Abstract - Currently, the study of the vascular interventional surgery (VIS) robot becomes more and more popular, which is to improve the safety of the surgery. In this paper, a novel master-slave robotic catheter system has been proposed for the VIS. The system uses MR (magneto rheological) fluid to implement force feedback. The force feedback to the operator on the master side is very important to improve the safety of the surgery. The damper is a piston structure with MR fluid. The coil winds around the piston. When the piston is moving in the piston cylinder, the resistance to the piston will appear as a certain amount of current applied to the coil. We can realize the force feedback by this way. The surgeon can feel the force through the operating catheter connected with the damper, which seems that the surgeon operates the catheter beside the patient. The force feedback evaluation experiments of the damper were done. The error between the detected force and the damping force is in the allowable range. The maximum of error is lower than 0.1N. According to a research presenting that the force larger than 0.12N will injure the vessel, it indicates that the error can meet our design requirement. The experimental results indicated that the damper was effective for realizing the force feedback of the master-slave system. It can provide force feedback to the surgeon in real time.

Index Terms - Vascular interventional surgery, Force feedback, MR (magneto rheological) fluid.

I. INTRODUCTION

Vascular Interventional Surgery (VIS) becomes more and more important in Minimally Invasive Surgery (MIS) which becomes increasingly popular in the medical practice with the development of medical technology [1]-[3]. Vascular Interventional Surgery (VIS) plays an important role in the MIS [4]-[5], and it has been widely applied all over the world for its less blood loss, smaller incisions, decreased pain and quicker recovery [6]. And more and more VIR (Vascular Intervention Robot) have been designed in previous researches [7]-[8]. However, most systems pay little attention to the natural catheter manipulation skills acquired by operators in the conventional catheter interventional surgery [9].

Another disadvantage of the most robotic navigation systems is lacking tactile feedback. In the high-risk surgery, it will bring about complications such as inflammation, thrombosis, perforation and haemorrhage when the collision force between the catheter and the vessel exceeds the safe range [10]. Some commercially-available interventional robotic systems have been developed, such as the Sensei and Magellan robotic navigation systems (Hansen Medical, Mountain View, CA, USA). And Saliba W. and Reddy VY et al have presented the initial clinical human experience with the use of a robotic remote navigation system (Hansen Medical, Mountain View, California), to perform left and right atrial mapping and radiofrequency ablation of atrial fibrillation (AF) and atrial flutter (AFL) [11].

More and more researchers have interesting in vascular interventional surgery robotic systems. Mitsutaka Tanimoto et al have presented a novel telesurgery system for intravascular neurosurgery which has three main components: a micro force sensor installed in the catheter tip, a catheter teleoperation system and a force display strategy to improve operability and safety during an operation [12]. And the force feedback in this system is not considered. J. Jayender et al have presented a hybrid impedance control scheme implemented on the Mitsubishi robot to perform simultaneous force/position control [13]. And the robot is used in experiments to insert a catheter into a test-bed by controlling the force of insertion and preventing the catheter from buckling or “bunching up”. N. Zakaria et al have developed a foolproof catheter guide system using their principle solution of mechatronic design. And they used the ER (Electrorheological) fluid to realize force feedback. This system can avoid human error [14]. Some other teleoperated force-reflecting systems have also been developed. These systems can realize provision of force feedback using proximal force measurements [15]-[17].

Compared to conventional vascular intervention method, these systems can improve stability and comfort of the surgery. However, these systems also have some advantages such as lacking force feedback or hard to control the force using the ER fluid.

In this paper, we proposed a novel master-slave robotic catheter system using force feedback to improve the safety of the catheter invention. We designed a damper with a special structure to realize the force feedback. The damper is a piston structure with MR fluid. The coil winds around the piston. When the piston is moving in the piston cylinder, the resistance to the piston will appear as a certain amount of current applied to the coil. This way can solve the inertial problem caused by using motor to realize the force feedback. In the meantime, the response time of the MR fluid is so short so that it can realize force feedback in real-time. And it has a
low power consumption. And we have done the force feedback evaluation experiments.

