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A NOVEL SURGERY ROBOTIC SYSTEM USED FOR MINIMALLY INVASIVE

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Abstract. *The paper presents a new project of a surgery robotic system for minimally invasive. The novel system includes a human-arm-like robot manipulator and a catheter intervention manipulation system. A six-dimensional force sensor is fixed on the manipulator to drag the arm movement and accomplish compliance control to the arm. According to the surgery requirement, the catheter intervention manipulation system should deliver and rotate the catheter and help it insert into the target focus of the vessel to check, diagnose and therapy. Based on the actuality of catheter intervention manipulation, this paper describes the system's structure and master-slave manipulate mode, shows the realization way of quick detachment and force feedback, gives out the deduction of the promoting velocity and feedback force to pave the way for writing the control program.*
Keywords: Minimally invasive surgery, Six-dimensional force sensor, Compliance control, Catheter intervention, Manipulation system, Force feedback

1. **Introduction.** As the social development and the continuous improvement of living standards, human beings give more and more attentions to disease diagnosis, treatment, prevention and health. To improve surgery's precision and medical devices' flexibility, increase doctor's comfort, decrease surgery's risk, minish doctor's tiredness, minimally invasive robotic surgery emerges as the times require. Minimally invasive surgical has the advantage of minimally invasive, quick recovery and painless, and rapidly becomes the development trend of modern surgery [1]. Currently, remote control robot has shown a good prospect in the medical and biological engineering and other non-traditional areas [2-4]. The development of minimally invasive surgical techniques will inevitably bring the research boom related to surgical robotics. Robotic manipulation of surgical instruments has many advantages, such as precise positioning in accordance with the medical images, executive action without vibration, working in the detrimental environments to human, repositioning or reaching multiple targets through a complex trajectory rapidly and exactly [5]. Moreover, minimally endovascular intervention surgical is an important aspect of minimally invasive surgery because cardiovascular and cerebrovascular diseases threaten human life and become human's first killer [6].

Vascular interventional surgical is the Digital Subtraction Angiography (DSA) to guide the doctor to insert the catheter into blood vessels and cure lesions so that the catheter reaches the embolism and malformed vascular to dissolve the clot of narrow blood vessels or for other purposes [7,8]. This surgical way not only can cure vascular disease effectively, but also significantly shorten operation time, which can greatly reduce postoperative pain, faster recovery and many other advantages. Therefore, it has been carried out extensively in the world. The traditional surgical method is that a skilled doctor manually operates a catheter under the guidance of the X-ray image and gray scales. However, since the bend radius of the existing catheter's end is determined, and the blood vessel of human is also bend, long and narrow, irregular, more embranchments [9], the catheter may destroy the walls of blood vessels and enter into wrong vessel embranchments.

During surgical operations, the medical staffs and patients shall exposure to the X-ray's radiation for a long time, which will influence the efficiency and safety of the operation. The traditional method needs skilled operators, so very time consuming and intensive training are required. In one word, the traditional method is high-risk, complex-operate, long time-cost. Physical fatigue, manual instability and other factors mentioned above will directly affect the quality of surgery, thus influence the quality of patients' life. Therefore, the robot technology applied to surgical system can make surgery more security, accuracy and convenient [10,11]. How to make the catheter reach to an appointed branch of blood vessels is an important step for surgery, which is a key issue for surgery robot system to resolve [7]. The minimally invasive vascular interventional surgery is that the doctor inserts a catheter whose diameter is less than 2mm into the specifically aorta, and then steers the catheter following the aorta to the desired position, injects the radiotetrane into coronary artery and observes the stenosis extent of coronary artery on computer screen. If more than 70% stenosis, that the doctor pushes a steel wire less than 0.3mm, along the catheter, cross cabined vessel, into coronary artery distal, and founds a track. In succession, the doctor pushes a balloon along the steel wire track to splay the cabined vessel, and then puts a steel stent in the cabined vessel to eliminate vessel stenosis thoroughly and achieves the purpose of improving the blood supply.

