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# A Novel Master-slave Robotic Catheter System for Vascular Interventional Surgery

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*Abstract* - **In minimally invasive surgery, the surgeons are exposed to X-ray, threatening the surgeons' health due to depositing long. It is important to find a method instead of using X-ray during Vascular Interventional Surgery (VIS). In this paper, a novel master-slave robotic catheter system for VIS has been proposed. The surgeons operate a real catheter on the master side, which can make full use of the natural catheter manipulation skills obtained in conventional catheter navigation. And the acquired operating information can be transmitted into the master controller. The control information from the master controller can be sent into slave controller. According to the control information, the slave controller can control the slave manipulator to operate catheter insert into the blood vessel during VIS. The operating force of catheter by slave manipulator can be acquired into the slave controller and be sent to the master controller. A novel type of master manipulator we proposed is based on the principle of magnetorheological fluid. A piston structure filled with magnetorheological fluid can transmit the force feedback to surgeon's hand through the operating catheter from the control of master controller, which seems that the surgeon operates the catheter beside the patient. The communication method and control strategy of designed system have been used in our previous developed system. Theoretical analysis of the designed system was done. The analyzed results indicated that the proposed robotic catheter system was effective for vascular interventional surgery. It can provide force feedback to surgeon in real time.**

***Index Terms – Vascular interventional surgery, Catheter, Master-slave system, Force feedback, Magnetorheological fluid.***

## I. Introduction

With the development of medical technology, Minimally Invasive Surgery (MIS) has become the most effective technique for vascular diseases, and it is popular for the diagnosis and treatment of endovascular diseases [1]-[3]. Vascular Interventional Surgery (VIS) is an important part of MIS [4]-[5], and it has been widely adopted all over the world because of its smaller incisions, less blood loss, decreased pain and quicker recovery [6]. In conventional VIS, Surgeons cut an incision in the groin where a catheter is inserted, and control the catheter to the target under fluoroscopic guidance [7]. Fig.1 shows the conceptual diagram of conventional catheter interventional surgery. However, it is very difficult to operate a catheter inside the blood vessels due to the narrowness and complexity of blood vessels. The difficulty causes not only an extension of operating time, but also the fatigue of the operators and patients, which maybe increase the risk of the surgery. Moreover, there is a problem that there are not enough well-skilled doctors who can operate a catheter for surgery appropriately as compared with the large number of patients who want to be treated with the vascular interventional surgery. Moreover, there are not enough well-skilled doctors who can operate a catheter appropriately for the surgery, while the number of patients who need to be treated is large. In addition, these doctors are always exposed to X-ray radiation. In order to solve these problems, we should design an efficiency telesurgery system [8].

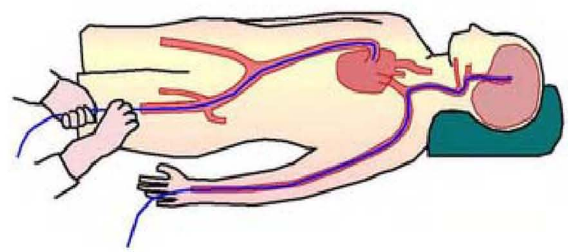

Fig.1 The conceptual diagram of catheter interventional surgery

The researchers are growing more interested in robotic catheter operation systems for vascular interventional surgery. A master-slave system with force-reflecting was developed [8]. Yili Fu et al reported a master-slave catheterization system for positioning the steerable catheter [9]. Weixing Feng et al presented a highly precise catheter driving mechanism for intravascular neurosurgery [10]. A tele-operating vascular interventional robot for medical applications was proposed. And the vascular interventional robot includes 5-DOF active supporting manipulator and 2-DOF catheter operating system [11]. Compared to manual catheter intervention method, these systems can provide advantages such as improving stability and comfort, reducing radiation exposure to the operator and eliminating physiological tremor. The disadvantage of these systems is that the axial motion (moving forward and back-ward) of the catheter is almost realized by the friction of wheels. And the friction between the wheels and catheter may cause damage to the catheter. The impaired catheter could bring damage to the fragile blood vessel as well. Moreover, most of these systems have been designed with little consideration of the natural catheter manipulation skills obtained through experiences and utilized by operators in conventional catheter navigation [12]. And the surgeons do not really manipulate a catheter, which removes some of the important tactile cues required in conventional catheter interventional surgery.

