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Design and Performance Evaluation of a Novel Master Manipulator for the Robot-assist Catheter System

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***Abstract*—According to the world health organization survey, the number of patients died of disease of heart head blood-vessel per year up to 15 million, a serious threat to human health. Vascular Interventional Surgery (VIS) has been an effective method for treatment of vascular diseases. However, the surgeons are exposed to X-ray threatening the surgeons' health due to the depositing which lasts long. It is imperative to protect the surgeons from X-ray during VIS. In this paper, a novel master manipulation system for VIS has been developed. With this system, 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 operation. In order to improve the safety of the vascular surgery, a damper is used to realize the force feedback based on the electro-magnetic induction. The damper contains a bobbin and permanent magnets. It could feedback the force to surgeon's hand through the operating catheter from the master controller, which seems that the surgeon operates the catheter beside the patient. The evaluation experiment for the proposed master manipulator was done. The experimental results show that the stability is high and the error is in the permitted range , so the novel operating system is suitable for the robot-assist catheter system.**

Index Terms- Vascular Interventional Surgery (VIS); Teleoperation*; *electro-magnetic induction ; Force feedback.

I. Introduction

With the development of medical technology, Vascular Interventional Surgery (VIS) has become the most effective technique for vascular diseases, and it is popular for the diagnosis and treatment of endovascular diseases [1]-[2]. Because of its smaller incisions, less blood loss, decreased pain and quicker recovery, VIS has been widely adopted all over the world [3]-[4]. 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 [5]. 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, in contrast to the large number of patients who need to be treated, the lack of well-skilled doctors who can operate a catheter appropriately for the surgery is an imperative problem we need to solve. In addition, these doctors are always exposed to X-ray radiation. In order to solve these problems, an efficiency tele-surgery system should be adopted, which can assist the surgeon to operate the catheter interventional from a safe space [6].

In recent years, many research teams around the word focus on the study of robotic catheter operation systems for vascular interventional surgery. A novel method for force feedback in tele-operative endovascular surgical simulators has been presented [7]. January 9, 2000, the United States Intuitive Surgical company successfully developed Davinei Da Vinci surgical robot, it is one of the few commercial use of technology and its design idea is through the use of minimally invasive methods to implement the complex surgery [8]. Japan Shibaura Institute of Technology Noor Ayuni CheZakaria developed a system which can avoid catheter failure and human error, the system is achieved by the rotation of the friction roller axial movement of the catheter, pipe by electro-rheological fluid force feedback [9][10]. The UK imperial college proposed an insertion robot which can transmit catheter and implement force feedback [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. 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 [12]. 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, a novel master manipulation system was developed with true force feedback to the surgeon's hands. The surgeons operate the real catheter at the master side, and the axial information will be acquired by the solid shaft photoelectric encoder. The rotary information will be collected by hollow shaft photoelectric encoder. The master side operation information transmitted to the slave side by protocol. Then 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. With an electric coils bobbin 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 calibration experiment between current and damping force was done. The results show that master side can adjust the damping force by changing the current, so that the damping force and from the operating force is equal.

II. The Structure of Robotic Catheter System

A. Overview of the robotic catheter system

A conceptual diagram of the master-slave robotic catheter system is shown in Fig.1. 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.

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. The slave side mainly follows motion of the catheter on the master side. 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. The slave controller can get force information and the visual information to transmit to the master side as to realize closed-loop control.

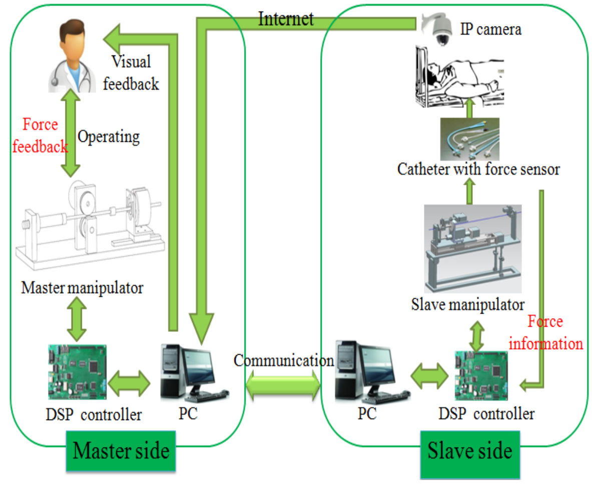

Fig.1 The conceptual diagram of the robotic catheter system

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. The master manipulator

The master manipulator is the operating platform of the doctor who operates the catheter interventional surgery. The diagram of our designed master manipulator is shown in Fig.2. The key character of the master manipulator is that the surgeons could operate a real catheter as conventional catheter interventional surgery. There are two main tasks of the master manipulator. 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. It contains axial operating force and rotation torque. Solid shaft photoelectric encoder is used to detect the catheter displacement and the hollow shaft photoelectric encoder is used to detect catheter hollow shaft rotation Angle. The surgeon operates the catheter move with around the coil bobbin. The operating lever driven guide rail rotating and the solid shaft photoelectric encoder measure the axial displacement with guide rail. Doctor rotating duct photoelectric encoder hollow shaft rotates to measure rotation Angle. The working height for the operator could be adjusted through the lifting platform according to different operating habit and demand.