Now, there are some problems under discussion in the existing machines. For positioning arm, based on the operation mode, the arms can be divided into active and passive types. Some drive devices are fixed on the active arms to drive their joints to move. This operation mode will bring about high-precision positioning, and does not need self-balance. However, the active arm only can move in accordance with a predetermined program and cannot be operated freely [12]. The passive arms have no drive device, and it moves with the help of the external force. It can be dragged freely by the operator. Currently, many passive positioning arms have been used for medical field, such as Da Vinci, Zeus [13], 'Liyuan' [14] and 'micro-hand' [15] system. The passive arms also have their limitations. According to the existing devices, some additional mechanisms should be designed to realize self-balance of the arm. And multi-brakes should be used in the whole mechanism. That will increase the design task and cost. How the functions of self-balance and self-lock realized using as little as possible additional mechanism is needed to be considered when designing. Minimally invasive surgical positioning arm needs to have a strong ability to adapt to the limited space of the operation room. The arm should be dragged freely at any time to adjust its position and orientation. The positioning arm proposed in this paper can meet these above requirements.

For catheter intervention device, on one hand, before operating, a catheter needs to be manually inserted into a catheter intervention device from one end, which wastes time and energy to operate. On the other hand, it is inconvenient to split implementation of components away off the motor to clean and disinfect. Furthermore, when the catheter rotates, the motors and other elements will rotate around the catheter. In this way, it is inconvenient for wiring and control, and also limits the circles of rotation. Some vibration may inevitably happen to influence the delivery accuracy by this rotating way. Current commercial systems include those of Hansen Medical Corporation [16] and MAKO Surgical Corporation [17], Imperial College London/St Mary's Hospital [18] and the American College of Cardiology Foundation [17]. However, no data exists demonstrating the relative effectiveness of those systems with and without haptic feedback [19]. The University of Electro-Communication developed a novel catheter operating system using micro force sensors for medical application [20]. Scuola Superiore Sant'Anna reported a miniaturized triaxial force sensorized cutting tool for minimally invasive robotic surgery whose outer diameter is less than 3mm [21]. All of the force detected devices are expensive or complex. In another hand, there is no data shown to us to explain how the device can be cleaned and disinfected. Accordingly, the research for the catheter intervention manipulation system has extremely important practical significance of application.

Before surgical robotics matures, there is a lot of work to be done [22]. The paper firstly proposes a novel minimally invasive vascular interventional surgical robot system which includes a positioning arm, a catheter intervention device and its manipulation device. Then the paper describes every part's motion control and gives some formulas deduction which will be used for control. Finally, we give the conclusion.

2. **System Description.** The surgery robotic system for minimally invasive includes four parts: a positioning arm, a six-dimensional force sensor, a catheter intervention device and its manipulator. The hardware system structure of surgery robot is shown in Figure 1.

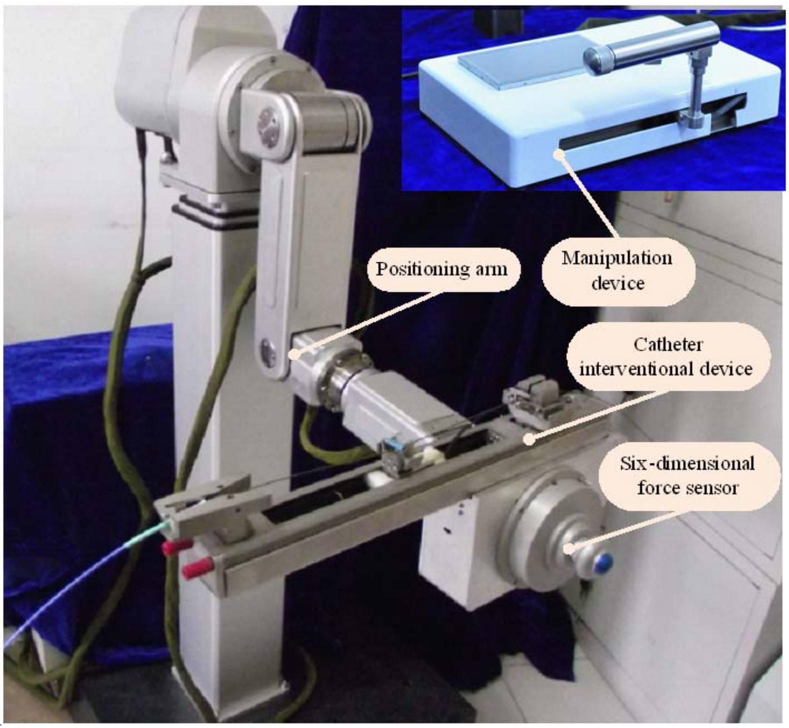

FIGURE 1. The hardware system structure of surgery robot

The six-dimensional force sensor and the catheter intervention device are fixed on the end of the arm. And the function of the arm is to position the catheter intervention device. A control method of mapping between master-hand and slave-hand is designed. The master-hands (six-dimensional force sensor and the manipulator of the catheter intervention device) are the signal input terminal of main controller, and the slave-hands (the positioning arm and the catheter intervention device) are controlled by the main controller. The slave-hand will move following the master's movement. When a joint of the master-hand rotates a certain angle, its position can be detected by an encoder fixed on the motor. The detected signals are transmitted to the controller that controls the rotation of corresponding joints. In this way, there is no much difference from the traditional surgery, and the doctor will operate the system comfortably and conveniently.