II. THE MASTER-SLAVE ROBOTIC CATHETER SYSTEM

A. Outline of the master-slave system

The master-slave system is a closed-loop system composed by the master side and the slave side this two units. When the surgeon operates the catheter, the controller will collect movement information of the catheter to transmit to the slave side. In the meantime, the slave side will transmit feedback force information to the master side so that it can form a close-loop system. Fig.1 shows the conceptual diagram of the master-slave robotic catheter system. As shown in the Fig.1, the robot catheter system is composed by a master side and a slave side this two parts. When the surgeon operates a real catheter while viewing a monitor on the master side, the operating information will be acquired by the controller and transmitted to the slave side. The slave mechanism will control the motors to drive the catheter to move when receiving the control information from master side. Motions of the slave mechanism will follow the motions of the master mechanism. In the meantime, an IP camera is used to collect the information of the operation process in the operating room to transmit to the master side for visual feedback. And the contact force information between the catheter and the blood vessel wall will be detected and transmitted to the monitor software on the master, which can ensure the surgeon see the information to improve the safety. And reacting force to the catheter can be detected by the LoadCell to be transmitted to the surgeon’s hand as tactile feedback. As if the surgeon is operating a real catheter beside the patient. The safety of the surgery can be improved in this way.

![Fig.1 The conceptual diagram of the master-slave robotic catheter system](image1)

The primary task of the master side is to get the operating information of surgeons and send it to the slave side. The information is processed by a controller and transmitted to the slave side by the TCP/IP communication protocol. The slave side mainly follows motion of the catheter on the master side. In the meantime, the slave controller can get force information and the visual information to transmit to the master side as to realize closed-loop control.

B. The designed master manipulator

![Fig.2 The master manipulator](image2)

The master side is the operating platform used by the surgeons to perform the interventional surgery. Our team had presented the master-slave system in the previous paper [18]. The Fig.2 is the diagram of the designed master manipulator in previous. But we have presented improved design for the system. The doctor can operate a real catheter as the conventional catheter interventional surgery, which is a speciality of the master mechanism. The master side has two main functions. Firstly, it is used to acquire the motion information of the catheter operated by the surgeon. And the motion information includes the axial and radial information two aspects. Secondly, it is used to realize force feedback to transmit the force information which is transmitted from the slave side to the surgeon. And the operating force includes axial operating force information and rotation torque information. In the improvement system, the grasper1 and the grasper2 are removed, because that using graspers to clamp the catheter to realize periodic movement is not necessary. This way can simple our system. In the meantime, the structure of the damper is also improved. Fig.3 shows the schematic diagram of the improved damper. We added two linear bearings between the piston rod and the outer casing, which can reduce the friction. The damper is used to realize the force feedback. The damping force can be controlled by changing current of the coil. The MR fluid is the key material to realize the force feedback for its advantages: short response time and low power consumption.

![Fig.3 The improved damper](image3)
The motion of the catheter operated by surgeon contains axial motion and radial motion two degrees of freedom. A linear displacement sensor was adopted to acquire the axial motion information of the catheter. The linear displacement sensor uses a floating magnetic block with non-contact as the sliding end, which can reduce the resistance in the axial motion. The sliding end has a synchronized movement with the piston rod of the damper. The piston rod and the catheter are fixed together through a rubber material. The motion information of the sliding end is same with the motion information of the catheter. The optical encoder installed on the torque motor can detect the radial motion of the catheter. The torque motor and the piston rod are connected by the synchronous belt, which can guarantee the torque motor and the piston rod have the same rotation angle. In meanwhile, the piston cylinder is used to realize the force feedback to enhance the safety of the operation.

Compared with the developed master-slave robotic catheter system in our previous study, we removed the graspers to simplify the system. And we added two linear bearings between the piston rod and the outer casing of the damper to decrease the friction.

C. The designed slave manipulator

The slave side is used to realize the motion of the catheter and the force feedback. The catheter will be rotated when moving difficulty or the branch of blood vessel appears. The surgical catheter on the slave side follows the motion of the catheter on master side. Fig.4 shows the slave manipulator.

![Fig.4 The slave manipulator](image)

The slide platform is fixed on the supporting frame. And the supporting can change the interventional angle from 0° to 45° easily. A stepper motor is installed to drive slide platform to move forward or backward. The position of slide platform is synchronous with the piston of the damper on master side. And another stepper motor is used to complete the rotation of the catheter. Two graspers are designed to imitate the surgeon’s grasping action. Fig.5 shows the clamping method of the graspers. The catheter will be fixed with the axial driven module when the grasper1 clamps the catheter and the grasper2 releases. In this situation, the catheter will have the synchronous movement with the driven module. It means that the driven module can drive the catheter on the slave side. On the contrary, the catheter will keep its position when the grasper2 clamps the catheter and the grasper1 releases. In the meanwhile the driven module can return to beginning position for next operation. And the catheter can be pushed to the lesion location through the process above in alternate cycle.

