An Endoscope Manipulating Robot Design

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Abstract. This paper mainly studies a new type of endoscope manipulating robot to replace the nurse or assistant to manipulate and hold the endoscope in surgery. By analyzing the operating environment of minimally invasive surgery, the paper presented the basic requirements of the endoscope manipulating mechanism design, and developed a endoscope manipulating system with seven degree of freedom. In order to meet the intraoperative spatially invariant point required by the minimally invasive surgery, a new remote-center-of-motion(RCM) mechanism, parallelogram RCM mechanism, was designed by improving composite parallelogram mechanism. In addition, a wire-driven modular joint with single-degree-of-freedom was also developed, which has been used for the endoscope operating in-out the human body. The motion test of RCM mechanism shows that the robot has good flexibility and can fully meet the design requirements of the endoscope manipulating mechanism.

1. Introduction

In the middle of the 20th century, industrial robots, as a production automation equipment, combined with the traditional mechanism and modern electronic technology, which enabled the robot technology start to be applied in the industrial manufacturing field [1,2]. The development of robots have caused a fundamental change in the appearance of traditional industrial production, which has enabled humans to enter a new era of intelligence from manual operations, mechanization, and automation. With the continuous development of the robot industry, the development of medical robots has gradually received more attention among the world researcher. At present, the research on the application of robots in the medical field is mainly focused on surgical robots, rehabilitation robots, nursing robots, and service robots [3-4].

In traditional surgery, incisions produced by surgery are generally larger than 10cm. The surgical trauma is obvious, which can easily cause tissue damage at the incision of the patient and cause complications of tissue infection. Minimally invasive surgery has solved this problem to a large extent. It only requires a small incision, and the surgical instruments and related medical equipment are probed into the body and operated under the guidance of the screen image. This method greatly...
reduces the risk of surgery, increases the success rate of surgery, reduces the patient's surgical pain, and has been widely used in various fields of surgery.

At present, the assisted minimally invasive surgery robot mainly adopts a master-slave control mode, and the slave robot manipulator follows the movement of master robot to complete the surgical task. However, there are many deficiencies in this surgical procedure. First, surgical robots cannot be used to sense when they should use much force sensor during surgery. Doctors can only use their own experience in manipulating robotic arms. This may cause a great deal of damage. Second, it takes a long time for the doctor to exercise the operation of the robot before the surgery.

Compared to using a robot instead of a doctor to perform a surgical operation, the doctor needs a series of assistant functions such as manipulating an endoscope. Therefore, it is very important to study a new type of robotic system to help doctors to hold endoscopes in surgery in order to free them in the tedious operation.

By analyzing the operating environment of minimally invasive surgery [5-7], the paper analyzed the basic requirements of the minimally invasive surgical robot mechanism design, and developed a surgical robot execution system consisting of endoscope manipulator robot in the slave part and master joystick. In order to meet the need of manipulating and holding endoscope required by the minimally invasive surgery, a new remote-center-of-motion(RCM) mechanism, parallelogram RCM mechanism, was designed by improving composite parallelogram mechanism. In addition, a wire-driven modular joint with single-degree-of-freedom was also developed, which had been used for the wrist mechanism design of the endoscope. The motion test of endoscope manipulating robot shows that the robot has good flexibility and can fully meet the design requirements of using endoscope in surgery.

2. Robot Design
As shown in Fig.1, the overall structure of the robot arm is given. The robot is composed of a rough positioning robotic arm with four degrees of freedom and a RCM mechanism with three degrees of freedom. Rough positioning robotic arm includes joint 1, joint 2, joint 3, and joint 4. The RCM mechanism consists of joint 5, joint 6, and joint 7. Joint 1 and 7 are linear joints, and joint 2 to 6 are revolute joints. Moving the linear joint 1, mainly drive the endoscope in the end of the robot to realize the positioning in the vertical direction. Rotating the joint 2 to the joint 4 and the three rotating joints are parallel to each other, and the endoscope in the end of the robot is driven to realize the positioning in the horizontal direction. The positioning of the joint with redundant degrees of freedom in the vertical and horizontal positions allows the endoscope at the end of the robot to flexibly reach the surgical incision position. The joints 5 to 7 that constitute the RCM mechanism can clamp the endoscope to realize the RCM motion around the incision, wherein the joint 5 can cause the endoscope to swing around the tangential X axis of the incision, and the joint 6 can drive the endoscope to achieve swing around the Y-axis of the incision, the joint 7 drives the endoscope to achieve linear expansion and contraction through the incision.