When operating, the doctor holds the six-dimensional force sensor and drags it along a certain direction. The six-dimensional force sensor sends the signal sensed to the control computer. After signal processing, the signal will be sent to the motor controller that drives every motor to rotate a certain angle and to make the manipulator reach to the destination. At the same time, every joint's position can be measured at any moment to realize compliance control to the arm.

Manipulation and intervention devices are master and slave hands. To make the operator have force telepresence, the catheter intervention device should have force detection function, and the manipulation device should have force feedback function. The manipulation device is used to operate the catheter intervention device. The device includes a moveable handle to control the catheter intervention device's movement and a rotary encoder fixed on the handle to control the catheter intervention device's rotation. When the operator moves the handle, the catheter manipulation device moves following it to promote the catheter. When the operator rotates the encoder, the device rotates at the same time to turn the catheter.

A minimally invasive surgery robotic system developed by our laboratory includes a positioning arm and a master-slave system. The positioning arm is a five-degree of freedom human arm-like robot. The master-slave system is the end-effector of the system.

3. Motion Control of the Positioning Arm.

A novel operation mode of the positioning arm is designed in this paper. With the help of a fixed six-dimensional force sensor, the positioning arm can be operated by an operator freely without given program. The new algorithm is given as follows.

3.1. Force signal transform.

From the six-dimensional voltage $L_v = [L_{v1}\, L_{v2}\, \cdots\, L_{v6}]^T$, the six-dimensional force can be obtained as follows:

$$\boldsymbol{F} = [\boldsymbol{G}]\, \boldsymbol{L}_v \tag{1}$$

where $\boldsymbol{F} = \left[\begin{array}{cccccc} F_x & F_y & F_z & M_x & M_y & M_z \end{array}\right]^T$, $[\boldsymbol{G}]$ is a calibration matrix of the force sensor [23]. The six-dimensional force signals outputted from the sensor are the elements of force vector.

The arbitrary spatial force system imposed on the rigid body can be composed of a wrench which has specific position. The wrench is the sum of a force vector $f_i(S_i; S_i^0 - h_i\, S_i)$ and a moment vector $f_i\,(0; h_i S_i)$ [24]. So we can obtain a wrench from six-dimensional force signal outputted from the sensor. Suppose a mapping which can convert the force vector to three displacements signals and convert the moment vector to three angle signals respectively along x, y, z axes of the sensor coordinate system. Then a position and orientation matrix can be given by the above six signals. Translating this matrix to the robot coordinate system, the end position and orientation matrix can be expressed. The whole transmission path can be shown in Figure 2.

The target matrix can be known after the mapping relation being given. Make the target matrix as the end position and orientation of the arm, and do inverse kinematics to change every target matrix into the joint angles. By fitting a smooth function to every joint and making the joint rotate follow the corresponding functions, the arm will pass

