Mechanism design and simulation analysis of robot system for vascular interventional surgery

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Abstract. At present, the mortality of cardiovascular and cerebrovascular diseases is getting higher and higher, interventional surgery has obvious advantages over traditional surgery, and robot technology has also entered this field. Combined with the existing research results, a set of surgical robot system is designed. The operating device uses magnetic powder brake to provide real force feedback of braking torque, the propulsion device adopts a clamping rod structure to accurately clamp the catheter or guide wire, and the force signal is collected by using the lever principle. Finally, the study of the dynamic characteristics of the propulsion device shows that the smaller the quality and the higher the tension force are, the more favorable the performance of the propulsion device is, and the calculation verifies the rationality of the transmission part of the propulsion device.

1. Introduction

Cardiac minimally invasive interventional surgery is an advanced method for the diagnosis and treatment of cardiac diseases [1, 2], which has great advantages: local anesthesia, high safety and low cost [3]. However, there are many problems in interventional surgery. Firstly, long-term operation will lead to fatigue and affect the success rate of operation. Secondly, doctors are exposed to X-ray and affect their health [4]. Therefore, the robotic technology should be applied to the vascular interventional surgery [5, 6].

At present, the robot operation device collects the motion state of the motor through the encoder, passes it to the computer processing, sends it to the corresponding driver of the propulsion device, and then controls the motor motion. But if the motor continues to provide braking torque, it will cause heat, vibration, influence feedback accuracy.

As the most important part of vascular interventional robot system, the performance of propulsion device determines the performance of the system. Both the propulsion mechanism developed by Imperial College London [7] and the propulsion mechanism developed by Kagawa University [8] can complete catheter or guide wire guidance intervention. But they lack specific delivery methods and procedures.
Based on the above problems, a robot system which can simulate the actual operation of human hands is proposed, and the motion process of the propulsion device is simulated and analyzed to verify its rationality. It lays a theoretical and technical foundation for promoting the practical application of vascular interventional surgery.

2. Operating device mechanism design
The operation mode of the doctor is roughly the same. If the operating device is used in the same or similar way, the operation will be better. For this purpose, an operating device using magnetic powder brake to provide feedback force is designed, as shown in figure 1.

![Virtual prototype of the operating device](image1)

When the catheter or guide wire meets the bifurcation in the blood vessel, it is necessary for them to carry out axial feed and circumferential rotation at the same time, so the delivery mechanism needs two degrees of freedom. While performing surgery, the surgeon pushes the handle forward or backward to achieve axial feed movement, and rotates the finger wheel with the thumb, index and middle fingers to achieve circumferential motion. So that the catheter or guide wire can rotate and feed in the blood vessel synchronously.

3. Master-slave control system
The master-slave control system flow chart is shown in figure 2 by analyzing the operation steps of the doctor.

![Master-slave control system diagram](image2)
The doctor pushes or twists the action to drive the corresponding encoder to rotate, the signal is transmitted to the patient end main control machine, the patient end main control machine processes the signal, the command driver drives the related motor action, realizes the feed and twist of guide wire. The resistance signal received by the pressure sensor is transmitted to the doctor's main controller through the communication module. The main controller sends out a signal to control the resistance moment of the magnetic powder clutch so that the doctor can feel the force [9].

4. Propulsion device mechanism design
The axial feed of the propulsion device adopts synchronous belt drive and the circumferential rotation adopts friction wheel drive. As shown in figure 3, the whole machine consists of six parts: fixed guide wire mechanism, friction wheel, axial moving mechanism, Y valve holder, gripping guide wire mechanism and swing force measuring mechanism [10].

4.1. Structure Design of Clamp Guide Wire
In interventional surgery, the catheter or guide wire needs to realize the motion of two degrees of freedom of axial feed and axial rotation. Friction is generally used to achieve. However, the reliability of this method is difficult to guarantee [11]. Therefore, a clamping rod structure is proposed, as shown in figure 4. The guide wire conduit passes through the pressure between the eccentric hole between the clamping rod and the clamping cap so that it is fixed with the clamping rod.