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. The motion information includes the axial and radial information two aspects. Moreover, the operating force includes axial operating force information and rotation torque information. The damper is used to realize force feedback to transmit the force information which is transmitted from the slave side to the surgeon.

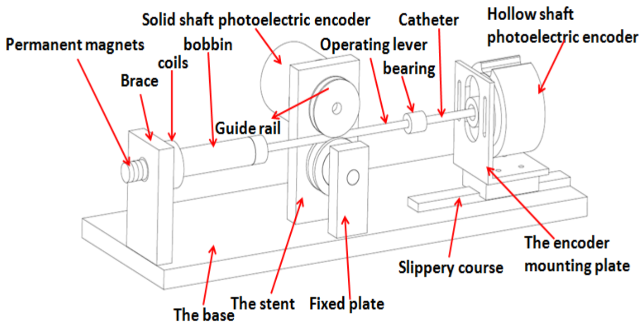

Fig.2 The master manipulator

In order to acquire the axial motion of the catheter, a solid shaft photoelectric encoder has been adopted, the circumference of the photoelectric encoder is 100 mm, 2500 lines of the photoelectric encoder forms through orthogonal decoding chip after 4 times frequency, need one revolution of the 10000 steps, thus precision can reach 0.01 mm. The radial motion of the catheter is acquired by the hollow shaft photoelectric encoder. The circum of the photoelectric encoder is 360 degree, 2500 lines of the photoelectric encoder forms through orthogonal decoding chip after 4 times frequency, need one revolution of the 10000 steps, thus precision can reach 0.036 degree.

Force feedback is an important part of a tele-operating robotic system. In our design, the operating forces 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. Around the electric coils bobbin is used to realize the axial operating force. Coil by electromagnetic force is the force feedback, as is shown in Fig.3. The coil number of turns is 500 turns; the bobbin is magnetic conductivity good iron bar inside. Magnetic iron bar ends is permanent magnets and one end of the lever on the bobbin. When electricity to coil, coil by electromagnetic force impeding the movement in the electromagnetic field, the greater the current of the electromagnetic force, the greater the damping force is larger. Operating rod connected to the catheter through the bearing and the damping force through the operating lever feedback to the surgeon's hand and then forming a closed loop system.

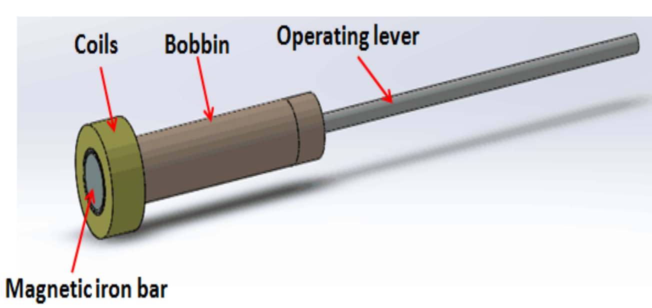

Fig.3 The realization of axial force feedback

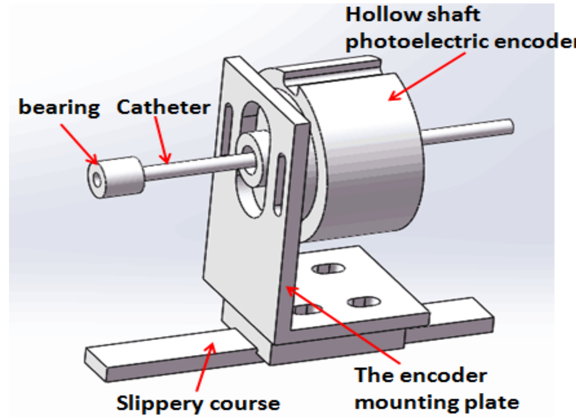

Fig.4 The realization of rotation Angle

The rotation Angle was realized with the hollow shaft photoelectric encoder. When the catheter rotation driven rotary optical encoder measuring rotation Angle. It is shown in Fig.4. 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 [13] [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 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.The slide platform is fixed on the supporting frame which can be adjusted easily to change the interventional angle for different patients [15]. 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 bobbin 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 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 (the driving motor in Fig.5). The rotation motor drives the catheter to move in radial direction through the synchronous belt.