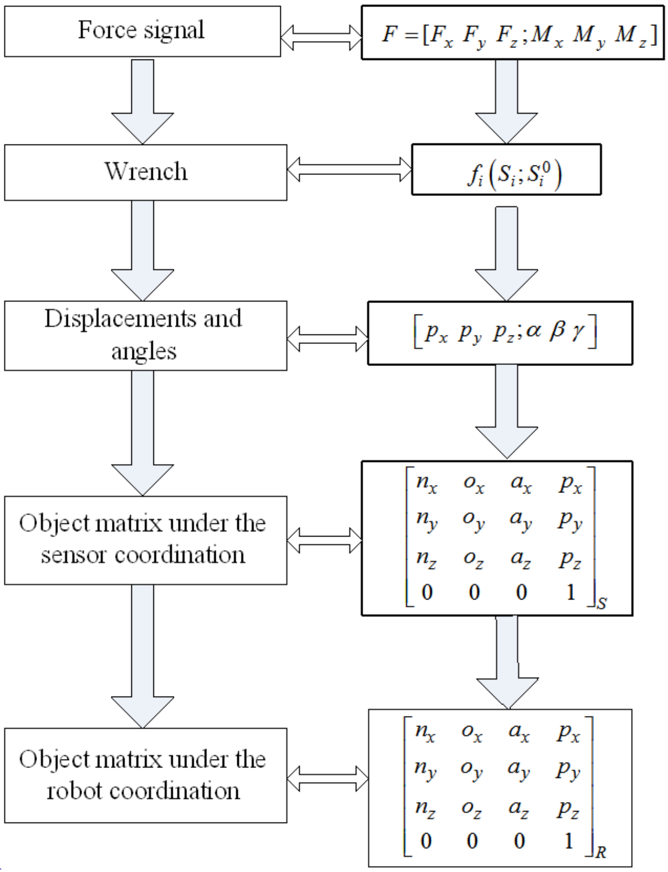

FIGURE 2. Force signal transform flow chart

all of the path point to reach the target position. Meanwhile, every joint should reach to the corresponding point at the same time.

3.2. **Discussion.** By disposing the six-dimensional force signal, the movement signals of every joint can be obtained. So the idea that compliance control to the positioning arm by operating a six-dimensional force sensor can be realized. Whereas the arm has 5 degrees-of-freedom (DOF), and the target matrix is obtained by a 6-DOF manipulator. We could not make sure that the positioning arm can reach every orientation of the matrix we have calculated. So add a fictitious joint to make the arm becomes a full freedom manipulator. The fictitious joint is located between the two end joints, and passes the intersecting point of the two end joint axis [25,26]. In this way, the problem of solving the inverse kinematics of the 5-DOF manipulator can be translated into a 6-DOF manipulator's problem. The above matrix translation of six dimensional force signals can be taken as the end position and orientation of the 6-DOF manipulator. Then do inverse kinematics of this mechanism. Locking the fictitious joint, the other five variables of the joints have been expressed. According to these expressions, we can further do trajectory planning to realize compliance control to the positioning arm by operating a six-dimensional force sensor.

4. **Control of Catheter Intervention.** The master-slave system includes two parts: a catheter intervention manipulation device as the master hand and a catheter intervention device as the slave hand. The working situation of the system is shown as Figure 3.

The catheter intervention device is fixed on the end of the positioning arm to assistant doctor to intervene the catheter into vessel. After positioning the arm, the catheter