2.1 Rough positioning robotic arm design
As shown in Figure 1, the joint 1 achieves the positioning of the robot arm in the vertical direction and bears the gravity the entire robot. High-precision linear motion module are used to ensure the stiffness and smoothness of the joint, and the weight of the arm is balanced by designing the counterweight in the robot base. It can realize the fast positioning of the manipulator in the vertical direction. In addition, the high-precision linear encoder installed in the linear motion module can detect the linear motion of the joint that its joint motion resolution can reach 0.01mm.
Endoscope manipulating robot includes seven degrees of freedom

The joints 2, 3, and 4 are passive joints with no motor which used in positioning the robot by manual operation before surgery to get a rough position. Therefore, by controlling open and close the electromagnetic brake at each joint, human can operate the joints with no or little force and get a reliable locking position of the joint in the surgery. In addition, zero and limit photoelectric switches are installed at each joint to detect the initial zero position and limit position of the joint.

2.2 RCM mechanism design

The joint 5 as the first active joint is responsible for the rotating motion around the horizontal axis of the entire RCM mechanism. In order to ensure the compactness of the joint structure and facilitate the internal wiring of the robot, this joint uses a servo motor biased joint design method, and the motor shaft output motion which is transmitted to the harmonic driver through the synchronous belt. Because the motor's own output torque is small, it will not cause greater elastic deformation of the synchronous belt, and the large reduction ratio of the harmonic driver can further subdivide the inter-tooth gear transmission gap of the synchronous belt, so the entire transmission system has good precision. There are zero and limit photoelectric switches installed at the joints to ensure the precision and safety of the joint.

![Fig.2 The sketch of composite and simplified parallelogram mechanism](image)

The joint 6 which is driven by a biased servo motor installed near joint 5 achieves a composite parallelogram mechanism required for minimally invasive surgery. The joint 6 and the joint 5 ensure the fixed apofocus of RCM mechanism and inverted cone space of surgery. The output motion/torque of the motor with a harmonic driver is transmitted to the joint 6 via a synchronous belt. The joint is also installed with zero position detection and motion-limited photoelectric switch to ensure safety.

In the composite parallelogram mechanism like A shown in the left of Fig.2, the rod 4 does not really exist in the actual mechanism, and only the pivotal connection is provided between the rods 1, 2, 3. The quadrilateral A does not independently perform the parallelogram motion, and thus cannot provide the fixed point of RCM for minimally invasive surgery. The effect of other rods on the quadrilateral B and C is that can provide the support to quadrilateral A to become a parallelogram mechanism. By analyzing the structure of the composite parallelogram in Fig.2, some conclusions can be got as follows:
First, there are many rods in the composite parallelogram mechanism, and the mechanism requires high precision in the component manufacturing and assembling the rods. If some errors occur in such process, they may cause the entire mechanism to be locked or even destroyed. Second, the composite parallelogram mechanism has relatively large volume, and it will need a large out-of-cavity operation space during the surgery process. Interference and collisions are likely to occur when the complex mechanisms are cooperated in performing surgery process. The third, the special configuration of the composite mechanism makes the mechanism has large radius of gyration and large moment of inertia during the motion, which will produce some difficulties in robot control and safety protection during the surgery.

![Fig.3 RCM mechanism realized in the robot](image)

In order to solve the above-mentioned problem in the composite parallelogram mechanism, a simple parallelogram mechanism like the right part of Fig.2 is presented to instead of composite parallelogram mechanism. To restrain the relationship among the angles of the kinematic pairs in the quadrilateral A, the synchronous belt is used to restrict the rotation angle of each joint in the quadrilateral A in order that the motion satisfies the parallelogram law and the RCM can be maintained as a fixed point. Thus the composite parallelogram mechanism can be simplified as a simplified parallelogram mechanism and it can be used in minimally invasive surgery to ensure safety. The RCM mechanism is realized as Fig.3.