In this paper, we proposed a novel master-slave robotic catheter system with true force feedback to the surgeon's hands. The surgeons operate the real catheter at the master side, and the operating information will be acquired by the master controller then transmitted to the slave controller. According to the operating information, the slave controller will control the slave manipulator to insert the catheter into the blood vessel during VIS. The insertion force of the slave manipulator will be acquired by the slave controller and transmitted to master controller. Then a piston structure filled with magnetorheological fluid will transmit the force feedback to surgeon's hands through the operation catheter under the control of master controller. The design of this system accords with the requirements of ergonomic.

## II. Design of the Master-slave Robotic Catheter System

### A. Overview of the robotic catheter system

A conceptual diagram of the master-slave robotic catheter system is shown in Fig.2.

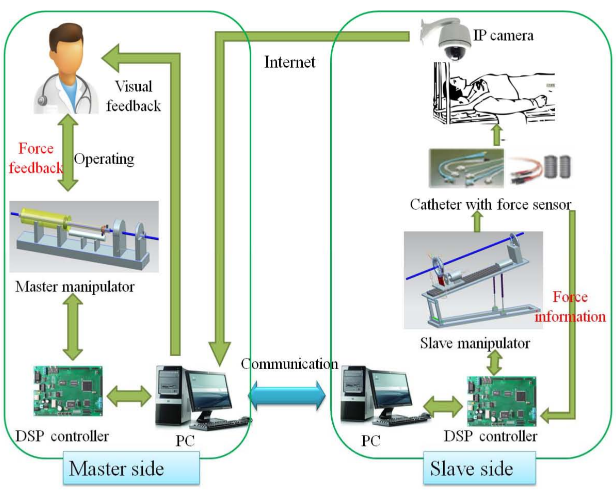


Fig.2 Conceptual diagram of the robotic catheter system

On the master side, the surgeon operates a real catheter with viewing a PC screen. The operating information will be transmitted to the slave side. Once receiving the operating information, the slave mechanism drives the catheter to insert into blood vessel. Motions of the catheter on the slave side follow the motions of the catheter on the master side. An IP camera is used to monitor the process of the operation and give visual feedback. If the catheter contacts a blood vessel wall, the force information will be detected and transmitted to the surgeon's eyes. And the driving force of the slave manipulator will be acquired and transmitted to surgeon's hands as force feedback. As if the surgeon operates the catheter beside the patient. In this method, the safety of the surgery can be improved.

The design of the robotic catheter system includes master side and slave side. The main task of master side is to acquire the operating information of surgeons, then send it to slave side. The operating force on slave side should be transmitted to surgeon's hands directly, which plays an overwhelming role in ensuring the safety of a vascular interventional surgery. According to the surgeon's operating information, the slave controller controls the slave manipulator to insert the surgical catheter into the blood vessel. The slave controller can also acquire the contact force between the catheter tip and blood vessel and send it to master side at the same time.

### B. Design of the master manipulator

In our design, the surgeons will operate a real catheter as conventional catheter interventional surgery on the master side. There are two main tasks in the designing of the mechanism. The first one is to obtain the motion of the catheter, which is produced by the operation of surgeon. The other one is to transmit the operating force to surgeon's hands directly. The force is generated when the slave manipulator drives the catheter to insert into blood vessel. The designed master mechanism is shown in Fig.3. Compared with the developed master-slave robotic catheter system in our previous study, which can simulate surgeon's operating skill to insert and rotate catheter [2], [13], the best advantage of this system is that the surgeon can operate a real catheter. The novel system accords with the requirements of ergonomic and can make full use of natural catheter manipulation skills obtained in conventional catheter navigation.

