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Design and Analysis of A Partially Decoupled Minimally Invasive Surgical Robot

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ABSTRACT: The safety of minimally invasive surgery has been much attention, in order to improve the safety of minimally invasive surgery, minimally invasive surgery for the end of the implementation of the existing shortcomings and defects of existing institutions, to design a new type of end effector for surgical instrument actuator. According to the clinical requirements, technical requirements and characteristics of minimally invasive surgery, and combining with the characteristics of the new mechanism, the motion of the fixed point. The new mechanism not only realizes the decoupling control of motor arranged on the base, will also move the end effector rod along the axial direction on the end effector, greatly reduce weight, improve the rigidity and stability of the actuator arm, and the flexibility of operation. At the same time, the weight of the mechanism is reduced, the inertia of motion is reduced, and the end of the mechanism is reduced to a certain extent.

Keywords: minimally invasive surgery; end effector; distal mechanism; Simulation analysis

I. INTRODUCTION

In vitro minimally invasive operation is to open one or more 0.5cm to the body in patients with 3cm the size of the incision, surgical wound by in vivo implantation in patients with small lesions in the patients, doctor of the resection and repair surgery in the treatment of specific tasks through image visualization system. Minimally invasive surgery has been widely used in foreign countries, the main advantages are: less trauma, less blood loss, faster postoperative recovery[1]. But the existing minimally invasive surgery there are a series of urgent problems, such as during the operation process, poor fatigue, hand eye coordination to the doctor, surgical instruments and fewer degrees of freedom in operation flexibility, hand tremor will seriously affect the operation precision of [2]. In order to effectively solve the problems of minimally invasive surgery, robot technology has been widely used in minimally invasive surgery, the combination of the two has become the main direction of the future development of minimally invasive surgery [3]. Minimally invasive surgical robot system overcomes the shortcomings of traditional minimally invasive surgery, while providing a good working environment for the doctor, in the premise to ensure the safety of patients under [4] greatly improve the quality of minimally invasive surgery.

At present, minimally invasive surgical robot technology has become many international universities and research institutions of the research in the minimally invasive surgical robot technology in the United States and the European research institutions at the international advanced level, the most representative is Da Vinci Computer Motion robot system in 1996 the United States company developed the Zeus robot system and the United States in 1999 Intuitive Surgical company[5]. In 2001, the United States Intuitive company developed Surgical Da Vinci minimally invasive surgery robot system by the U.S. Federal Food and Drug Administration (FDA) certification, has realized the commercialization of minimally invasive surgical robot [6].

Intuitive Surgical's Da Vinci minimally invasive surgical robotic system, the end of the end of the actuator arm is provided with two driving motor, a control rod for performing a rotation, by controlling the screw rotation along the axial direction of the actuating lever to move up and down, to meet the clinical needs of minimally invasive surgery [7]. Due to the end of the installation of two motors and a number of connecting the transmission device, resulting in weight concentrated in the end, the rigidity of the manipulator, the flexibility of operation, the accuracy of the movement have a certain impact [8]. There are drawbacks in this paper in order to make the cushion through the branched synthetic method to design a new type of end effector, the motion characteristics of crank slider mechanism, and quadrilateral transfer and stability, will control the end effector rod along the axial direction on the rear motor moving, fixed on the frame. Through the crank slider device, not only to achieve the implementation of the rod moving along the axis direction, but also to avoid the ball screw rotation and movement of the movement of the way to improve the movement efficiency and transmission accuracy.

The active joint of end effector in this paper are introduced in this paper, through the kinematics analysis of the mechanism using D-H method and vector algebra method, and use the simulation analysis and verification of ADAMS model was established by partial decoupling.

II. STRUCTURAL DESIGN

2.1 design principles

Through the patient's body surface wound, the minimally invasive surgical end effector implanted into the patient's abdominal cavity, to complete the whole operation process of minimally invasive surgery. Two degrees of freedom by the actuating lever of the body surface, the actuator in the human body movement is allowed to have only four degrees of freedom: the surface around the wound roll and pitch of the two rotational degrees of freedom along its axis of rotation and the actuating lever on-line translation of the two degrees of freedom. In order to ensure the safety of the operation, the quadrilateral structure will power surgical instruments translational remote mechanism improves the flexibility and reduce the inertia, and the structural characteristics of the quadrilateral structure itself fixed-point distal movement, to ensure that the mechanism has high stiffness, while the front end part of the cantilever is big enough operation space, prevent operation and body interference. The design of a new type of minimally invasive surgery at the end of the implementing agencies as shown in figure 1.

