Microsyst Technol
DOI 10.1007/s00542-015-2659-4

TECHNICAL PAPER

Design and performance evaluation of a novel robotic catheter system for vascular interventional surgery

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Received: 26 March 2015 / Accepted: 11 August 2015

Abstract Vascular interventional surgery (VIS) is an effective treatment method for vascular diseases. However, there are many problems in traditional VIS, such as surgeons are radiated by X-ray, the lack of well skilled surgeons, the security of the surgery will be reduced due to the Surgeons' fatigue, high risk of the surgery. To solve these problems, a robotic catheter system is needed to protect the surgeons and enhance the safety of the surgery. In this paper, a novel robotic catheter system with master–slave structure for VIS has been developed. This system is designed with the consideration of the operation method in traditional VIS, which allows the surgeon to operate a real catheter on the master side, then the surgeon make full use of the natural catheter manipulation experience and skills obtained in conventional catheter operation. The salve manipulator operates the catheter insert into the blood vessel with following the operation of the surgeon, and the operating force of the salve manipulator is detected. On the master side, a novel damper-based magnetorheological (MR) fluid is designed to realize the force feedback, which is also used to reappear the operation force from the salve manipulator. The damper connected directly with real catheter is a piston structure using the MR fluid to realize the force feedback. It can transmit the feedback force to surgeon's hand through the operating catheter connected with damper, which seems that the surgeon operates the catheter beside the patient. The operating transparency of the developed system has been enhanced. The mechanism of the developed system has been introduced in detail. Performance evaluation experiments for the developed robotic catheter system have been done. The experimental results indicated that the developed robotic catheter system is fit for VIS.

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1 Introduction

Vascular diseases have become one of the most serious threaten to human health, the statistics of the World Health Organization show that more than 17 million people died of vascular disease each year. And vascular interventional surgery (VIS) is an effective treatment method for vascular diseases (Zhao and Duan 2011; Zhao et al. 2011; Guo et al. 2012). Because of its smaller incisions, less blood loss, decreased pain and quicker recovery, VIS has been widely adopted all over the world (Fu et al. 2011a). However, there are many problems in traditional VIS, such as surgeons are radiated by X-ray (Mohapatra et al. 2013; Kim et al. 2012), the lack of well skilled surgeons (Zhang et al. 2011), the security of the surgery will be reduced due to the Surgeons' fatigue, high risk of the surgery. In order to solve these problems, an efficiency tele-surgery system should be adopted, which can assist the surgeon to operate

Published online: 04 September 2015

the catheter interventional from a safe space (Tanimoto et al. 2000; Liu et al. 2011).

In recent years, a lot of medical and surgical robots have been applied with the development of technology, and most of the robots system currently used in surgery contain master and slave side (Simorov et al. 2012; Gomes 2011). Among the surgical robots, the vascular interventional robot has become a promising technology (Lu et al. 2013; Li et al. 2013; Antoniou et al. 2011). Many research teams around the word focus on the study of robotic catheter operation systems for vascular interventional surgery. A master–slave remote controlled vascular interventional robot assisting doctor was designed (Cao et al. 2014). Tercero et al. (2013) have presented a novel method for force feedback in tele-operative endovascular surgical simulators. Fu et al. (2011b) reported a master–slave catheterization system which including the steerable catheter integrated with two magnetic tracking sensors, interventional mechanisms with force feedback and 3D guiding image with the collision test. A network-based master–slave system with a 3-degree of freedom robotic manipulator for operation conventional cardiac ablation catheter has been developed (Park et al. 2010). Srimathveeravalli et al. (Srimathveeravalli et al. 2010) have designed and fabricated a robotic mechanism for remote steering and positioning of interventional devices. A robotic system was developed by Kesner et al. (2011), which can servo the catheter inside the heart with a control system that utilizes 3D ultrasound information and force feedback. Feng et al. (2006) presented a highly precise catheter driving mechanism for intravascular neurosurgery. Zakaria et al. (2013) developed a catheter guide system with force feedback using ER fluid, and this system can avoid system malfunction or human error. 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. However, these systems also have many disadvantages. Firstly, the axial motion of the catheter is almost realized by the friction of wheels. And the friction between the wheels and catheter may bring damage to the catheter. The impaired catheter could cause 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 (Payne et al. 2012). And the surgeons do not really manipulate a catheter, which removes some of the important tactile cues required in conventional catheter interventional surgery. What's more, to realize the force feedback with motors have the force of inertia, which cannot provide an accurate force feedback to the operator in real time.

In this paper, we developed a novel master–slave robotic catheter system with true force feedback to the surgeon's hands. During the interventional surgery, the developed system allows surgeons to operate a real catheter at the master side, and the operating information will be transmitted to the slave controller. Then the slave controller controls the slave manipulator to insert the catheter into the blood vessel during VIS. The insertion force of the slave manipulator will be acquired and transmitted to master side. A damper is designed to realize the operating force feedback of the salve manipulator based on the intelligent fluid magnetorheological (MR) fluid. It can transmit the force feedback to surgeon's hands through the operation catheter under the control of master controller. Evaluation experiments for force feedback of the MR fluid damper, movement tracking of the master–slave system have been done. The results of experiments indicated that the developed robotic catheter system is fit for vascular interventional surgery.

