Feedback Force Evaluation for a Novel Robotic Catheter Navigation System

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Abstract - In Vascular Interventional Surgery (VIS), the surgeons are exposed to X-ray threatening the surgeons’ health due to the depositing which lasts long. It is significant to find a method to keep away from X-ray during VIS. In this paper, a novel master-slave robotic catheter system for VIS has been proposed. The surgeon operates a real catheter on the master side, which can make full use of the natural catheter manipulation experience and skills obtained in conventional catheter navigation. The feedback of catheter operating force on the master side plays an important role in improving the safety of the vascular surgery. In order to realize the force feedback, a damper is used based on the intelligent fluid magnetorheological (MR) fluid. The damper is a piston structure with MR fluid. It 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 feedback force evaluation experiments of the damper were done. 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, Catheter, Catheter navigation 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 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 order to solve these problems, we should design an efficiency telesurgery system, which can assist the surgeon to operate the catheter interventional from a safe space [8].

The researchers become 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 teleoperating 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]. N. Zakaria et al developed a catheter guide system with force feedback using ER fluid, and this system can avoid system malfunction or human error [12]. 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 [13]. 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 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 damper filled with MR 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. The feedback force evaluation experiments of the damper were done.

II. THE DESIGNED ROBOTIC CATHETER NAVIGATION SYSTEM

A. Overview of the robotic catheter system

A conceptual diagram of the master-slave robotic catheter system is shown in Fig.2. On the master side, the surgeon operates the real catheter with viewing a monitor. The operating information is acquired and 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.

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. 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 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. The radial motion of the catheter is acquired by
the optical encoder which installed on the torque motor. The
connection between the torque motor and the piston rod is a
synchronous belt. Therefore, the torque motor and the piston
rod have the same rotation angle, and optical encoder can
detect the radial motion of the catheter.

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 surgeon can feel the operating force just like the
way in conventional catheter navigation. 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.

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], [14],
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.

C. The Designed 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.4.

The slide platform is fixed on the supporting frame which
can be adjusted easily to change the intevensional angle for
different patients. 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. All the graspers on master side and slave side
have the same structure. 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
imates 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.4). The
rotation motor drives the catheter to move in radial direction
through the synchronous belt.

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 operating force contains axial
driving force and rotation torque. In order to get the axial
driving force, a load cell is adopted. The detecting mechanism
is designed as shown in Fig.5 in detail. The load cell is fixed
on the slide platform. A clamp plate fixed on 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 grasper1
clumps the catheter to move on axial direction, the counter-
acting force of the catheter applying to grasper1 will lead to the
micrometric displacement of the axle of grasper1. And
micrometric displacement will affect the clamp plate, then the
counter-acting force is acquired by the load cell.

Torque sensor is applied to measure the torque
information during the operation. The torque sensor is linked
to rotation motor and the axle of the pulley below. The
rotation torque of the catheter can be transmitted to the torque
sensor by coupled pulleys then measured by the torque sensor.
The torque information will be sent to the master side and
generate a torque feedback to the surgeon.
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 [15]. And the relationship between the contact area and the conductivity was analyzed using finite element analysis method [16]. The obtained contact information on the slave side will be transmitted to the master side.

III. FORCE FEEDBACK METHOD OF THE MASTER-SLAVE SYSTEM

In a master-slave robotic catheter system, force telepresence is the key factor to ensure the safety and accuracy of the vascular interventional surgery. Visual-only feedback is ineffective, and a haptic device can create better human/machine interface through force feedback [17]. In order to realize the force feedback, a damper is used based on the intelligent fluid-MR fluid. 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 [18]. The viscosity of the MR fluid can be controlled by applying an external magnetic field. The damper is a piston structure with MR fluid, as is shown in fig.6. 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 shearing resistance will produce. Then different shearing resistance will be applied to the piston body when it moves.

The greatest feature of master manipulator is the damper with MR fluid, 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. The designed force feedback mechanism is shown in fig.7. Two graspers 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 damper, grasper1 will fix the catheter on the piston rod. Then the piston body 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 damper with input current in the coil which is wrapped on the piston body. 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 body reaches to the tip of damper, grasper 2 will fix the catheter on frame, and grasper 1 will be out of working. Then the operator can adjust the piston body to the end of damper through operating piston rod.

IV. THE FEEDBACK FORCE EVALUATION EXPERIMENTS

In order to apply the MR fluid damper into the master slave robotic catheter system. The feedback force evaluation experiments of the damper must be done. The evaluation theory sketch map is shown in fig.8. 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 with different movement speed.

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 200mm. After the experiments, we get other suitable parameters. The gap between the piston body and outer casing is 2mm. The outer diameter of the damper is 48mm and the thickness of outer casing is 4mm. The diameter of piston body is 36mm. It was coiled with approximately 510 turns of insulated copper wire,
as is shown in fig.9. 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.10. The use of the op-amp LM324, transistor TIP122, as well as some other electronic components, the electronic circuit allows the input voltage to control the current of the piston coil. 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.

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.11. The system consists of a data acquisition card, a damper, a load cell, a serial electric circuit, a MCU, DC power supply, a slide platform, a step motor and a PC. 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 10mm/s in our experiments. The experimental result shows that the resistances of the MR fluid damper almost the same with different velocities under 10mm/s when the current of the piston coil is a constant value.

The measuring range of load cell is from -5N to 5N, which correspond to the value range from -5V to 5V acquired into the PC. The outputs of the load cell were positive values when the piston moved forward, and the outputs were negative values when moved in reverse direction. A set of data were acquired by the PC with the same input voltage. We used excel to get average as the current value of the resistance. The correlation between the input voltage and the resistance of the MR fluid damper is shown in fig.12. 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 with MATLAB. Compared to other fitting result, quadratic fitting result is better, as is shown in equation (1) and equation (2). Equation (1) shows the relation when the piston moved forward, and equation (2) shows the relation when the piston moved backward. The fitting curve results of the damper are shown in fig.12.

\[
F_f = -171.25v^2 + 1506.91v + 1531.31 \quad (1)
\]

\[
F_b = 184.07v^2 - 1545.76v - 1430.45 \quad (2)
\]

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.

V. CONCLUSION AND FUTURE WORK

In order to improve the safety of the vascular interventional surgery and protect the surgeons from radiating X-ray, a novel master-slave robotic catheter system was proposed. The force feedback evaluation works for the robotic catheter navigation system were done. The following conclusions can be obtained:

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) The damper based on MR fluid could be used to transmit the driving force to surgeon’s hand as force feedback.

4) The force feedback evaluation experiments of the damper indicates that it is fit for the force feedback of the system.

In the future, we will perfect the developed master-slave robotic catheter navigation system with the damper based on MR fluid.

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