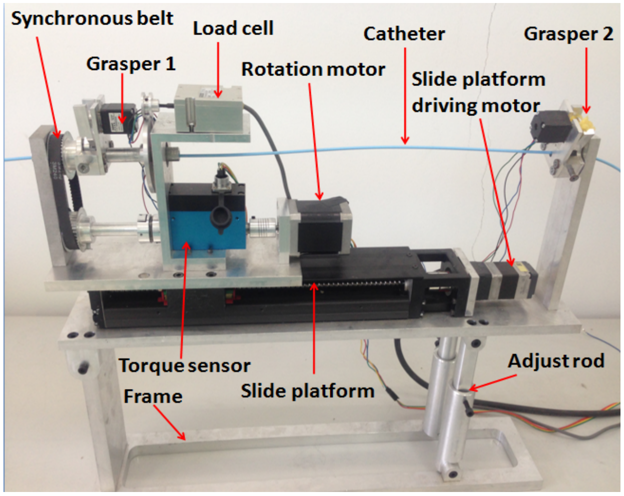

Fig.5 The slave manipulator

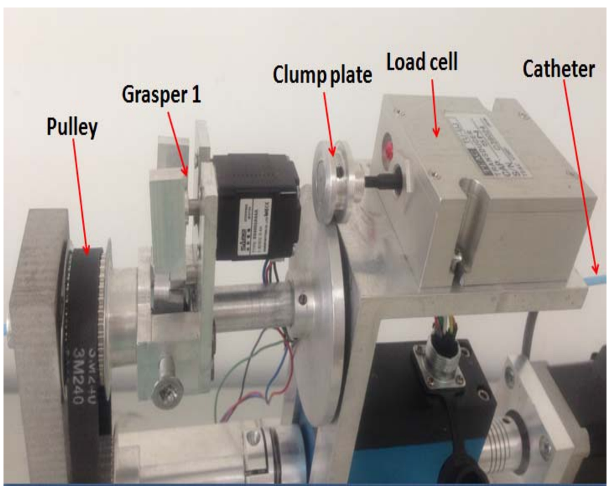

Fig.6 Axial driving force measurement mechanism

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 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.

The 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. The relationship between the contact area and the conductivity was analyzed using finite element analysis method [16]-[19]. The obtained contact information on the slave side will be transmitted to the master side.

III. The Force Feedback

In order to assess the performance of new master manipulator system, force feedback experiments have been done, setting a simulating force to simulation of internal force of side catheter in the vessel, with a force sensor feedback to physicians, comparing the results of the errors. 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 solide shaft optical encoder and the radial motion is detected by the hollow shaft 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 [20].

Fig.2 shows this system through the electromagnetic induction to implement force feedback. The calibration experiments between the electromagnetic force and the current had done. The doctor operation the catheter, the operating information transmitted to the slave side, once receiving the moving information of the master catheter, the slave controller controls the slave manipulator to drive the surgical catheter on slave side with tracking the movement of master catheter. The motors adopted to drive the surgical catheter are step motors. The speed of the step motor is controlled by pulse frequency, and the number of pulses decides the distance. On the slave side, catheter operating information of vascular within the collision force feedback to the master side of the doctor's hands, thus forming a closed loop system.

In our design, we consider that the master catheter have the same speed among two times communication of the system. Then we can calculate the pulse frequency with the moving variation of master catheter and communication cycle. Therefore, the surgical catheter can track the master catheter in a high accuracy.

IV. Experiments And Resluts

A. Experiments

In the calibration test, we can obtain the relation of the current and damping force. Fig.7 is shown the calibration experiment result of force and current. Until when the coil is energized after, due to the influence of magnetic field of permanent magnets to form, power coil by magnetic force. As shown in it that with the increase of coil current, magnetic force tends to a constant value. But the implementation equipment coil to the maximum current is 0.6 A, and the input current of the coil is the output current by voltage controlled current source. Damping force of the range is 0 to 5 N, as shown in figure experiment for magnetic force of the measured values in the permitted range. Based on the data of correlation between the input current and the magnetic force, the fitting curve equation was established with MATLAB. Where F is the electromagnetic force, I is the input current.

The fitting formula is as follows with MATLAB,

$$F = -290I^2 + 556I \quad (1)$$

According to the fitting formula can get the relationship between the feedback force and current by controlling the current to change force. Using the formula can be changed by adjusting the current magnitude of the electromagnetic force.