### 2.3 Surgical instrument module design

In the minimally invasive surgery, surgical instrument need to be worked in the inverted cone operation space to ensure safety. The size of the inverted cone operation space will directly affect the effect of the surgical operation. The movement of joint 5 and the joint 6 described above can only adjust the conical apex angle of the inverted conical space. To facilitate the adjustment of the size of the operating space in the direction of the instrument axis, a movable joint 7 which can drive the surgical instrument to perform a linear motion is designed. By controlling the length of the instrument in the cavity it can adjust the surgical operation space. Furthermore, since the axis of motion of the joint 7 passes through the RCM fixed point of the mechanism, the linear motion of the joint during the operation does not cause large damage to the abdominal wall. In order to reduce the size and mass of the end of the robot, the driving motor of the joint 7 is installed at the joint 6, and the movement of the sliding table on the linear slide is realized by the wire driving method. The wire driving principle of the joint 7 is shown in the Fig.4. In order to reduce the friction in the process of driving steel wire, thin-walled bearings are installed in the guide wheel and the tension wheel, and high-precision linear guides are installed at the slide table.
3. Calibration of RCM fixed point

The endoscope manipulating robot with RCM mechanism is used in minimally invasive surgery. The stability of the fixed apofocus point in the spatial space will directly affect the final effect of the surgery. Therefore, it needs to calibrate the robotic system before using it. Calibrating operation must be performed on the RCM mechanism of the manipulator to ensure that the spatial position of the fixed apofocus point during the operation is within the safe range allowed in the minimally invasive surgery.

Considering that in the assembly process of the robot, there may be an assembly error between the real fixed position and the ideal fixed position of the belt, so that the RCM mechanism after the assembly is not a standard parallelogram mechanism. That is, the intersection angle \( \theta \) between the robot sliding table and the rod 3 may not be equal to the standard angle \( \theta_0 \), which will cause the marked apofocus point on the trocar not in the same position as the ideal apofocus point of the mechanism, as shown in Figure 5. In the Fig.5, there are two cases showed that the intersection angle \( \theta \) is larger than the designed angle \( \theta_0 \) or smaller than it. If minimally invasive surgery is performed under such conditions, trocar’s movement during the operation may cause injury to the patient's abdominal wall wounds which is not allowed in any surgery. Therefore, a parallelogram mechanism calibration method that can determine the spatial position of the apofocus point is needed in assembly operation.

Taking the case of \( \theta > \theta_0 \) as an example, the calibration method of parallelogram mechanism is described as follows. It is assumed that the length of the rod 1 is \( D \) in the RCM mechanism designed in this paper. When the joint 6 moves to the vertical state as shown in Fig.6, according to the parallelogram principle, the fixed apofocus point is located just under the revolving axis of the sliding table, and the distance from the fixed point to the revolving axis is same as \( D \). Only by adjusting the angle of \( \theta \) the operator can make the marking point of the Trocar coinciding with the designed fixed RCM point of mechanism. By doing so, calibration of the parallelogram mechanism can be done.
4. Experiments and conclusion

According to the design requirements and in order to ensure the safety of the operation, the manipulating robot is designed in the master-slave structure. The master controlling joystick is shown in the first column of the Fig. 7. The doctor operates the master joystick to control the slave manipulating robot. The joystick has three degree of freedom like 1,2,3 joints that are controlling the speed of the three motors like 5,6,7 joints in the slave robot one-to-one correspondence. The six joints like 1,2,3 in the master joystick and 5,6,7 in slave robot are shown as red color in the Fig.7. The 5,6 joints are active joints in the slave robot to fulfill a composite parallelogram mechanism required for minimally invasive surgery and the 7 joint is another active joint that can drive the surgical instrument to perform a linear motion. The design details of the 5,6,7 joints can be seen in the section two in this paper.

Some experiments needed to be done on the RCM mechanism to test the moving effect of robot system. In the experiment, the manipulating robot is controlled to pass in and out the simulated abdomen. By observing the movement, the data and offset of the RCM fixed point on the Trocar can be got. The figure about the experiments is shown as Fig. 7.
Experiments show that RCM fixed point is almost in the domain of the designed position like the bottom two figures in the Fig.7. The figures show two different postures when the robot moves in the work domain. The mechanism does parallelogram motion and the offset of the position offset is not beyond 2mm. By these experiments, it is proved that the designed fixed RCM fixed point meets the design requirements and the manipulating robot structure is feasible.

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