As shown in figure 5, push the clamping cap under the action of the motor, open the release guide tube with the clamping rod. Withdraw the thrust, the guide wire is fixed by the clamping cap and the clamping rod under the action of the spring.
4.2. Design of Swing Measuring Structure

Based on the purpose of improving the detection accuracy and simple structure, a force measurement scheme is proposed by using the lever principle. As shown in figure 6, the resistance is amplified proportionally by lever action, and the sensor is converted into electrical signal after receiving it.

The structure of the resistance measuring mechanism is shown in Figure 7. The guide wire mechanism clamps the guide wire, the guide wire meets the blood vessel bifurcation or touches the blood vessel wall, the resistance of the guide wire increases, the swing angle of the swing base increases the sensor's feeling pressure, the sensor converts the pressure signal into digital signal. The brake torque changes and the doctor feels the resistance to determine the state of the guide wire.

![Figure 6. Principle of force measurement](image)

![Figure 7. Force-measuring mechanism](image)

5. Simulation and Analysis of Propulsion Device

As the core part of vascular interventional robot system, the propulsion device directly controls the propulsion of catheter or guide wire and the realization of twisting function. Its dynamic characteristics are very important for delivery accuracy. In the study of dynamic characteristics, the most affected factors come from the transmission part of the synchronous belt system, including the center distance of the belt wheel, the moving load quality, the tensioning force of the synchronous belt, etc.

![Figure 8. Simplified axial propulsion model](image)

5.1. Analysis of Motion Characteristics

The simplified motion model of the propulsion device was made, as shown in figure 8, and the corresponding motion characteristics were analyzed. For example, the angular velocity of the active wheel and the linear velocity of the moving load obtained from the simulation in the ADAMS are shown in figure 9 and figure 10.
Figure 9. Angular velocity curve of active wheel  
Figure 10. Linear velocity curve of moving load

The active wheel angular displacement curve and the moving load displacement curve are shown in figure 11 and figure 12.

Figure 11. Angular displacement curve  
Figure 12. Displacement curve

It can be seen from figure 11 and figure 12 that the active wheel angular displacement curve and moving load displacement curve do not fluctuate in the speed control mode. Referring to figure 9 and figure 10, the influence of the precision of the guide wire of the propulsion device is mainly focused on the velocity fluctuation, and the range of the fluctuation affects the specific position of the terminal execution of the guide wire.

5.2. Dynamic Motion Velocity Wave Analysis

It can be seen from the previous section that in the speed control mode, the maximum velocity fluctuation of the synchronous belt is concentrated in the uniform motion part. By means of controlling variables, the maximum velocity fluctuation under different moving load quality and different pretightening forces is analyzed respectively.

In the case of speed control mode, motion mode unchanged, belt wheel center distance 390mm, initial tension force 40N, change the moving load quality, the dynamic performance of the transmission system simulation analysis, the results are shown in figure 13. In the same way, when the moving load quality is 0.8kg, the initial tension of the synchronous belt is changed. The results are shown in figure 14.
From figure 13, it can be seen that the max velocity fluctuation of synchronous belt driven propulsion device increases with the increase of moving load quality. As shown in figure 14, the max velocity fluctuation of the synchronous belt driven propulsion device decreases with the increase of initial tension force.

6. Conclusion
Based on the existing research results and the requirements of practical operation process, this paper designs a surgical robot system with force feedback function, including propulsion device and operation device. A guide wire clamping mechanism is designed to realize the accurate control of the guide wire conduit, the force acquisition in the force feedback system is realized by using the lever principle, and a force sensing is realized by providing the resistance moment by the magnetic powder brake. The actual operation length and propulsion end of the same isomorphic control device. Finally, the influence of quality and tension on the dynamic performance of the propulsion device is studied, and the rationality of the design of the transmission part of the propulsion device is verified by calculation.

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