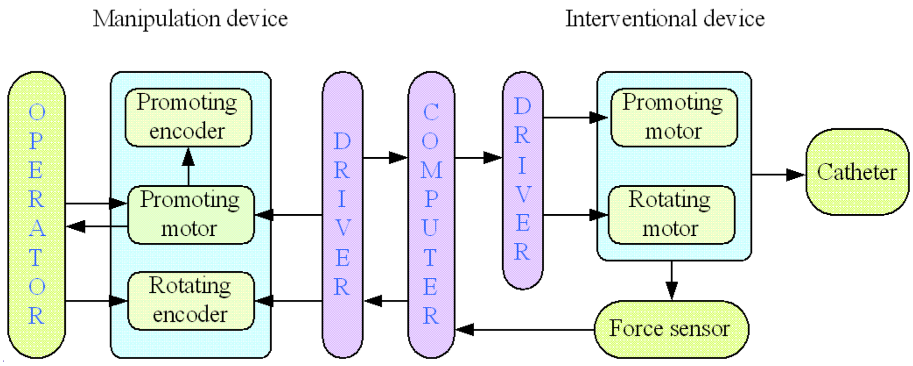

FIGURE 3. Working situation of the master-slave system

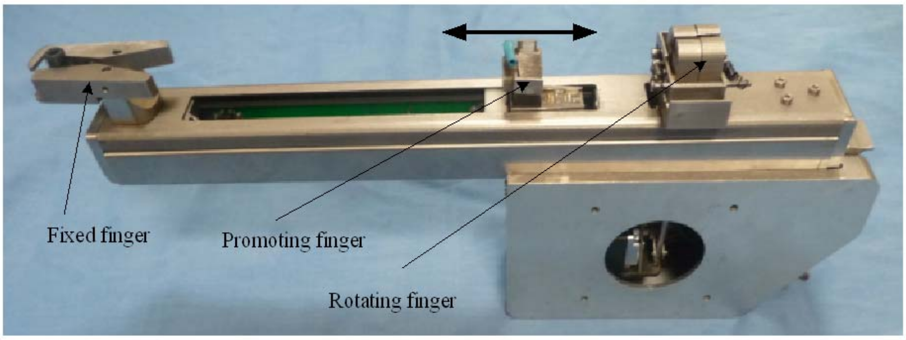

FIGURE 4. Catheter intervention device

intervention device begins to work. Doctor pushes and rotates the catheter alternately to make the catheter reach the focus. The catheter intervention device is composed of a fixed finger, a promoting finger and a rotating finger as shown in Figure 4. The fixed finger is located in the front of the device. It is used to locate the first catheter that has inserted into vessel and pave a way for subsequent guidewire, balloon and stent. The promoting finger is located in the middle of the device. It is used to grasp the catheter and bring the catheter to move along axial directions. The rotating finger is located in the end of the device. It is used to rotate the catheter. Cooperation action of three fingers can promote the catheter to the lesion location. The manipulation and intervention devices are the master and slave hands. The master-hand is used to control slave-hand's movement. To realize the operator's force sensing telepresence, the slave-hand should have a force detection function, and the master-hand should have a force feedback function. After the catheter intervention device is positioned, the doctor moves and rotates the manipulation device. At the same time, the catheter intervention device moves and rotates. A force sensor is installed on the catheter intervention device. Once the catheter touches the vessel wall, the sensor will send the force signal to the control system. Depending on received signal, the control system sends commands to the motor controller to make the motor start. At this time, the doctor who operates the catheter manipulation device has force sensing telepresence by the feedback force. In this way, the force between the catheter and vessel wall can be changed into motor's moment which can be felt by the operator. The application of force feedback technology can make the operator have force sensing telepresence [5,27]. German Aerospace Center found that haptic feedback reduced unintentional injuries during a dissection task [28]. The results showed that force feedback could save the time to complete the task by 40% [29].

4.1. **Functions of the catheter intervention device.** Due to the particularity of the environment and application objects, the device should have rotational and translational degrees of freedom. In addition to, the device should have the function of the following aspects:

(1) Medical devices need to be cleaned and disinfected before and after surgery, so the catheter intervention device could be quickly separated into implementation part and drive part in order to facilitate disinfection;

(2) The application object of the device is patient, so the device must have very high security. In an accidental situation, a timely action to stop intervening is required. That is, the operator can do some manual interventions to protect patient's safety;

(3) To avoid the vessel wall being destroyed, it is very important to detect the touch force timely and exactly. Depending on the force detected, the doctor should timely operate the device to improve surgery's security, so the device must have reliable detecting function.

4.1.1. *Realization of disinfection function.* The implementation part and drive part of the catheter intervention device can be separated and connected by snap and lock as shown in Figure 5. It is convenient for implementation's disinfection.

FIGURE 5. Realization of disinfection function

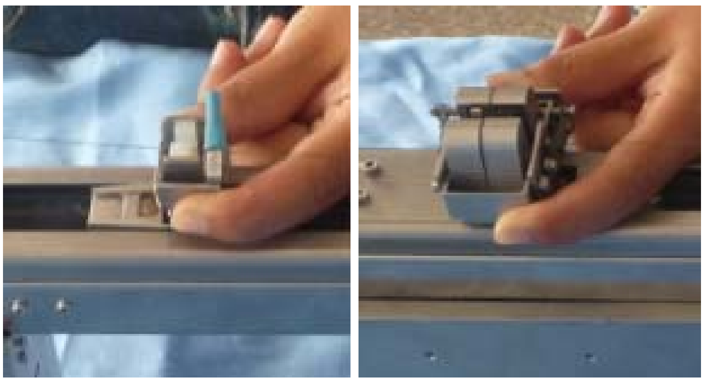

FIGURE 6. Manual intervention

4.1.2. *Realization of manual intervention function.* The clamping force of promoting finger to the catheter is supplied by a spring. When operating, if some unexpected situations happened such as mechanical failure and inadequate control, emergent brake is required. At this time, the operator can open the finger and stop promotion immediately (Figure 6). This improves the security and controllability of the operation to protect the safety of patients.