2 Structure design of the master–slave system

The developed master–slave robotic catheter system is according with ergonomic compared with existing systems. The surgeon can operate a real catheter directly, and the feedback force can be transmitted to the surgeon's hand through the catheter, which is similar conventional catheter operation in VIS. This system can avoid human operation errors or system failures. In this section, the designed system will be introduced in details.

2.1 Design requirements and description of the robotic catheter system

The major design requirements were: (1) tele-operation, (2) ergonomic, (3) acquirement of the surgeon's operation, (4) insert operation of the surgical catheter, (5) surgical catheter operating force detect, (6) surgical catheter operating force feedback, (7) safety.

1. *Tele-operation* Since the catheter is inserted to the blood target under fluoroscopic guidance, doctors have to operate the surgery in X-ray environment, which may lead to severe injury. Tele-operation is an important method for solving this problem. On other hand, tele-surgery can relieve the stress of lack of well-skilled doctors in some remote regions.

   A conceptual diagram of the master–slave robotic catheter system is shown in Fig. 1. To protect the surgeon from the radiation of X-ray, the surgeon can tele-operate the VIS in a secure area on master side. The operating information is acquired and transmitted to the slave side. Once receiving the operating information,

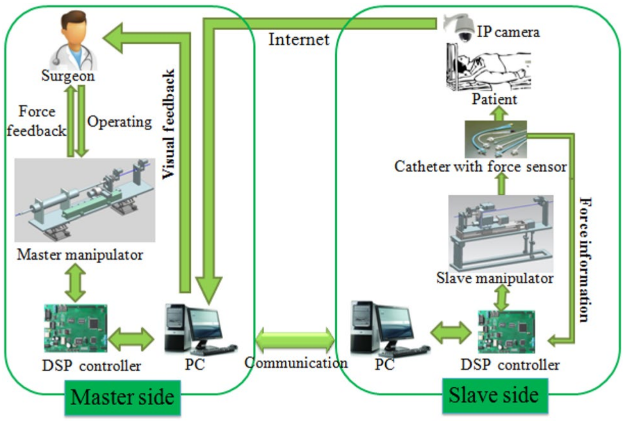


Fig. 1 The conceptual diagram of the robotic catheter system

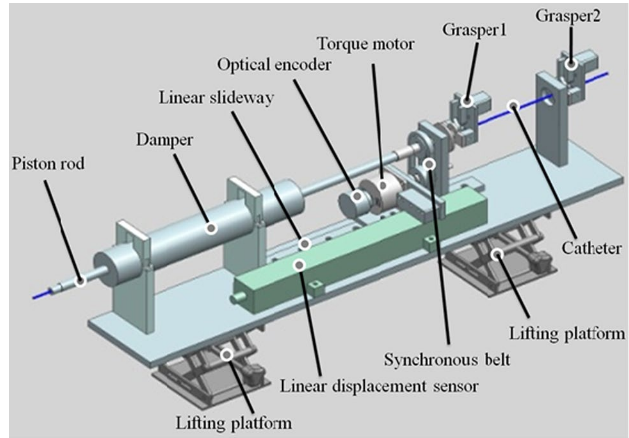


Fig. 2 The master manipulator

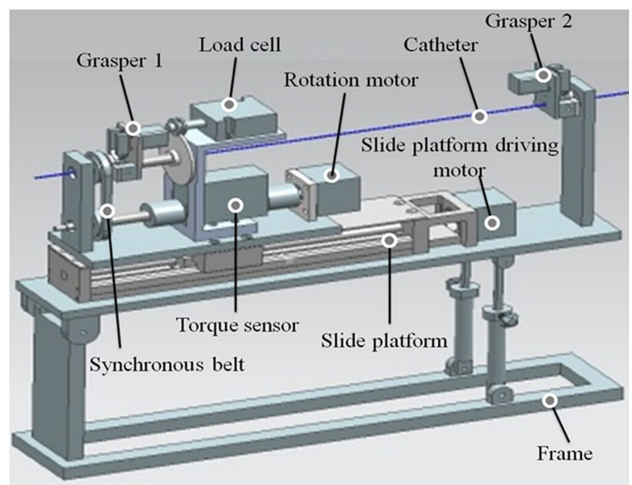


Fig. 3 The slave manipulator

the slave manipulator 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 get the image of the operation site as 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.

2. *Ergonomic* In conventional vascular interventional surgery, the surgeon operates the surgical catheter directly to insert into the blood vessel. Only well-skilled surgeons have the ability to do the high risk surgery. The surgeons accumulated lots of natural catheter manipulation skills through experiences and utilized by operators in conventional surgery. In order to use these skills into tele-operated surgery, the design of master manipulator must allow the operator to operate a real catheter.

   The diagram of our designed master manipulator is shown in Fig. 2. The surgeon can operate a real catheter, which is similar to conventional catheter navigation. The surgeon also feels the tactile feedback with the operated catheter. Then the make full use of the manipulation skills obtained in conventional surgery.

3. *Acquirement of the surgeon's operation* On the master side, the motion of the catheter operated by surgeon has two degrees of freedom, one is axial motion, and the other is radial motion.