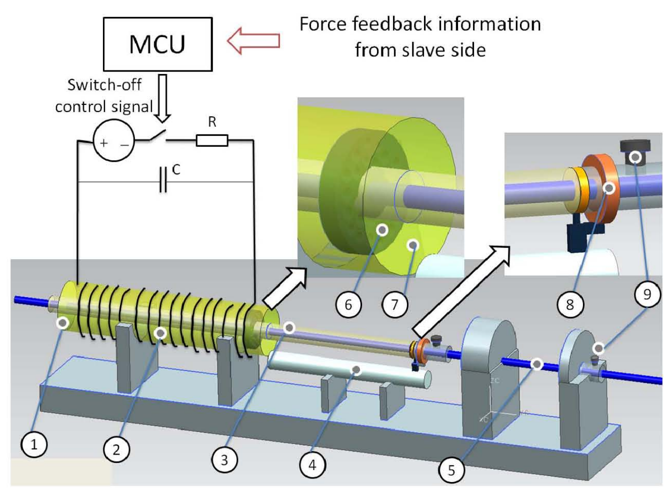


Fig.3 Mechanism of master manipulator: (1) Piston cylinder (2) Conducting wire coil (3) Catheter over-tube (4) Linear displacement sensor (5) Catheter (6) Piston with holes (7) Magnetorheological fluid (8) Optical encoder (9) Clutch

The greatest feature of master mechanism is the piston structure with magnetorheological fluid (MRF), which is used to achieve force feedback. It can transmit the operating force that the slave manipulator drives the surgical catheter to surgeon's hands. MRF is a smart material, and it is in the free flowing liquid state when magnetic field is absence. The main characteristic of MRF is its ability to change reversibly from free-flowing, linear viscous liquids, to semi-solids with the yield strength swiftly and continuously controllable (milliseconds scale dynamics) when exposed to a magnetic field [14]. Because the viscosity of the MRF can be controlled by applying an external magnetic field, MRF is applied into dampers, resistive force devices and so on [15]. According to the characteristics, a piston structure was designed. The piston with lots of holes is fixed together with a catheter over-tube. The conducting wire coil will be wrapped around the piston cylinder filled with MRF, as is shown in Fig.1. Different current will be produced in the coil when the electrical switch get different on-off signal from master controller. Then the MRF will have different viscosity, and different resistance will be applied to the piston when it moves in the cylinder. Two clutches have been designed in master mechanism, and only one will be used to fix the catheter at a time. When the piston is located at the end of cylinder, the clutch in the front will fix the catheter on catheter over-tube. Then the piston will move with catheter under the operation of surgeon. According to the force feedback information from slave side, the master controller controls resistance of the piston with giving the electrical switch different on-off signal. The changeable resisting force will be transmitted to surgeon's hands, and the surgeon could feel the driving force information on master side through his hands as a conventional catheter interventional surgery. When the piston reaches to the tip of cylinder, the back clutch will fix the catheter on frame, and the front clutch will be out of working. Then we can adjust the piston to the end of cylinder through operating catheter over-tube.

On the master side, the motion of the catheter operated by surgeons has two degrees of freedom, one is axial motion, and the other is radial motion. In order to acquire the axial motion of the catheter, a linear displacement sensor has been adopted, which use a floating magnetic block with non-contact as the sliding end. Therefore, the sliding end will be moved without any fraction. Through the output voltage the location of the block can be obtained. The connection of linear displacement sensor and catheter over-tube is shown in Fig.4. An annulus connected with the sliding end is embedded into the catheter over-tube. Then the sliding end can move forward and back-ward as catheter over-tube moves and will not affect the rotation of the catheter over-tube.