![Fig.5 The clamping method of graspers](image)

The load cell is fixed on the driven module. A clamp plate fixed on the load cell is linked to the plate installed on the axle of grasper1. Fig.6 shows the the partial schematic diagram of the improved slave manipulator. And the axle of grasper1 is supported by two linear bearings, which allows clamping part to have a certain displacement to push or pull the load cell to detect the counterforce. We added two linear bearing in the improved slave manipulator to decrease the friction, which can make the axle of grasper1 move easier to detect the counterforce easier. The clamp plate can rotate freely when the catheter moves in the axial direction. When the catheter clamped by grasper1 moves on axial direction, the counterforce of the catheter will lead to a micro displacement of the axle of grasper1. In the same time, the micro displacement will be transmitted to the load cell through the clamp plate for detecting the counter force.

![Fig.6 The partial schematic diagram of the slave manipulator](image)

The torque information is detected by the torque sensor during rotation operation. And the rotation movement of the catheter is synchronous with the torque sensor. The torque information will be transmitted to the master side to realize a torque feedback to the surgeon. It is very important to detect the contact force between the catheter tip and blood vessel. A optical fiber sensor and a novel type of catheter sidewall tactile sensor array developed in our previous research [19] are used to detect the contact force.
III. THE DESIGN OF THE EVALUATION SCHEME

A. Force feedback method of the master-slave system

In Tactile telepresence play an important role in a master-slave robotic catheter system to ensure the accuracy and safety of the vascular interventional surgery. It is ineffective to perform the operation only rely on the visual feedback. A damper is designed based on the intelligent fluid-MR fluid in order to realize the force feedback. When the magnetic field is absence, the MR fluid is in the free flowing liquid state. But it can change reversibly from free-flowing to semi-solids with the yield strength swiftly and continuously controllable when exposed to a magnetic field. Fig.7 shows the schematic diagram of the MR fluid damper. The MR fluid damper adopts a piston structure. The MR fluid damper mainly contains outer casing, piston body winded by coil and foam saturated with MR fluid. When different current flow in the coil, the piston body will suffer different damping force. So the force feedback can be realized according to this principle. The most important feature of the master manipulator is the MR fluid damper which is used to realize force feedback. It can transmit the counterforce of the catheter on the slave side, which can improve the force transparency of the master-slave system.

B. The evaluation experiment scheme

The evaluation experiment is done to estimate the performance of the MR fluid damper used in the master-slave system. We can see whether the method of force feedback can be applied in practice. And we can know how to improve the precision of the force feedback. Fig.8 shows the structured flowchart of the evaluation experiment. In the experiment, the master manipulator is driven by an operator. And the motion information of the catheter will be detected by the DSP controller to be transmitted to the slave side. The slave manipulator will drive the catheter to realize a synchronous movement with the master side. The counterforce to the catheter will appear when the catheter moves forward in the vascular model in a mannequin. And the counterforce will be detected by the load cell to be transmitted to the master side through the slave controller. The master controller will control the MR fluid damper to generate a corresponding damping force through changing the current of the coil.

In the experiment, the counterforce on the slave side and the damping force on the master side will be detected. The precision of the force feedback can be acquired by comparing the value detected by the load cell on the slave side and the value of damping force on the master side. A voltage-controlled current source circuit has been designed in order to get a controlled current.

IV. THE FEEDBACK FORCE EVALUATION EXPERIMENTS OF THE IMPROVED SYSTEM

In order to estimate the performance of force feedback in the improved master-slave system used the MR fluid damper, the feedback force evaluation experiments must be done. The structured flowchart of the evaluation experiment shown in Fig.8. The master manipulator is driven by an operator. And the motion information of the catheter will be detected by the DSP controller to be transmitted to the slave side. The slave manipulator will drive the catheter to realize a synchronous movement with the master side. The counterforce to the catheter will appear when the catheter moves forward in the vascular model in a mannequin. And the counterforce will be detected by the load cell to be transmitted to the master side through the slave controller. The master controller will control the MR fluid damper to generate a corresponding damping force through changing the current of the coil.