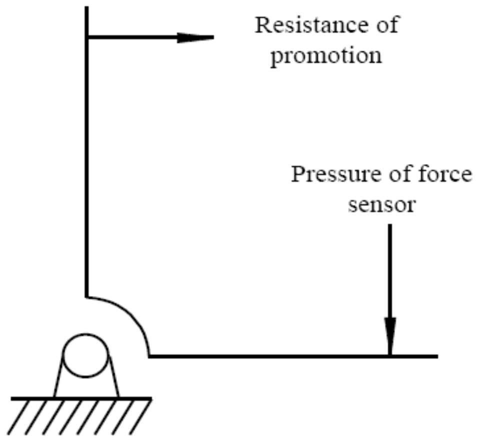

FIGURE 7. Force detecting principle

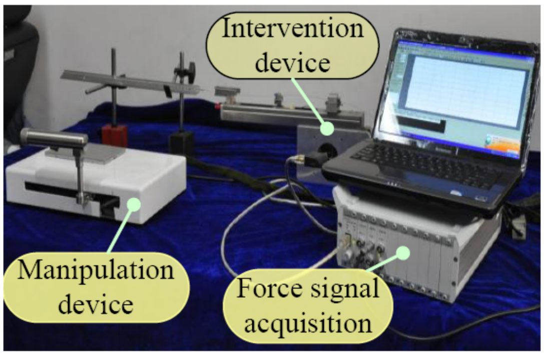

FIGURE 8. Experimental platform

4.1.3. *Realization of force detecting function.* The promoting finger is equipped with a force sensor so that it can detect the force between the catheter and vessel wall. The relationship between resistance of catheter and pressure of the sensor is based on the leverage as shown in Figure 7. Since the detected force is not influenced by friction of machine and transmission structure, the force signals from the sensor are correct and credible. Figure 8 and Figure 9 are force detecting experimental platform and experimental results. An experiment platform is set up as shown in Figure 8. A force sensor is installed in promoting finger. A force signal acquisition is used to extract the force signal. A PC computer is used to calculate the results. During experiments, the catheter moves along a glass tube, makes the catheter's tip bump a tampon, and obtains the change of force values from computer as shown in Figure 9. From the results, it can be easily found that this way of force detecting is accurate and credible.

4.1.4. *Realization of arbitrary circle rotation.* The rotational joint of the catheter intervention device adopts two parallel transmission belts to press the catheter, and these two parallel belts do countermove to rotate the catheter. The output torque of motor is transferred to the belts by a column roller as shown in Figure 10. The motor's position is immobile, which can avoid enwinding wire and realize arbitrary circles' rotating.

4.2. **Catheter interventional manipulation device.** From the requirement of the catheter intervention device, the manipulation device has rotational and translational degrees of freedom. The 2-DOF device can control the movement of promoting part and the rotation of rotational part (Figure 11).