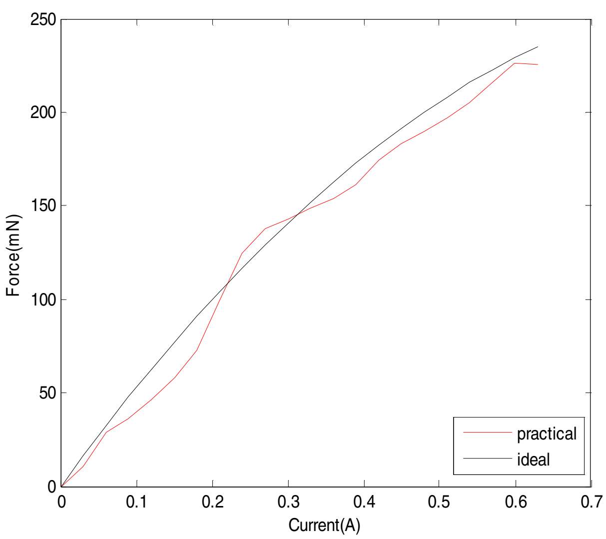

Fig.7.The calibration experimental results of the force and current

According to the range of the electro-magnetic force setting a simulating force, the maximum force is lower than 241m N and the maximum current is lower than 0.6 A, Simulating force is a simulation within the catheter in the vessel. On the master side, the force feedback obtained by the force sensor, then compare the two results. The comperison results is shown in Fig.8, Fig 9. is the errors force.

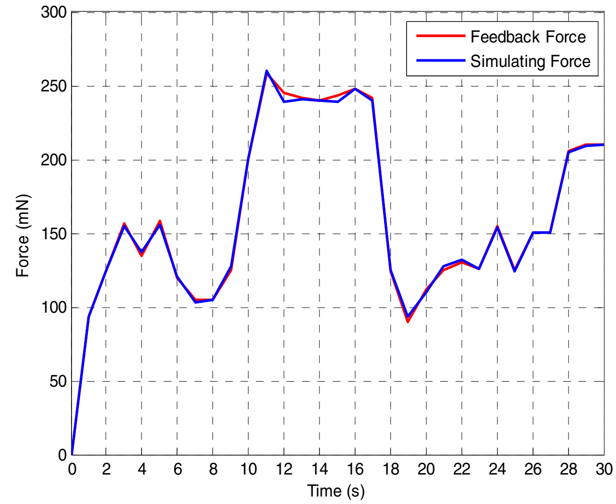

Fig.8 Comparison curve of the simulating force and the feedback force

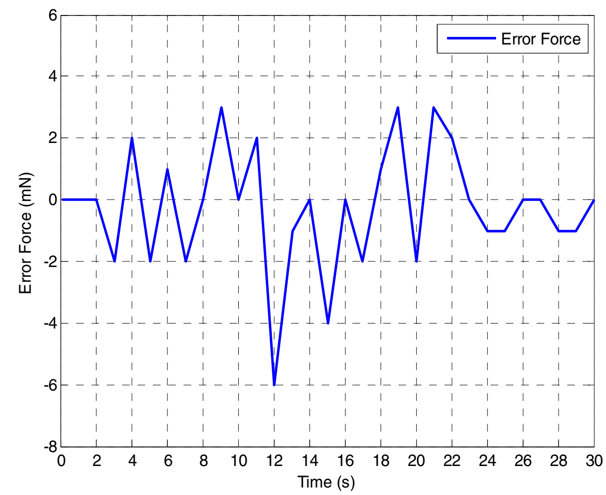

Fig.9 The error between the simulating force and the feedback force

B. Results

The experiments set a simulating force, then according to the formula (1) to calculate the current value by adjusting the current measuring feedback force, compared the results of the forces and error. Fig.8 shows the result of the comparison experiment and the Fig.9 shows the error of the experiment. Fig.8 shows the simulating force and the feedback force generated by the damper as time going on. In the Fig.8, 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.9, we can see the maximum error between the simulating force and the feedback 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 . So the error is in a safe range. The force feedback of the system is effective through the experiment.

V. Conclusions and Future Work

In order to improve precision of force feedback for the vascular interventional surgery, a novel master manipulator for the robot-assist catheter system was proposed. The results of calibration experiments and force feedback experiments proved that the novel master system is feasible. The following conclusions can be obtained:

1) A novel master manipulator for the robot-assist catheter system was proposed.

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 electro-magnetic could be used to transmit the force feedback to surgeon's hand.

4) The force feedback experiments indicated that the accuracy is high and the maximum error is 6 mN in the permitted range.

In the future, we will add the position feedback in our real time control. Moreover, we will optimize the dynamic performance of developed master-slave robotic catheter navigation system.

Acknowledgments

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