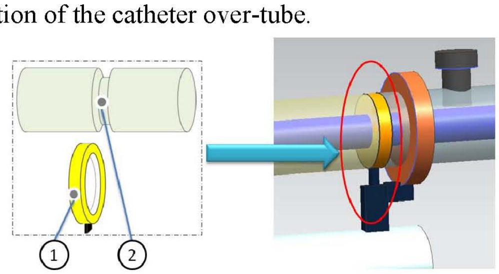


Fig.4 Connection of Linear displacement sensor and catheter over-tube: (1) Annulus on sliding end of linear displacement sensor (2) Groove on catheter over-tube

In order to get the radial motion of master catheter, a photoelectric encoder was designed in master mechanism. The body of photoelectric encoder will be linked to the sliding end of linear displacement sensor and code disk of it will be located on catheter over-tube, as is shown in Fig.5. Then it can move forward and backward with the sliding end and detect the rotation of over-tube.

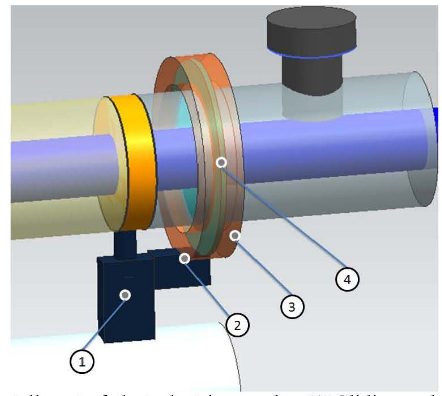


Fig.5 Installment of photoelectric encoder: (1) Sliding end of linear displacement sensor (2) Connect part (3) Body of photoelectric encoder (4) Code disk of photoelectric encoder

## C. *Design of the slave manipulator*

The slave manipulator inserts the surgical catheter into blood vessel under the control of slave controller. Surgical catheter moves forward and backward in general situation. When the branch of blood vessel or moving difficulty appears, the catheter must be rotated. The motion of the surgical catheter follows the surgeon's operation on master side. The design of slave mechanism is shown in Fig.6.

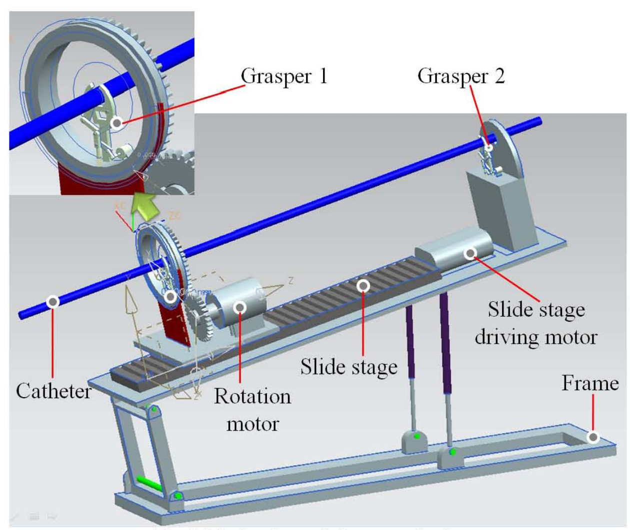


Fig.6 Mechanism of slave manipulator

The slide platform is fixed on the supporting frame. A motor is used to drive slide platform to move forward and backward, the position of slide platform is determined by the position of the piston on master side. Two graspers have been designed to simulate the surgeon's grasping action. Grasper 1 is located at a rotation ring. The ring can rotate around the semicircular base fixed on the slide platform. Grasper 2 is fixed on the frame of slave side. The structure of grasper is shown in Fig.7. The grasping action is achieved through the up-down motion of moving terminal. A stepping motor is used to realize the up-down motion, and the drive principle is shown in Fig.8. The manipulator can drive the catheter to move along both axial and radial directions, when the catheter is clamped by grasper 1. The catheter keeps its position and the catheter driven part can move smoothly when the catheter is clamped by grasper 2. The selected grasper used for clamp the catheter is related to the two clutches on master side. Semicircular base moves forward and backward with slide platform to drive catheter moving in axial direction. And rotating ring rotates through gear transmission with a rotation motor to drive catheter moving in radial direction. Slave frame can be adjusted easily to change the interventional angle in our design.