There are many parameters should be taken into consideration to develop an effective MR fluid damper. The length of the damper is 200mm. The gap between the outer casing and the piston body is 2mm. And the thickness of outer casing is 4mm. The diameter of piston body is 36mm, as is shown in the Fig.9. And the number of turns of the coil approximately 500. The piston body was covered with the foam saturated with MR fluid. The damping force of the MR fluid damper can be controlled by changing the current of the coil. The current of the coil is supplied by a voltage-controlled current source circuit. In the circuit, the value of the current equals the value of the control voltage. The output of the D/A conversion is the input voltage of master controller. Therefore, the input current of the coil can be controlled by the master controller.
In order to control the damping force of the damper based on the MR fluid effectively, a calibration experiment of the damper was done. And we got the relationship between the damping force and the current of the coil. Fig.10 shows the physical map of the calibration experiment. In the experiment, the Load Cell is used to detect the damping force and the constant-current source is used to supply variational current of the coil. And the result is shown in the Fig.11. The relationship between the damping force and the current of the coil is as follows:

\[ F = -795.93I^2 + 2274.70I + 933.38 \]  

(1)

Where \( F \) is the value of the damping force, \( I \) is the current of the coil. As shown in the Fig.11, the damping force is greater than zero when the current is zero. It’s because the damper has an intrinsic friction.

![Fig.10 The calibration experiment of the damper](image)

![Fig.11 The result of the calibration experiment](image)

The force feedback evaluation experiment was done to evaluate the performance of the improved master-slave system. Fig.12 shows the physical map of force feedback evaluation experiment. In the experiment, the counterforce to the catheter will be detected by the load cell on the slave side and transmitted to the master side after data processing by the DSP controller. The controller will control the current of the coil to make the damper to produce a corresponding damping force. And the damping force is detected by the pressure sensitive rubber which can produce certain voltage when the pressure changing. The counterforce to the catheter and the damping force produced by the damper are collected in the experiment.

![Fig.12 The force feedback evaluation experiment](image)

![Fig.13 Comparison curve of the detected force and the feedback force](image)

![Fig.14 The error between the detected force and the feedback force](image)

Fig.13 shows the result of the evaluation experiment and the Fig.14 shows the error of the experiment. Fig.13 shows resistance detected by the load cell and the damping force generated by the damper as time going on. In the Fig.13, the force is maximal in the time range of 10s to 18s. It’s because that the catheter is inserted in the vessel bend and suffers larger resistance. In the Fig.14, we can see the maximum error between the detected force and the damping force is lower than 0.1 N, which can meet our design requirement according to a study presenting that the force larger than 0.12 N will injure the vessel [14]. So the error is in a safe range. The force feedback of the system is effective through the experiment. The operator can feel the reactive force when operating the catheter on the master side. In addition, the force information is transmitted from the slave side. The experimental results indicate that the damper can reflect the resistance to the catheter on the slave side. When the operator uses this system, he can feel the resistance generated by the damper on the master side. In addition, the force information is transmitted from the slave side.
operator can change the motion of the catheter when he feels the resistance changing larger, which can improve the safety of the surgery. In the future, we will use our system to carry out the vitro experiments and the vivo experiments to execute further verification of the reliability of the system.

V. CONCLUSION AND FUTURE WORK

It’s important to improve the safety of the vascular interventional operation. And furthermore, tactile feedback plan an important role in improving the safety of the VIS. In the paper, we proposed a novel master-slave system using a damper based on the MR fluid to realize the force feedback. We have done the calibration experiment of the damper to get the fitting relationship between the damping force and the current of the coil so that we can control the damping force through changing the current of the coil. The force feedback evaluation experiment of the improved master-slave system was done. According to the experimental results, we can see that the error between the counterforce detected by the load cell and the damping force produced by the damper is relatively small. And the max error is lower than 0.1 N, which can meet our design requirement. In the future, we will carry out the vitro experiments and the vivo experiments to execute further verification of the reliability of the system.

In addition, we found that the counterforce to the catheter is very hard to detected on account of very small force. So we will further improve our system to detect the counterforce easily.

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