   As is shown in Fig. 2, a linear displacement sensor has been adopted to acquire the axial motion of the catheter. The linear displacement sensor uses a floating magnetic block with non-contact as the sliding end. Therefore, the sliding end will be moved without any fraction. The output voltage the sensor has a linear relationship with the location of the sliding end. The linear displacement sensor is installed on the installation board of the lifting platform, and the sliding end is installed on an adapter plate of the linear sideway. The sliding end and piston rod of the damper have synchronous movement. During the catheter operation, the catheter and piston rod are fixed together through grasper1. Then motion of the sliding end equals to the axial motion of the catheter. Therefore, the output voltage the linear displacement sensor can be used to reflect the axial movement of the catheter.

   A torque motor, which is used to realize the radial force feedback, connects with the piston rod through a synchronous belt. So the torque motor and the piston rod have the same rotation angle. Therefore, the optical encoder which installed on the torque motor can get detect the radial motion of the catheter.

4. *Inserting operation of the surgical catheter* The slave manipulator inserts the surgical catheter into blood ves-

sel 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. 3.

The supporting frame can adjusted easily to change the interventional angle. The slide platform is installed on the on the supporting frame, and it can be driven to move forward and backward by a motor. Two graspers have been designed to simulate the surgeon's grasping action. All the graspers on master side and slave side have the same structure, and the clamping force of the grasper can be adjusted. Compared with the previous grasper using roller friction method, the novel grasper can clamp the catheter tightly without relative sliding. The manipulator can drive the catheter to move along both axial and radial directions, when the catheter is clamped by grasper1. The grasper1 clamps the catheter just as the surgeon's hand, and the slide platform imitates the pushing and pulling motion of the surgeon. 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 graspers on master side. To realize axial movement, all catheter driven parts are placed and fixed on slide platform. The slide platform is driven by a screw which is driving by a stepping motor (slide platform driving motor in Fig. 3). The rotation motor drives the catheter to move in radial direction through the synchronous belt.

5. *Surgical catheter operating force detect* The detecting of surgical catheter operating force is an important task of the slave manipulator. It is the base of force feedback on master side. The slave manipulator operates the catheter move in axial and radial directions, so the operating force also contains axial driving force and rotation torque. A load cell is adopted to detect the axial driving force of the slave manipulator. As is shown in Fig. 4, the load cell is fixed on the slide platform. A clamp plate installed on the detecting shaft of the load cell is linked to the plate which is stalled on the axle of grasper1. The axle of grasper1 is supported by two bearings. The clamp plate doesn't affect the rotating motion of the plate. When graper1 clumps the catheter to move on axial direction, the counter-acting force of the catheter applying to graper1 will lead to the micrometric displacement of the axle of grasper1. And micrometric displacement will affect the clamp plate, and then the counter-acting force is acquired by the load cell.

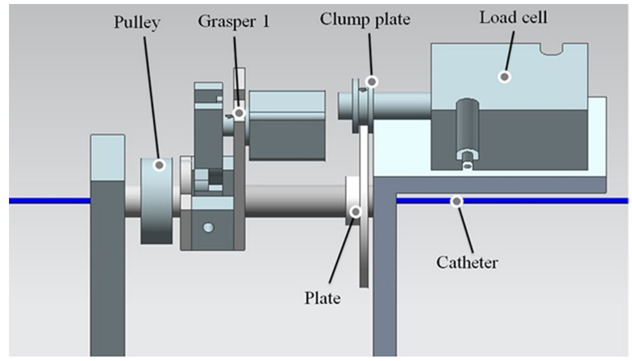


Fig. 4 Axial driving force measurement mechanism

As is shown in Fig. 3, the torque sensor is linked to the output axle of the rotation motor is used to measure the torque information. The output torque of the rotation motor is transmitted to the grasper1 through torque sensor and coupled pulleys, and the grasper1 drives the surgical catheter rotation in the blood vessel. The torque sensor can get a torque when the surgical catheter is absence. And the real torque of rotating the catheter is the difference between the output of torque sensor the in real time and the output when the surgical catheter is absence. The torque information will be sent to the master side and generate a torque feedback to the surgeon.

6. *Surgical catheter operating force feedback* Force feedback is an important part of a tele-operating robotic system. In our design, the operating force feedback to the surgeon through the catheter which is operated by the surgeon. The feedback force contains axial operating force and rotation torque. The damper with MR fluid is used to realize the axial operating force. The damper is a piston structure with MR fluid, as is shown in Fig. 5. The MR fluid is in the free flowing liquid state when magnetic field is absence. But it can 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 (Kasemi et al. 2011). The viscosity of the MR fluid can be controlled by applying an external magnetic field. The MR fluid damper contains polyurethane foam soaked and saturated in MR fluid and wound around an electromagnetic piston. When different current flow in the coil, different magnetic will produce. And the green line in Fig. 6 shows the direction of the magnetic field. Then different shearing resistance will be applied to the piston body when it moves. Grasper1 connects to the piston rod with nipple joint. When the catheter was clamped by grasper1, the piston rod and catheter were fastened together. Then the damping force of damper could be

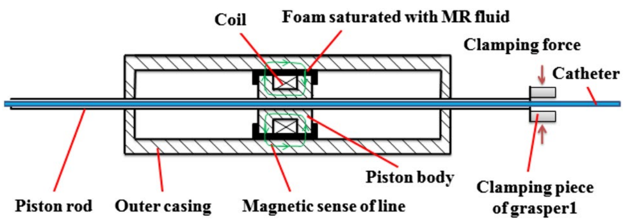


Fig. 5 The realization of axial force feedback

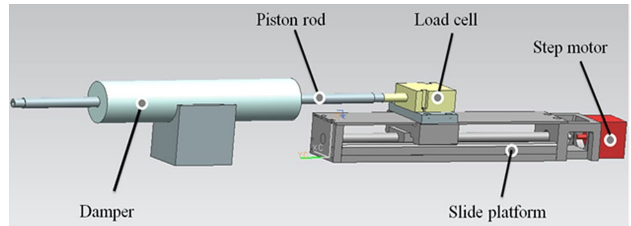


Fig. 6 The calibration theory sketch of the MR fluid damper

transmitted to the surgeon's hand witch operating the catheter.