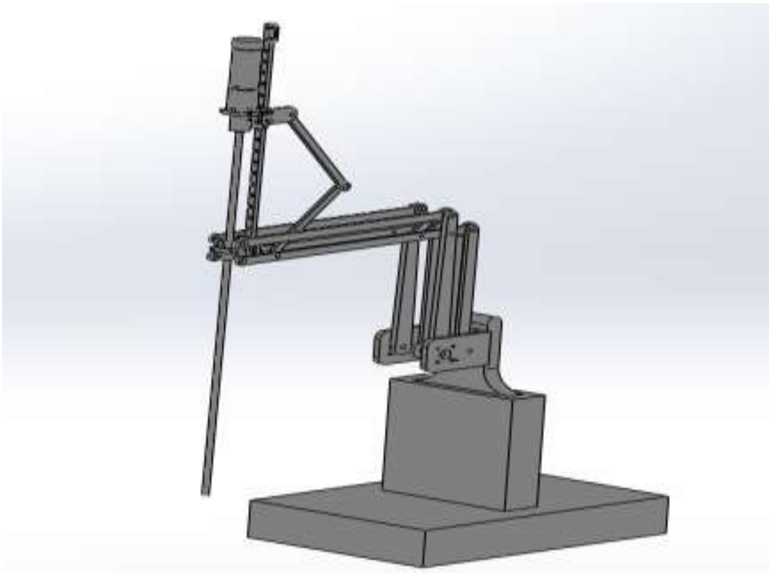


Fig.1 Novel in vitro minimally invasive operation mechanism

2.2 structural design

This paper mainly introduces four active joints design, will be able to achieve surgical instruments, pitch and roll degrees of freedom joint respectively first, 2 joint translation and rotation joint respectively 3, 4 joint. In order to reduce the size of the whole body, to achieve lightweight design, the design of the spiral bevel gear, to change the direction of rotation, the control of roll, pitch and move the motor is placed in a box.

2.2.1 first joint structure design

All of the weight of the whole terminal executing mechanism is applied to the first joint, and the rolling motion of the motor is realized by the drive shaft. The maximum transmission error of the planetary gear box and the average backlash under no load are not more than 2 degrees, so the motion accuracy of the mechanism is improved.

2.2.2 Second joint structure design

The pitching motion of the actuator at the second joint is realized by using the parallelogram structure. The motor is driven by the gear, and the planetary gear box is used as the power end, which greatly reduces the transmission error.

2.2.3 Third joint structure design

The third joint is based on the slider crank mechanism, which converts the rotary motion into linear motion, so as to realize the movement of the end surgical instrument along the axis direction. In order to reduce the weight of the end effector holding the end of the surgical instrument, the drive motor is moved to the base by a quadrilateral structure.

2.2.4 Fourth joint structure design

The fourth joint is installed at the end of the joint, and the power transmission is carried out through the coupling to control the rotation motion of the surgical instrument.

III. KINEMATIC ANALYSIS

Kinematics is mainly used to describe the kinematic relationship between the various joints of the robot and the rigid structure of the robot. Most of the robot is composed of a set of kinematic pairs and rigid rods which are sequentially connected, regardless of the joints by using what kind of motion pair can be decomposed by rotating a single degree of freedom and moving joints to express.