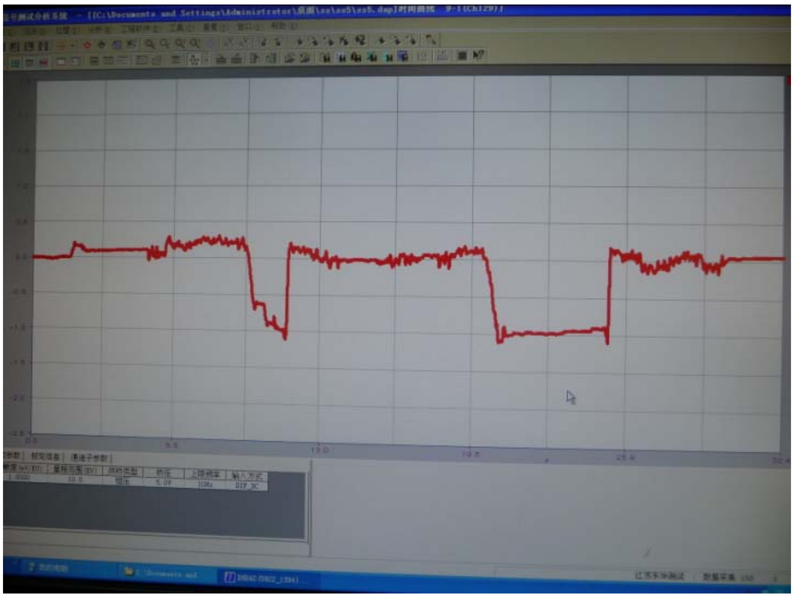

FIGURE 9. Experimental result

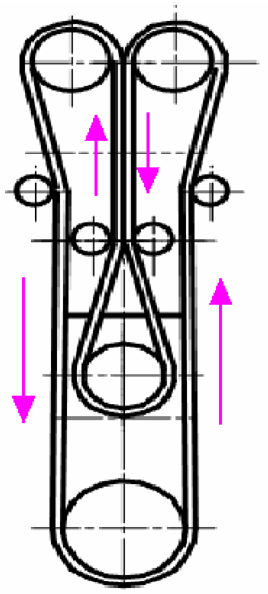

FIGURE 10. Transmission path

4.2.1. *Design of the catheter intervention manipulation device.* At the beginning of the surgery, the catheter intervention device is connected to the end of the positioning arm. Then the positioning arm is controlled to locate the catheter intervention device at a right position, and the doctor places the catheter on the device. The operator moves the manipulation handle to drive the motor component rotate. Since a rotary encoder is connected to the motor, the speed of intervene motion can be controlled depending on the pulse signal per unit time of the rotary encoder. If we need to rotate the catheter, we should rotate the handwheel on the catheter manipulation device. There is also a rotary encoder installed in the handwheel. The encoder pulse signal is detected and is sent to the control system. The control system can make the motor fixed on the rotational part rotate the catheter. Table 1 gives out the working states of every part and the whole operational processes, which can give us clear control logic.

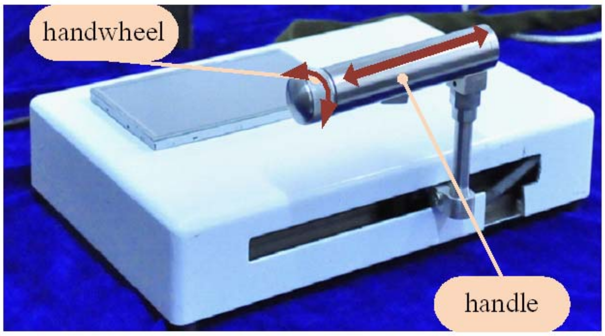

FIGURE 11. Manipulation device

TABLE 1. Operating state

medical devices	action	switch	fixed finger	promoting finger	rotating finger	manipulator
catheter, guide wire	promoting	on	open	closed	open	drag the handle forward
	return empty carrying	off	open	open	closed	drag the handle afterward
	pullback	on	open	closed	open	drag the handle forward
	promoting empty carrying	off	open	open	closed	drag the handle afterward
	rotate	off	open	open	closed	rotate the handwheel
balloon, stent	promoting	on	open	closed	closed	drag the handle forward
	return empty carrying	off	closed	open	closed	drag the handle afterward
	pullback	on	open	closed	closed	drag the handle forward
	promoting empty carrying	off	closed	open	closed	drag the handle afterward
	rotate	off	closed	open	closed	rotate the handwheel
	pullback	on	open	closed	closed	drag the handle forward
	promoting empty carrying	off	closed	open	closed	drag the handle afterward

4.2.2. *Control of the delivery displacement.* The slave-hand should move following the master-hand, and its velocity is corresponding with the master-hand. Different stalls of the master-hand are corresponding to constant, slow speed and fine tuning of these three states. By adjusting the coefficient k_i, the switching among those three states can be realized.

The coefficient $k_i = v_s/v_m$ ($i = 1, 2, 3$ are corresponding to the different stalls respectively. v_s is the promoting velocity of the slave-hand. v_m is the forward velocity of the master-hand.)

$$\begin{aligned} v_m &= (e_m \times 2\pi \times r_m)/(4 \times d_{im} \times i_m) \\ v_s &= (e_s \times 2\pi \times r_s)/(4 \times d_{is} \times i_s) \end{aligned} \tag{2}$$

where, e is the recorded data of the encoder per second, r is the radius of the output axis, d_i is the resolution of the encoder, i is the ratio of transmission from the motor to the end output. The subscripts m, s denote master and slave hands respectively.

The delivery drive motor is maxon RE13, whose nominal speed is 10200r/m. When the motor working at its nominal speed, the catheter delivery velocity is $v_s = ((10200/60) \times 2\pi \times r_s)/i_s$, where, $r_s = 4.5$mm, $i_s = 67$. For example, set $k_1 = v_s/v_m = 1$, that is to say that the catheter delivery velocity is equal to the velocity of the operator moving the handle. So make $v_s = 71.7$mm/s, v_m should be equal to 71.7mm/s. According to the designed mechanism, $r_m = 5.5$mm, $i_m = 3.71$. Substitute these parameters into Formula (2), we can obtain $e_m = 3080$, $e_s = 173980$.