The rotation torque was realized with the torque motor, as is shown in Fig. 2. The connection between the torque motor and the piston rod is a synchronous belt. Then the output of the torque motor could be transmitted to the surgeon's hand through the catheter which was fastened together with the piston rod by grasper1.

7. *Safety* As the system inserts the catheter into the blood vessel of the patients, safety should be considered first. During the VIS, surgeons must avoid mangling the brittle blood vessel. In conventional VIS, well-skilled surgeons judge the contact information between the catheter and blood vessel by the feeling of their hands which operate the surgical catheter. But in a tele-operated system, the operator couldn't get this feeling, it's vital to detect the contact information and present to the operator in real time so as to improve the safety of the surgery. In our design, an optical fiber force sensor was installed on the catheter tip to detect the contact force between the catheter tip and blood vessel. A novel 3 × 3 tactile sensor array with pressure sensitive rubber was designed and developed to acquire the contact information between the catheter sidewall and blood vessel (Guo et al. 2013). The tactile sensor array can get the contacting information which contains magnitude of the contact force and position information.

   This system designed with the consideration of the possibility of human error and system malfunction during operation. As the surgeon manipulates the master manipulator on master side, the axial displacement and rotation of master catheter are acquired and analyzed. When the axial displacement and rotation speed of master catheter exceed the safe range which are caused by human error and system malfunction, the system will cut-off the motion control command.

2.2 Operating methodology of the master–slave robotic catheter system

The developed system allows the surgeon tele-operate the surgery in a safe space. The catheter on master side and the surgical catheter on slave side have the same motion. Both the master side and the slave side have two graspers, and the graspers on the corresponding position of the master side and slave side have the same clamping action. The two graspers on the same side alternate to clamp the catheter. On the master side, when the grasper1 clamps the catheter and the grasper2 releases, the catheter is connected with the piston rod, and the operator can drive the catheter in both axial and radial directions. And when the piston rod reaches the front of the piston body, the grasper2 clamps the catheter and the grasper1 releases, the grasper2 keeps the catheter still, the operator can drive the piston rod back to the starting position. Similarly, on the slave side, when the grasper1 clamps the catheter and the grasper2 releases, the catheter is fixed with the axial driven module through the grasper1 so that it has the synchronous axial and radial movement with the driven module. When the grasper2 clamps the catheter and the grasper1 releases, the catheter will keep its position and the driven module will return to start the next operation.

With the visual feedback which contains the real time image of the slave side, collision between the catheter tip and blood vessel, contact information between the catheter sidewall and blood vessel, the surgeon operates the catheter on master manipulator. The axial displacement is measured by the linear displacement sensor and the radial motion is detected by the optical encoder. Then the master DSP controller analysis if the operation is false operation or system malfunction. Once the operation is right, the master DSP controller transmits the motion information to the master PC, and the master PC communicate with the slave PC using internet. Then the slave DSP gets the motion information and controls the slave manipulator to insert the surgical catheter into the blood vessel. The slave grasper1 clamps the surgical catheter just as the surgeon's hand,

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.

3 Results and discussion

3.1 Evaluation of the catheter operating force feedback

On the slave side, a load cell is adopted to detect the axial driving force of the slave manipulator. The output of the load cell will be transmitted to master side, then the master manipulator reappear the operating force to the surgeon with a MR fluid damper.

In order to apply the MR fluid damper into the master slave robotic catheter system. The calibration experiments of the damper must be done. The calibration theory sketch map of the MR fluid damper is shown in Fig. 6. The load cell is fixed on the slide platform. The detecting terminal of the load cell connects with the piston rod. The step motor drives the slide platform to make the load cell moving forward or backward with the piston rod. Therefore, the load cell can detect the resistance of the damper when it moves.

To develop an effective MR fluid damper there are a number of parameters should be taken into consideration. According to the compact require of the master manipulator, the stroke of the damper is set as 200 mm. After the experiments, we get other suitable parameters. The gap between the piston body and outer casing is 2 mm. The outer diameter of the damper is 48 mm and the thickness of outer casing is 4 mm. The diameter of piston body is 36 mm. It was coiled with approximately 510 turns of insulated copper wire. The foam saturated with MR fluid was covered on the piston body. The resistance of the MR fluid damper can be controlled by the current, all other parameters left unchanged. The current of the piston coil is supplied by a current control circuit, as is shown in Fig. 7. The input voltage is from a DA output port of master controller. The resistance of resistor R1 can be adjusted. Therefore, the range of the input voltage could be adjusted with resistor R1 when the range of the current in the piston coil is determined.

