the robot. In this case, the sensor-encoder, located in the node of free rotation in the horizontal plane (figure 7), produces a non-zero value of the angle $\beta_0$, which means that the patient moved to the side and compensation is necessary. Position compensation is performed by a drive that shifts the structure to the right or left relative to the patient.

In the case shown in figure 9, angle $\beta_0$ is positive - the patient has shifted to the right. It means that it is necessary to move the structure to the right until the angle $\beta_0$ becomes zero.

Another situation observes when the patient moved along the axis of the instrument. Figure 10 shows this offset. Note that the angle $\beta_0$ does not change and remains zero. The system will not be able to determine where the patient has moved. Stroke C' indicates the location of the entry point to the patient's body after the shift.

When the tool rotates relative to the axis passing through point A (the main vertical axis of rotation), the angle $\beta_0$ deviates from zero. The value of the angle $\beta_0$ will be directly proportional to the angle of rotation of the tool in the horizontal plane. In this way, you can determine that the patient is displaced along the axis of the tool and compensate for this by using drives that shift the entire structure back and forth.

Shifting the patient will change the spatial coordinates of the instrument's entry point into the patient's body C. Let's call them $x, y, z$, where $x$ is the displacement of the coordinates of the input tool "right and left" relative to the robot; $y$ – offset entry-point tool "back and forth" relative to the robot; $z$ – offset of the entry point in a vertical plane. Taking into account the above, we will write down a system of equations that relate the patient's displacement to the value of the encoder sensors for the rotation angles of free rotation nodes. When the patient displaced in the vertical plane, the value $z$ changed on $\Delta z = K_z \alpha_0$, where $\Delta z$ is the change in position in the vertical plane; $K_z$ is the coefficient that connects the vertical displacement with the value of the angle $\alpha_0$. We need to shift the structure in the vertical plane by an amount to compensate for the patient's vertical displacement:

$$ z_0 + \Delta z = z_0 + K_z \cdot \alpha_0. $$

Similarly, you record compensation for the displacement of the patient's "left and right":

$$ x_0 + \Delta x = x_0 + K_x \cdot \beta_0. $$

Compensation for the patient's forward-backward displacement is different because it must take into account the current angle $\beta$ of the tool rotation:

$$ y_0 + \Delta y = y_0 + K_y \cdot \beta_0 \cdot \beta. $$
Figure 9. Operation of the stabilization system when the patient shifted to the right (top View). Left-offset, right-offset compensated.

Figure 10. The offset of the patient along the axis of the instrument. The left – a shift of the patient; the Center of rotation of the tool with the offset of the patient; Right – offset compensation of the patient.

The practical implementation of patient displacement compensation using the above expressions is possible if the values \( x_0, y_0, z_0 \) and \( \alpha_0, \beta_0 \) are measured using feedback sensors because the result of the calculations will be the value by which the robotic complex needs to move. Solving problem using two sensors measuring angles \( \alpha_0 \) and \( \beta_0 \), the following is necessary: if a deviation is detected, perform a compensating movement until its minimized. You do not need to measure the current \( x_0, y_0, z_0 \) values. The speed of movement along the axes depended on the patient's deviation:

\[
\begin{align*}
    v_x &= K_x \cdot \alpha_0, \\
    v_y &= K_y \cdot \beta_0 \cdot \beta, \\
    v_z &= K_z \cdot \alpha_0.
\end{align*}
\]
In the right part of the system of equations, there are expressions for calculating the speed of the robot's movement along the axes X, Y, Z. Moving along each of the axes is carried out by drives, which makes the implementation of such control very simple.

4. Conclusion
The paper describes the monitoring system for the patient's position in the surgical complex. A tracking system is an implementation of a system with passive safety because the patient remains mobile during the operation. The patient's position is monitored by analyzing deviations of the position angle encoder sensors. It is possible to compensate for the patient's movements using a tracking system and speed and changing the position control.

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