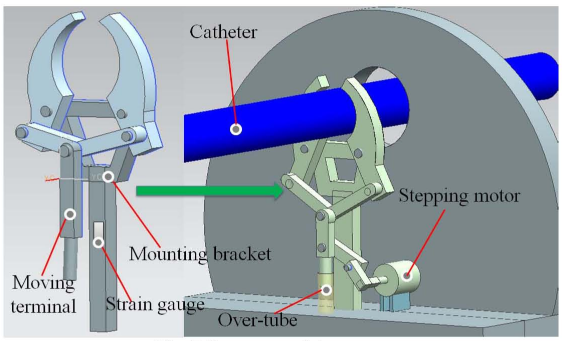

Fig.7 Structure of the grasper

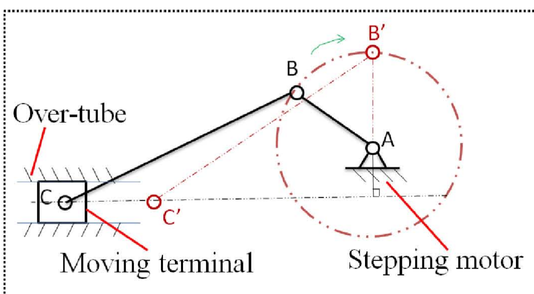

Fig.8 Drive principle of the moving terminal

In order to get the driving force of the slave manipulator, a strain gauge will be fixed on the mounting bracket of grasper 1, as is shown in Fig.7. Mounting bracket of the grasper will be made of the material which has a certain degree of flexibility, so that the driving force could make the mounting bracket produce a deformation. Then strain gauge can detect the deformation and get the driving force. The clamping force of graspers on slave side is vital to avoid being damaged for the surgical catheter. The step motors used to drive the graspers must have a high precision, with which we can control the clamping angle precisely. Experiments will be carried out to obtain the smallest force of the graspers. The clamping force can drive the catheter to move forward and backward without any relative movement. In order to get real-time clamping force, contact force sensors will be fixed on the graspers.

The contact force between the catheter tip and blood vessel is vital to improve the safety of the vascular interventional surgery. To obtain the contact information, a novel type of catheter sidewall tactile sensor array was developed in our previous research [16]. And the relationship between the contact area and the conductivity was analyzed using finite element analysis method [17]. The obtained contact information on the slave side will be transmitted to the master side

## III. Communication and Control Strategy for the Robotic Catheter System

### A. *Communication method in this system*

Communication is an important part in the master-slave system. The communication method taken in this design has been verified in previous study [18]. And the sketch map is shown in Fig.9.

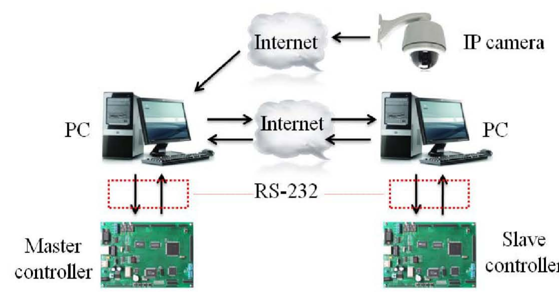

Fig.9 The sketch map of communication

The surgical catheter follows the motion of master catheter operated by the surgeon. Therefore, the surgeon could operate the system smoothly and easily. Both master side and slave side employ two pieces of DSPs as their controllers. An internet based communication is built between the master DSP controller and the slave DSP controller. Serial communication is adopted between PC and controller. Through the Internet communication, the control commands can be transmitted from the master side to the slave side, at the same time the feedback information can be transmitted from the PC of the slave side to the PC of the master side. And the monitoring image gained by IP camera will be transmitted to the surgeon.

### B. *Control strategy for this system*

Control strategy is vital for the robotic catheter system, which can influence the stability and instantaneity of the system The devices that need to be controlled include an electrical switch on master side and four motors on slave side. The current in the conducting wire coil have a linear relationship with On-off duty cycle of electrical switch The control of electrical switch is simple, so the desired current can be obtained easily. What we should consider more is the control of motors. The digital PID is used as the control method to ensure the accuracy of inserting motion on slave side. Principle diagram of digital PID control is shown in Fig.10, where y is our desired output, y(k) is the actual output at the time of kT. DA converter isnot needed when the motor is step motor.