3.1 kinematics positive solution

This paper studies the minimally invasive surgery end actuator for asymmetric parallel mechanism, divided into two limbs, first branched along the axial direction of the mobile terminal surgical instruments, second limbs of the end of roll and pitch motion of surgical instruments. The first movement of the structure of the chain structure of the slider crank, the principle of structure shown in figure 2. The kinematics equation is used to obtain the kinematics equation of the slider, and the obtained equation is the displacement of the end effector :

$$L = r\cos\omega t + l\sqrt{1-\lambda^2\sin^2\omega t} \quad (\lambda = r/l) \qquad (1)$$

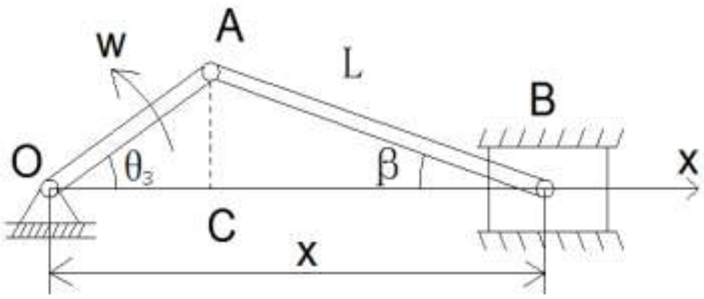


Fig.2 The principle diagram of the realization mode of the mobile degree of freedom

The first moving chain is simplified, it can be used as a mobile freedom series to the end effector of the End effector rod, the mechanism can be simplified as a series of institutions, as shown in figure 4. In order to determine the position of the end effector of the robot, the relative pose of each member is described, and the reference coordinate system of each joint is established according to the D-H parameter method. This paper adopts the method of coordinate system, as shown in figure 3.

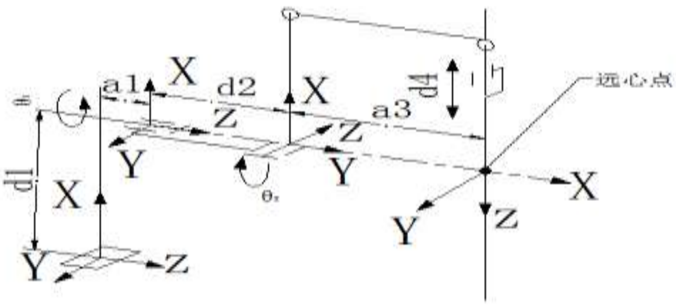


Fig.3 Simplified schematic of the end actuator

Forward kinematics of robot:

$$n = \begin{bmatrix} c\theta_2 c\theta_3 \\ s\theta_2 c\theta_3 \\ s\theta_3 \end{bmatrix}$$

$$o = \begin{bmatrix} -s\theta_2 \\ c\theta_2 \\ 0 \end{bmatrix} \quad a = \begin{bmatrix} (-c\theta_2 c\theta_3 + s\theta_2)d_4 + a_3 c\theta_2 c\theta_3 + a_1 \\ -(s\theta_2 s\theta_3 + c\theta_2)d_4 + a_3 s\theta_2 s\theta_3 \\ c\theta_3 d_4 + a_3 s\theta_3 + d_1 + d_2 \end{bmatrix} \quad p = \begin{bmatrix} a_3 c\theta_2 c\theta_3 + a_1 \\ a_3 s\theta_2 s\theta_3 \\ a_3 s\theta_3 + d_1 + d_2 \end{bmatrix} \qquad (2)$$

In type: $s = \sin$; $c = \cos$

3.2 Inverse kinematics

In the case of known end effector pose, as shown in formula (2): n_x、n_y、n_z、……、p_y、p_z， the corresponding joint variables θ_2、θ_3。

1) The joint angle θ_2 is solved by the formula (2):

$$\theta_2 = -\arctan(\frac{o_x}{o_y}) \qquad (3)$$

2) the solution of joint angle θ_3 can be solved by formula (2):

$$\theta_3 = \arctan(-\frac{n_z}{n_y} s\theta_2) \qquad (4)$$

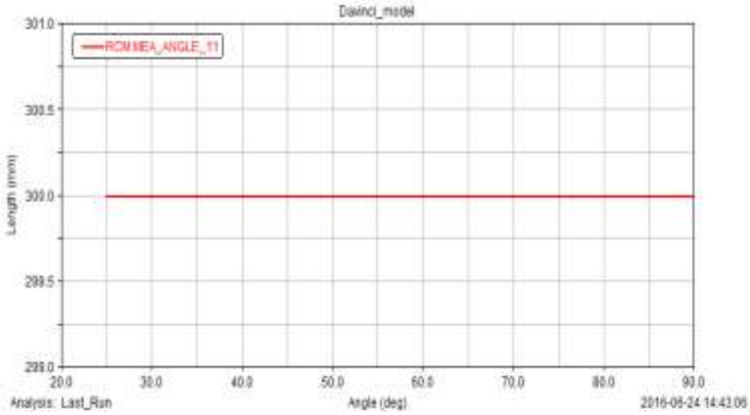
3) The solution of the probe distance d_4 isobtained by formula (1) and (2): $d_4 = L$ (5)