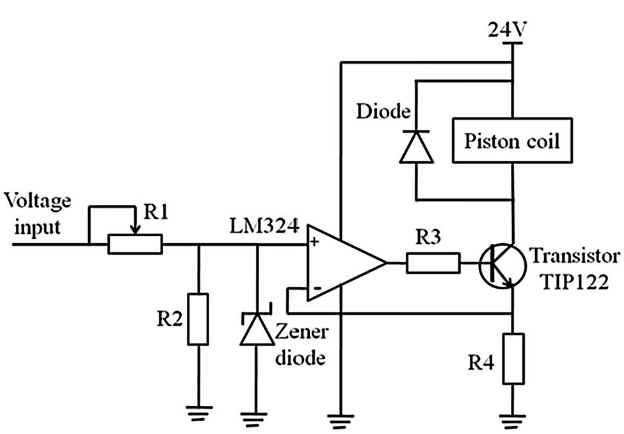


Fig. 7 Electronic diagram of the piston current control circuit

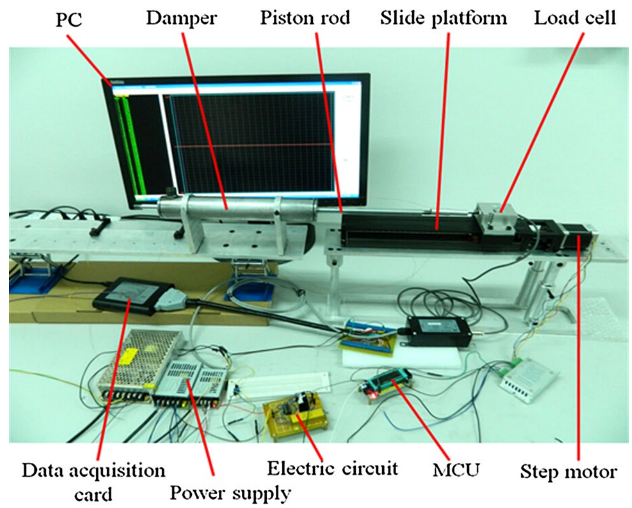


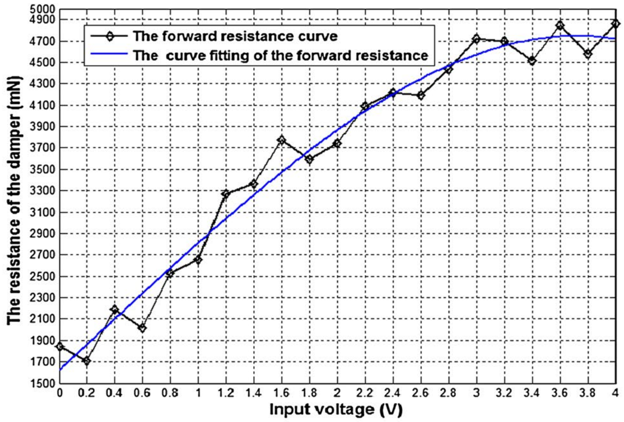
Fig. 8 Calibration system for the developed MR fluid damper

To get the correlation between the input voltage and the resistance, speed of the MR fluid damper, an experimental system was established, as is shown in Fig. 8. The detecting terminal of the load cell connects with the back-end of the piston rod. The load cell can acquire resistance when the step motor drives the slide platform to make the load cell moving forward or backward with the piston rod. The output of the load cell is sent to the PC through a data acquisition card. The MCU is used to control the speed of the step motor. Different current produced in the piston coil with controlling the input voltage of the electronic circuit.

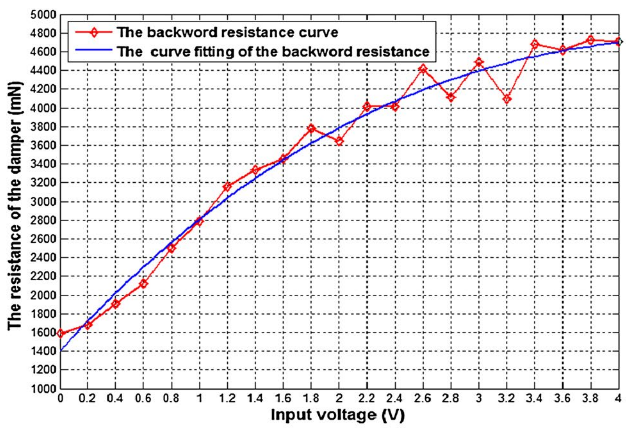
Due to the surgical catheter have low velocities in a vascular interventional surgery. The speed of the slide platform is controlled less than 10 mm/s in our experiments. The experimental result shows that the resistances of the MR fluid damper almost the same with different velocities under 10 mm/s when the current of the piston coil is a constant value.

The output voltages of the load cell were positive values when the piston moved forward, and the outputs were negative values when moved in reverse direction. The correlation between the input voltage and the resistance of the MR fluid damper is shown in Fig. 9. The results indicate that the mean off-state force of the developed MR fluid damper is about 1.6N. The resistance of the damper increased as the input voltage increased. The resistance and the input voltage have a good linear relation.

Based on the data of correlation between the input voltage and the resistance of the damper, the fitting curve equations were established. Compared to other fitting result, quadratic fitting result is better, as is shown in Eqs. (1) and (2). Equation (1) shows the relation when the piston moved forward, and Eq. (2) shows the relation when the piston



(a) The calibration result of the forward resistance



(b) The calibration result of the backward resistance

Fig. 9 The calibration result and curve fitting result for the damper

moved backward. The fitting curve results of the damper are shown in Fig. 9.

$$F_f = -171.25v^2 + 1506.91\text{v} + 1531.31 \tag{1}$$

$$F_b = -184.07v^2 + 1545.76\text{v} + 1430.45 \tag{2}$$

where F_f is the forward resistance, F_b is the backward resistance, v is the input voltage. These equations will be transformed into control algorithm applied in master controller. According to acquired signal of catheter operating force on slave side, the master controller will control the input voltage to realize accurate force feedback with the control algorithm.