4.2.3. *Realization of force feedback.* Manipulation and intervention devices are master and slave hands. When the catheter touches vessel wall, the force sensor can measure the force signal and send the force signal to the control system. After processing the signal, the control system sends the current command to the motor controller and the motor will produce a corresponding reverse torque and cause a reverse pullback trend. The feedback force is transferred to the handle, and the operator could have force telepresence. In this case, the operator can stop to promote the catheter and pull back the handle until he/she cannot feel the presence of feedback force. Then the operator rotates the handwheel and continues to intervene again. Force feedback path diagram is shown in Figure 12.

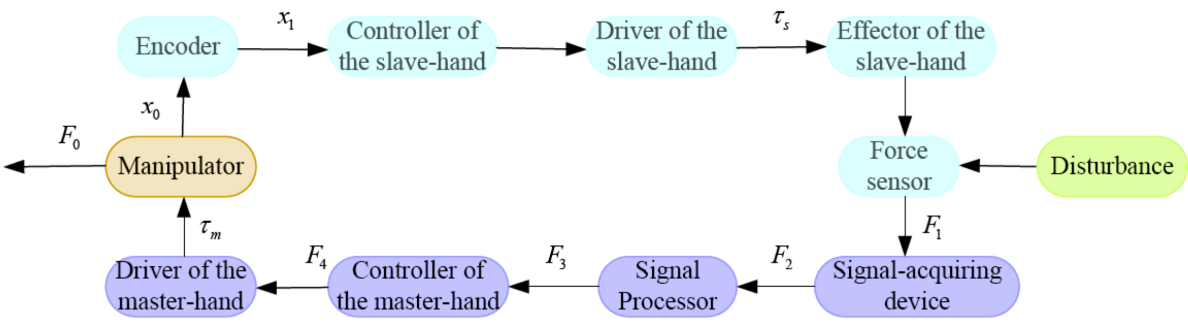

FIGURE 12. Force feedback path diagram

We use the DC motor controller based on PIC single chip microcomputer developed by our laboratory [30,31], and choose its current control mode to control the system.

4.2.4. *Control of force feedback.* On one hand, the velocity of promoting the catheter should be controlled to make the operator know the displacement of delivery. On the other hand, the functional relations between the forward resistance and the feedback force to the operator also should be deduced. A study showed that the least force threshold apperceived by human is about 170.096g [32]. Therefore, that the minimum force threshold of the manipulator being less than the people's is one of the design goals. In addition, to make the manipulator have good force telepresence, its force feedback should give the operator a haptic whose size and orientation are easy to identify. In recent years, the maximum feedback force of the new foreign development of dexterous manipulator is generally taken to be 10-25N [33].

The feedback force can be expressed as

$$F_o = T/r = (9550 \times P/n)/r = (9550 \times U \times I)/(n \times r) \quad (3)$$

where, F_o is the feedback force, U is the motor voltage, the current $I = f(v)$ is the function of the output voltage v of the pressure sensor, n denotes the rotate speed which is related to the rotate speed of the motor and the reduction ratio of the reducer. Those parameters can be obtained after the motor and reducer being selected out. Then referring to the experience value of F_o, the specific function relationships $I = f(v)$ can be given. And this function is the basis of the controller for processing the output signal of the sensor.

5. **Conclusion.** This paper presents a new robotic system for minimally invasive surgery. The system mainly consists of a positioning arm and a catheter intervention manipulation system. Under the help of this system, the surgery can be operated more conveniently, get higher positioning precision. This way avoids human operating error; reduces the operating skills of the surgeon's requirements. Use a six-dimensional force sensor to drag the positioning arm move to realize compliance control. The catheter intervention device's implementation part and drive part can be separated and connected by snap and lock, which is convenient for implementation's disinfection. The promoting finger is equipped with a force sensor, so it can detect the force between the catheter and vessel wall. The relationship between resistance of catheter and pressure of the sensor is based on leverage. Since force detected is not influenced by friction of machine and transmission structure, it is correct and credible. The most important is that when operating, if some unexpected situations happened, such as mechanical failure and inadequate control, operator can open the finger and stop intervention immediately, which improves the security and controllability of the operation to insure the safety of patients. The promoting velocity and feedback force have been deduced to pave the way for writing the control program. All of these researches above will promote the application progress of robotics in the medical and surgical aspects.

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