IV. SIMULATION ANALYSIS

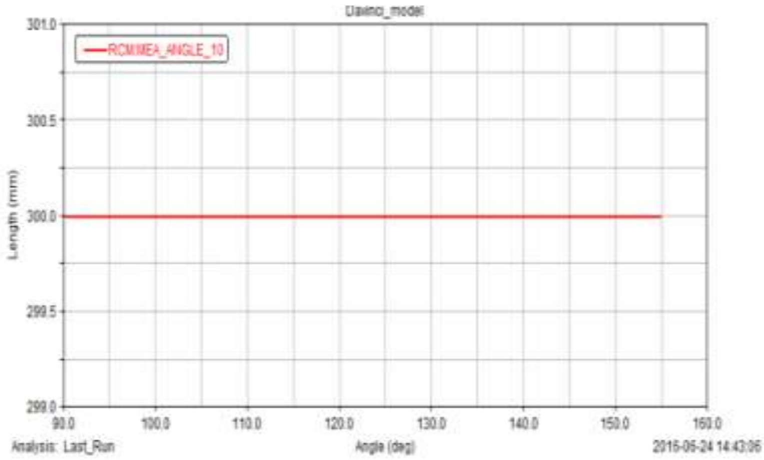
In this paper, the design of the end effector, the key technology is to achieve control of freedom of movement of the drive motor rear, reduce the weight of the implementation of the end of the rod, improve the flexibility and accuracy of the entire mechanism. Due to the particularity of the structure, it is necessary to carry out a positive analysis on whether the mechanism can realize the fixed point far center motion and whether the mechanism can control the moving degree of freedom when the pitching motion is realized. The kinematics model is established by ADAMS, and the simulation analysis is carried out.

3.1 Analysis of the pitch movement wound surgical instruments

The joint 1 rotates to the position of 90 degree to 25 degree, 2 rotating joint position, joint rotation 3 to 0 degrees, then the surgical instruments in such a posture by inserting into the wound 100mm. Simulation measurements with this attitude, the drive motor 2 and 3 at the start of the 2, through the control of joint movement to 90 degrees, and measuring the apocenter position in pitching motion under the change of the results as shown in Figure 4 (a) shows. The measurement results are shown in Figure4 (a) and (b).



a）

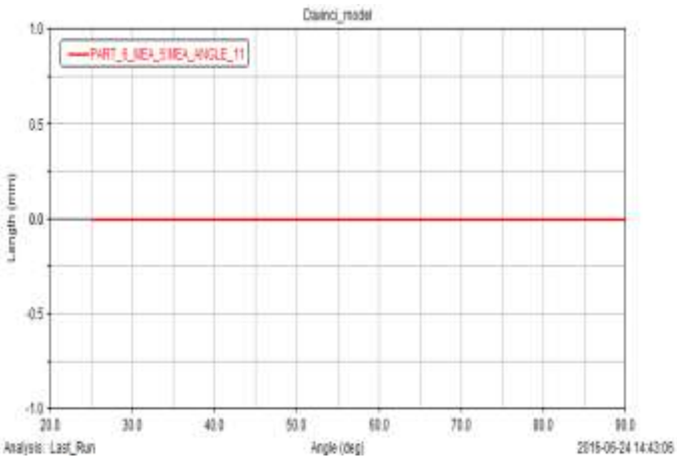


b）

Fig.4 Simulation results of fixed point motion

In Figure4 (a) and (b) as shown by the analysis results, when pitching from 25 degrees to 155 degrees, apocenter position has been in 300mm, has not changed, the results are consistent with the original intention of the design, to meet the needs of clinical.