After calibration of the MR fluid damper, Evaluation of the catheter operating force feedback experiment was done. As is shown in Fig. 10, The operator operate the surgery on master side, the operating information was gathered and transmitted to slave side, then the slave controller controls the slave manipulator operate the catheter insert into the vascular model. The load cell was adopted to detect

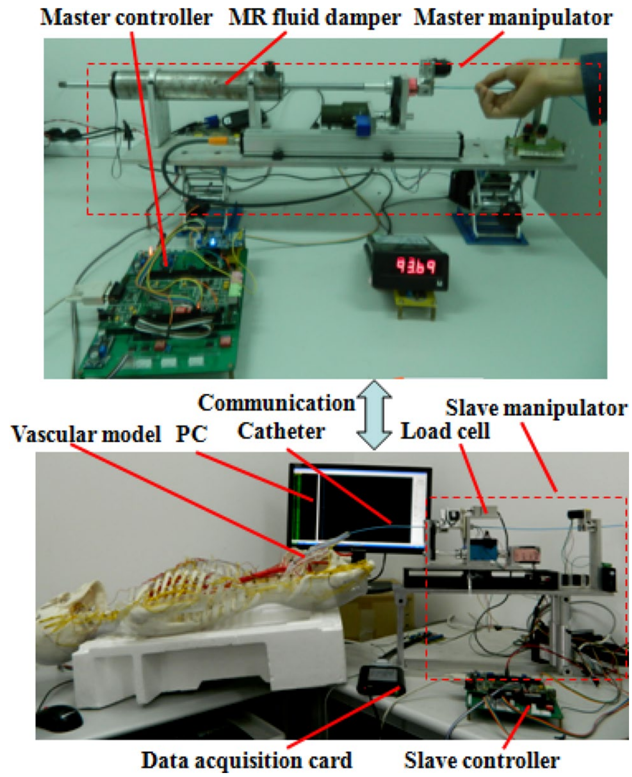


Fig. 10 Evaluation of the catheter operating force feedback

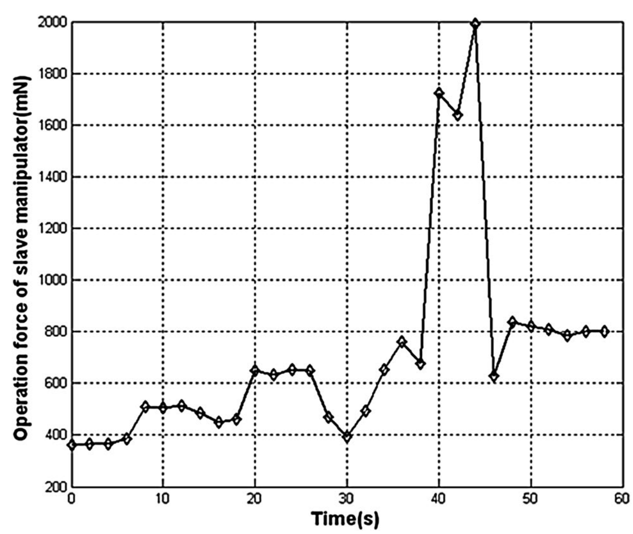


Fig. 11 The output data of the load cell

the axial driving force of the slave manipulator. The master manipulator reappear the operating force to the surgeon with a MR fluid damper according to the output of the load cell.

During the evaluation experiment, to learn about the output of the load cell, a data acquisition card was used to acquire them into the PC. In one operation process, the output data of the load cell is shown in Fig. 11, in normal situation, the operation force increased gradually, but when the catheter reached to the position of the vascular model which has larger bending, the catheter operating force changed larger. The direction of the catheter was adjusted with the rotation operation. And the operating force decreased when the catheter passed the bending of the vascular model.

3.2 Evaluation of movement tracking performance

In this paper, the experiments for evaluating the movement tracking have been done. The block diagram of the movement tracking is shown in Fig. 12. On the master side, to reduce the amount of data which need to be transferred to slave side, the acquired motion information data of the master catheter were preprocessed and integrated.

The slave manipulator operates the surgical catheter to move following the master catheter which operated by the surgeon on master side. As is shown in Fig. 13, on the master side, the axial movement of the master catheter is acquired into the master controller by the linear displacement sensor. And displacement could be read from the digital display meter. The optical encoder is used to detect the rotation of the master catheter. The orthogonal pulses of the optical encoder were input the master controller and the MCU. The MCU board can figure out and display the rotation angle in real time.