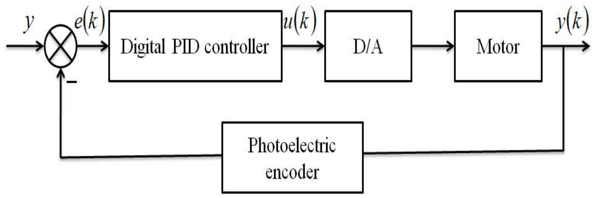

Fig.10. Principle diagram of digital PID control

A desired output is necessary when the PID method is applied. The desired outputs of the two motors used for graspers are the smallest clamping force, which will be gained through experiments. The other desired outputs of two motors are the position of master catheter operated by the surgeon in real-time. Each of the motors has its own photoelectric encoder, so we can get the rotation information of the motor easily. The input of PID controller is real-time error, as is shown in equation (1).

$$e(k) = y - y(k) \quad (1)$$

where y is the desired output, y(k) is actual output, e(k) is the error between desired output and actual output at the time of kT. Equation (2), (3) are outputs of PID controller at the time of kT and (k-1)T.

$$u(k) = K_p\left[e(k) + \frac{1}{T_I}\sum_{i=0}^{k} e(i)\times T + T_D\frac{e(k)-e(k-1)}{T}\right] \quad (2)$$

$$u(k-1) = K_p\left[e(k-1) + \frac{1}{T_I}\sum_{i=0}^{k-1} e(i)\times T + T_D\frac{e(k-1)-e(k-2)}{T}\right] \quad (3)$$

where u(k) is the output of PID controller at the time of kT, T is sampling period, $K_P$ is constant of proportionality, $T_I$ is constant of integral time, $T_D$ is constant of derivative time. Equation (4) and (5) show the relationship between u(k) and u(k-1).

$$\begin{aligned} u(k)-u(k-1) &= K_P\left[e(k)-e(k-1)+\frac{T}{T_I}e(k)+T_D\frac{e(k)-2e(k-1)+e(k-2)}{T}\right] \\ &= K_P\left(1+\frac{T}{T_I}+\frac{T_D}{T}\right)e(k)+K_P\left(-1-\frac{2T_D}{T}\right)e(k-1)+K_P\frac{T_D}{T}e(k-2) \\ &= a_0e(k)+a_1e(k-1)+a_3e(k-2) \end{aligned} \quad (4)$$

$$u(k) = u(k-1) + a_0e(k) + a_1e(k-1) + a_2e(k-2) \quad (5)$$

where $a_0$ is $K_P(1+T/T_I+T_D/T)$, $a_1$ is $K_P(-1-2T_D/T)$, $a_2$ is $K_PT_D/T$. Therefore, we can get the output of the digital PID rapidly, which will improve the control efficiency and reduce the time delay.

## IV. Feasibility Analysis of the Designed Manipulators

After the mechanism design, feasibility analysis of the system is necessary.

### A. *Feasibility analysis of the designed master manipulator*

On the master side, there are two problems we should consider seriously. One is whether the motion (axial motion and radial motion) of master catheter could be acquired accurately, and the other is whether the catheter driving force on slave side could be transmitted to surgeon's hands as force feedback.

The linear displacement sensor in our design uses a floating magnetic block with non-contact as sliding end, so no friction will be produced when the sliding end moves. The body of photoelectric encoder (Weighs about 100g) is fixed on the sliding end (Weighs about 10g). Pushing and pulling the sliding end and the body of photoelectric encoder on the track produce no friction. Then the detect devices can move with the catheter easily and the motion information can be detected effectively.