In the case of pitching motion, it is necessary to avoid the linear movement of the surgical instruments along the guide rail to prevent mutual interference between the motions. At the same time, the relationship between the degree of freedom and the pitch motion is measured, and the results are shown in Figure 5 (a) and (b).



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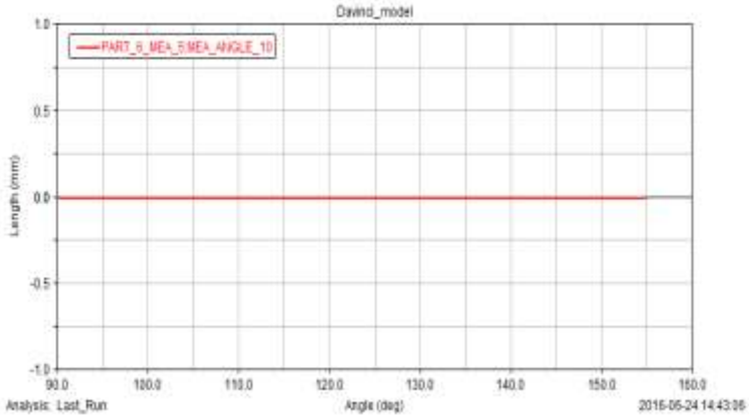

b）

Fig.5 Simulation results of fixed point motion

3.2 simulation and analysis of motion decoupling of surgical instruments

The joint 1 rotates to the position of 90 to 25 DEG, 2 rotating joint position, joint rotation 3 to 0 degrees, then the surgical instruments in such a posture by inserting into the wound 100mm. In this way, the simulation is carried out to start the drive motor at 3 joints. When surgical instruments along the axial direction of movement is measured, simulation of its quantity and change the vertical distance between the base coordinates, the simulation results are shown in figure 6.

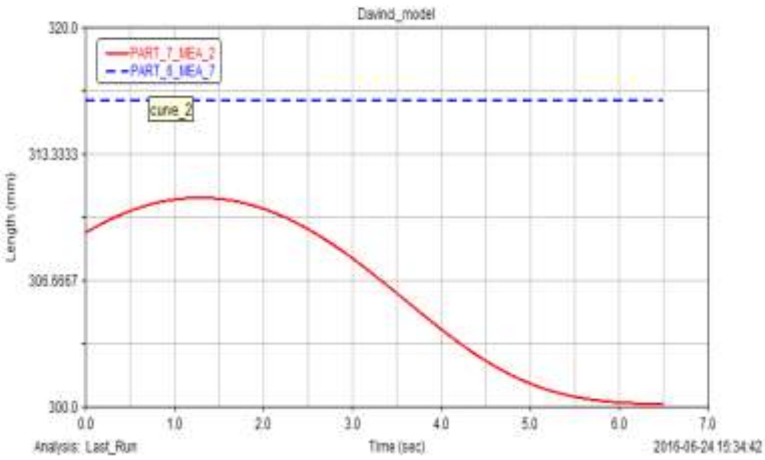

Fig.6 Mobile simulation result

Through ADAMS simulation analysis of data from the data shown in Figure 7 can be seen when the joint drive motor start control only 3 degrees of freedom movement, the manipulator has been in its original state, does not rotate, realized partial decoupling mechanism, no other degrees of freedom have any impact, meet clinical requirements. The results prove the feasibility of the control of the driving motor, and the performance of the mechanism is greatly improved.

V. CONCLUSION

Through the analysis of the requirements of minimally invasive surgery robot performance, for the end of the minimally invasive surgery is a new type of actuator is designed, and the current commonly used minimally invasive surgery in vitro end actuator is compared, the agency will realize the control of moving drive motor is arranged on the base of freedom, while avoiding the use of screw. The new mechanism through the motor rear significantly reduced inertia ends, effectively improve the flexibility of the robot and the accuracy of the mechanism with revolute; driving, avoid the ball screw rotation and transfer mode of movement, improve exercise efficiency and transmission accuracy. Based on the kinematics analysis, the simulation of mechanism motion is carried out, and the feasibility of the new mechanism is demonstrated.

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