In order to get the performance of the axial movement tracking, a laser displacement sensor was used to detect the movement slide platform. As is shown in Fig. 14, the laser displacement sensor was fixed on a metal frame, and

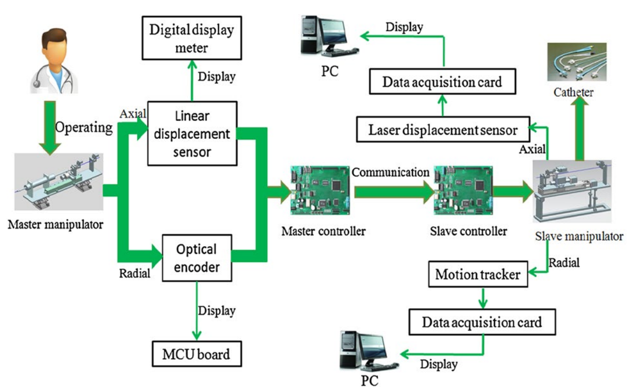


Fig. 12 The block diagram of the movement tracking

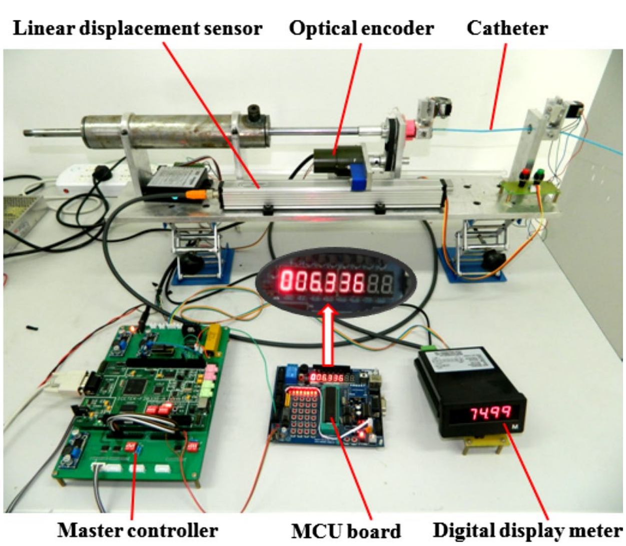


Fig. 13 The motion information acquisition of the catheter operated by a surgeon on master side