In our system, a piston structure has been designed to realize the force feedback. The changeable resistance of piston will be transmitted to surgeon's hands as the direct force feedback. Catheter over-tube drives the piston to move along radial direction in the cylinder filled with MRF, which forces the MRF to flow through the holes of the piston. When the magnetic field is absence (i.e., zero magnetic field), MRF exhibits Newtonian-like behavior. When MRF is given a magnetic field, it can converts from Newton-like fluid into viscoplastic instantly. The viscosity increases in order of magnitude, and flow resistance of the fluid increases rapidly, which can be treated as Bingham fluid, as is shown in equation (6)

$$\tau = \tau_y(H)\times \mathrm{sgn}\left(\frac{du}{dy}\right) + \eta\times\left(\frac{du}{dy}\right) \quad (6)$$

where $\tau$ is shear stress, $\tau_y(H)$ is the field dependant yield stress, $\eta$ is the newtonian viscosity, and du/dy is the velocity gradient in the direction of the field. First of the right equation called Coulomb shear stress, and the second is called viscous shear stress. Shear stress could produce viscoplastic flow and form the Coulomb shear stress only on the condition of reaching the MRF yield shear stress. Moreover, $\tau_y(H)$ associates with the magnetic field strength, and changes with the magnetic field strength. Therefore, the yield shear stress can be controlled by the magnetic field. In our design, a conducting wire coil is used to generate the changeable magnetic field. So the goal of our design can be realized.

### B. *Feasibility analysis of the designed slave manipulator*

The slave manipulator inserts the surgical catheter into the blood vessel. The goal of the designed system is to realize that surgeon appears to operate the catheter as though adjacent to the patient. Therefore, the driving force should be acquired and sent to master side, and the motion of the slave catheter should follow the master catheter with a high degree of accuracy.

To get the driving force, mounting bracket of grasper 1 was designed using a material which has a certain degree of flexibility, and a strain gauge will be fixed on it. Strain gauge selected for the designed system has a high level of sensitivity. Then a slight deformation of the mounting bracket will be acquired. And the driving force could be figured out with the output of strain gauge.

Two problems about the accuracy of slave manipulator following the master manipulator need to be solved. One is the control accuracy of the driving motors, the other one is time delay in communication. Previous study has verified that time delay of communication can be ignored. Control accuracy of the driving motors is mainly determined by the control algorithm and sampling frequency. With strong data processing ability of DSP controller and digital PID control algorithm, the control accuracy of driving motors could be solved.

## V. Conclusion and Future Work

In order to improve the safety of the catheter interventional surgery and protect the surgeons from radiating of X-ray, a novel master-slave robotic catheter system was proposed in this paper. Based on the analysis of the designed system, the following conclusions can be drawn:

1) Mechanism and principle of the master-slave robotic catheter system was described in details. According to the design, the slave manipulator could follow the operation of the master manipulator.

2) This system was designed in accordance with the requirements of ergonomic, which allowed the surgeon to operate a real catheter on master side.

3) Based on the principle of magnetorheological fluid, the piston structure filled with magnetorheological fluid could be used to transmit the driving force to surgeon's hand as force feedback effectively.

4) Communication method introduced in this paper has been applied into practice in our previous research.

5) The analyzed results of the designed system confirmed the validity of the proposed robotic catheter system for intravascular interventional surgery.

In future work, we will realize the designed master-slave robotic catheter system. Experiments will be carried out to verify the designed system.

## Acknowledgment

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## References

[1] H. Zhao and X. Duan, "Design of a Catheter Operating System with Active Supporting Arm for Vascular Interventional Surgery," 2011 Third International Conference on Intelligent Human-Machine Systems and Cybernetics, pp. 169-172, 2011.

[2] J. Guo, S. Guo, N. Xiao, X. Ma, S. Yoshida, T. Tamiya and M. Kawanishi, "A Novel Robotic Catheter System with Force and Visual Feedback for Vascular Interventional Surgery," International Journal of Mechatronics and Automation, vol. 2, no. 1, pp. 15-24, 2012.

[3] H. Zhao, X. Duan, Q. Huang, X. Wang, Y. Chen and H. Yu, "Mechanical Design and Control System of Vascular Interventional Robot," Proceedings of the 2011 IEEE/ICME International Conference on Complex Medical Engineering, pp. 357-362, 2011.