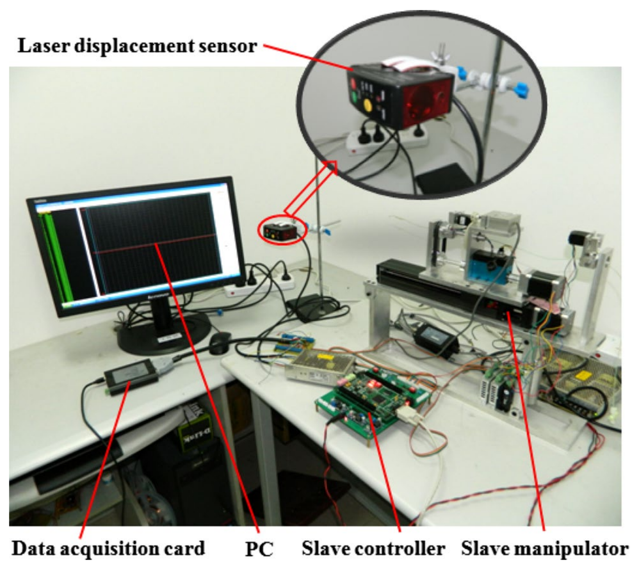


Fig. 14 The axial movement detection of the slave manipulator

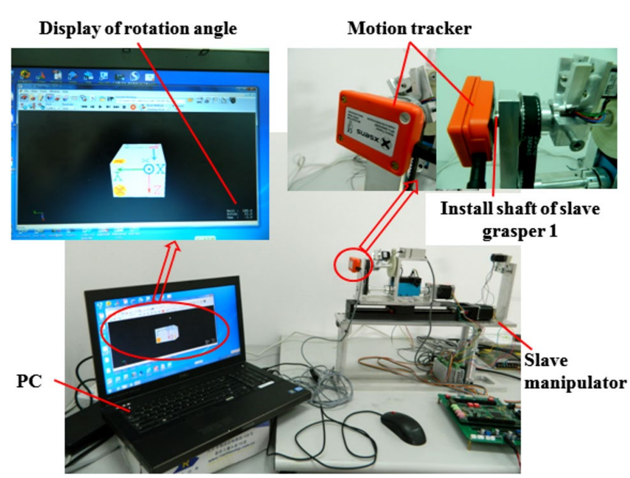


Fig. 15 The rotation angle detection of the slave manipulator

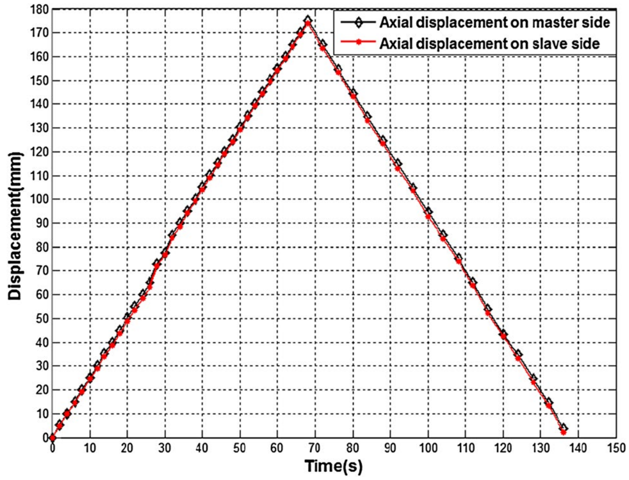


Fig. 16 The axial movement tracking

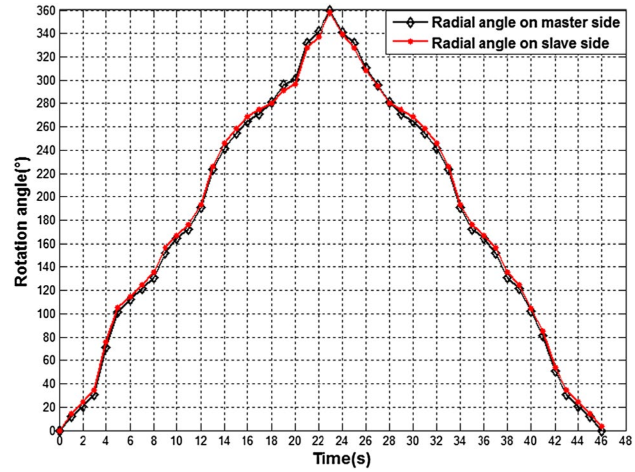


Fig. 18 The radial movement tracking

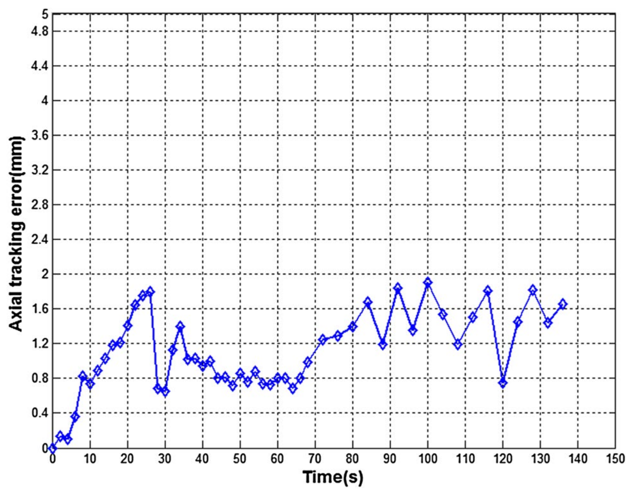


Fig. 17 The axial movement tracking error

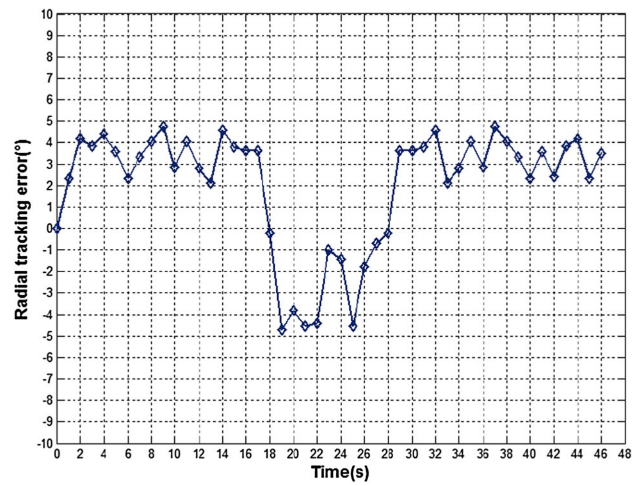


Fig. 19 The radial movement tracking error

the output voltage of the laser displacement sensor was acquired into the PC with a data acquisition card.

As is shown in Fig. 15, a motion tracker MTx-28A53G25 was adopted to detect the rotation angle of the slave manipulator. The motion tracker was the fixed on the install shaft of the slave grasper1 which clamp the surgical catheter to insert into blood vessel. The slave grasper1 and the surgical catheter have the same rotation angle. Therefore, the motion tracker could detect the rotation angle of the surgical catheter. Output of the motion tracker was acquired into the PC, and the rotation angle could be read from the PC screen directly.

Based on the movement data acquired on the master side and slave side, we can get the performance of the movement tracking. The axial movement tracking performance is shown in Fig. 16, and the axial movement tracking error is shown in Fig. 17. The results show that the error of axial movement tracking is less than 2 mm which meets the requirement of the surgery, because in conventional interventional vascular surgery, the precision of catheter operated by well skilled surgeon is more than 2 mm in axial direction.

The radial movement tracking performance is shown in Fig. 18, and the radial movement tracking error is shown in Fig. 19. The results show that error of radial movement tracking is less than ±5°. During the catheter operation, the rotation of the catheter has low risk, because the rotation of the catheter just adjusts the direction of the catheter. So the radial movement tracking precision can meets the requirement of the surgery.

4 Conclusions

In order to improve the safety of the vascular interventional surgery and protect the surgeons from radiating of X-ray, a novel master–slave robotic catheter system was developed. The following conclusions can be obtained:

1. Mechanism and principle of the master–slave robotic catheter system was described in details.
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. The damper based on MR fluid could be used to transmit the driving force to surgeon's hand as force feedback.
4. The movement tracking evaluation experiments of the system indicated that the error of axial movement tracking is less than 2 mm and the error of radial movement tracking is less than $\pm 5°$, both axial error and radial error are within the range of allowable error during VIS.

In the future, we will do experiments in vitro and in vivo by using the developed robotic catheter system.

Acknowledgments This research is supported by National High Technology Research Development Plan (863 Plan: 2015AA040102) and General Research Program of the Natural Science Foundation of Tianjin (13JCYBJC38600) and the Project-sponsored by SRF for ROCS, SEM (2014020).

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