[4] J. Zhang, C. Meng, Y. Ma, B. Liu and F. Zhou, "Catheter Localization for Vascular Interventional Robot with Conventional Single C-arm." Proceedings of the 2011 IEEE/ICME International Conference on Complex Medical Engineering, pp. 159-164, 2011.

[5] G. Liang and Y. Xu, "Mechanism Design of a Medical Manipulator for Vascular Interventional Surgery," Proceedings of the 2011 IEEE International Conference on Mechatronics and Automation, pp. 2291-2296, 2011.

[6] Y. Fu, H. Liu, W. Huang, S. Wang, and Z. Liang, "Review of steerable catheters in minimally invasive vascular surgery," Int J Med Robotics Comput Assist Surg, pp. 381–391. 2009.

[7] X. Wang, X. Duan, Q. Huang, H. Zhao, Y. Chen and H. Yu, "Kinematics and Trajectory Planning of a Supporting Medical Manipulator for Vascular Interventional Surgery," Proceedings of the 2011 IEEE/ICME International Conference on Complex Medical Engineering, pp. 406-411, 2011.

[8] M. Tanimoto, F. Arai, and T. Fukuda, "Telesurgery System for Intravascular Neurosurgery," Medical Image Computing and Computer-Assisted Intervention - MICCAI, pp. 29-39, 2000.

[9] Y. Fu, A. Gao, H. Liu, S. Guo, "The master-slave catheterization system for positioning the steerable catheter," International Journal of Mechatronics and Automation," vol. 1, no. 2, pp. 143-152, 2011.

[10]W. Feng, C. Chi, H. Wang, K. Wang, X. Ye and S. Guo. "Highly Precise Catheter Driving Mechanism for Intravascular Neurosurgery." Proceedings of 2006 IEEE International Conference on Mechatronics and Automation, pp 990-995, 2006.

[11]H. Zhao, X. Duan, H. Yu and X. Wang, "A New Tele-operating Vascular Interventional Robot for Medical Applications," Proceedings of the 2011 IEEE International Conference on Mechatronics and Automation, pp. 1798-1803, 2011.

[12]C. Payne, H. Tari and G. Yang, "A Force Feedback System for Endovascular Catheterisation," 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1298-1304, 2012.

[13]J. Guo, S. Guo, N. Xiao, X. Ma, S. Yoshida, T. Tamiya, and M. Kawanishi, "A New Master-slave Robotic Catheter System," Proceedings of the 2011 IEEE/ICME International Conference on Complex Medical Engineering, pp. 610-613. 2011.

[14]B. Kasemi, A. Muthalif, M. Rashid and M. Rahman, "Optimizing Dynamic Range of Magnetorheological Fluid Dampers: Modeling and Simulation," 2011 4th International Conference on Mechatronics (ICOM), pp. 1-4, 2011.

[15]Y. Sato and S. Umebara, "Power-Saving Magnetization for Magnetorheological Fluid Control Using a Combination of Permanent Magnet and Electromagnet," IEEE TRANSACTIONS ON MAGNETICS, vol. 48, no. 11, pp. 3521-3524, 2012.

[16]J. Guo, S. Guo, P. Wang, W. Wei and Y. Wang, "A Novel Type of Catheter Sidewall Tactile Sensor Array for Vascular Interventional Surgery," Proceedings of the 2013 ICME International Conference on Complex Medical Engineering, pp. 264-267, 2013.

[17]S. Guo, Y. Gao, J. Guo, Y. Ji and Y. Wang, "Characteristics Evaluation of a Pressure Sensitive Rubber-based Tactile Sensor," Proceedings of the 2013 ICME International Conference on Complex Medical Engineering, pp. 249-253, 2013.

[18]N. Xiao, S. Guo, B. Gao, X. Ma, T. Tamiya and M. Kawanishi, "Internet-based Robotic Catheter Surgery System -System Design and Performance Evaluation," Proceedings of the 2012 IEEE International Conference on Automation and Logistics, pp. 645-651, 2012.