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Development of a Tactile Sensing Robot-Assisted System for Vascular Interventional Surgery

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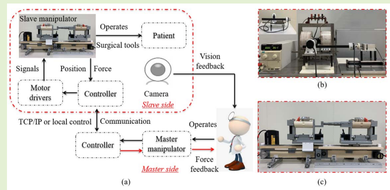
***Abstract*—The challenge of vascular interventional surgery is that surgeons require to be exposed to X-ray for a long time, operating guidewires and catheters to complete the treatment. To reduce the burden of the surgeons, it is of great significance to develop a tactile sensing robot-assisted system for vascular interventional surgery. Therefore, a slave manipulator with the function of collaborative operating guidewires and catheters was developed to replace doctors to perform the surgery in the operating room. In addition, a master manipulator based on magnetorheological fluids was located on the master side, and the haptic force feedback of the system was realized by generating the tactile force acting on the doctor's hand. To verify the proposed system, a series of experiments were carried out, the results of experiments in "Vitro" indicated that the proposed system has good performance in collaborative operating and can accurately deliver a guidewire and a catheter to the target position. The maximum tracking error of the axial motion was less than 2 mm, and the maximum tracking error of the radial motion was less than 2 degrees, which is acceptable. And under the guidance of the force feedback, the safety of the system was obviously higher than that of without force feedback, after the experiment was completed by 5 participants, the safety increased by 4.32% on average. So, we can get the results that our system is feasible and effective.**



The developed robot-assisted system for vascular interventional surgery. (a) The concept of the robot-assisted system. (b) The master manipulator. (c) The slave manipulator.

***Index Terms*— Vascular interventional surgery, guidewire and catheter, collaborative operation, force feedback.**

I. Introduction

NOWADAYS, some diseases are caused by people's unhealthy lifestyle. Among them, cardiovascular disease is a typical disease that seriously endanger human health, usually affecting the heart and blood vessels, leading to heart attacks and strokes and accounting for one third of all deaths worldwide each year [1]. With the development of the medical technology, vascular interventional surgery has saved more and more patients with cardiovascular disease, its operation procedure can be described as the following 5 steps [2]: 1) Needle placement, 2) Guidewire inserted, 3) Needle removed, 4) Catheter threaded on guidewire and 5) Guidewire removed, however, due to the complexity and specificity of the surgery, doctors need to be exposed to X-rays for a long time to operate a guidewire and a catheter. That's bad for doctors' health, some publications [3]–[5] have reported that doctors who are exposed to X-rays for a long time are prone to cancerous tumors, eye diseases (lens opacity) and bone diseases (cervical and lumbar injuries). In order to successfully complete the operation and ensure the health of doctors, researchers have combined medical, computer, sensor technology and robotics to develop vascular interventional surgery robotic systems, which can help doctors perform the operation safely and accurately.

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A. Current Research Status

In Kagawa University, a research team led by Professor Guo developed a master manipulator based on the characteristics of MR (magnetorheological) fluids to achieve system haptic force feedback [6]–[8], improve the transparency of teleoperation and reduce the cognitive workload of doctors.

In Beijing Institute of Technology, a novel remote-controlled vascular interventional robot was proposed by X. Bao, et al to improve the accuracy of surgical procedures and reduce the X-rays radiation risk of the surgeons [9]. Also, this robot was reported to have successfully completed the operation evaluation experiment of human being in 2018 [10]. In Chinese Academy of Sciences, a classification framework and analysis framework were proposed by X. Zhou, et al [11]–[13]. The frameworks were used to analyze the natural behaviors of surgeons and identify the motion patterns of the guidewire. In Imperial College London, in order to maintain the natural bedside skills of the doctors, a master-slave system with navigation system and integrated the visual and haptic feedback was developed by Dagnino *et al.* [14]. The developed system has been proved that it can enhance the precision and the safety of the endovascular procedures. In University of Hong Kong, a robotic manipulator based on hydraulic drive was developed by K. H. Lee, et al to realize robot-assisted cardiac catheterization in magnetic resonance imaging environment [15]. In Shanghai Jiao Tong University, an endovascular interventional robot with 12 DOFs (degrees of freedom) was developed by Wang *et al.* [16] and Li *et al.* [17], the developed robot not only has the ability to operate the intervention device, but also deploy the stents. In University of Twente, an advanced robotics for magnetic manipulation was proposed by Sikorski *et al.* [18], [19]. This system was used to generate the precise magnetic fields and gradients to adjust the posture of the catheter. In Hanyang University, a robotic system can shorten the completion time and reduce the contact force by manipulating a steerable catheter was proposed by Woo *et al.* [20]. And in Polytechnique Montréal, to enable flexible surgical instruments to navigate deeper blood vessel regions, a concept of FFN (fringe field navigation) was proposed by Azizi *et al.* [21], [22]. The concept of the FFN has been proven to have great potential in terms of the safety. Finally, the above achievements have been summarized in TAB.I.

B. Challenges & Contributions

According to the current research status, the function of most robotic systems is not very comprehensive. Some systems have realized the collaborative operating between the guidewire and the catheter, improved the navigation ability of the system, but lack the haptic force feedback. And some systems have realized the haptic force feedback and improved the safety of the system but lack the collaborative operating between the guidewire and the catheter. In addition, the guidewire plays the role of guiding and supporting the catheter during the operation. For the system that lacks collaborative operating, the catheter is easily buckled.

In view of the above-mentioned challenges in the research of robot-assisted systems for vascular interventional surgery, this paper developed a slave manipulator has the ability of collabora tive operating the guidewire and catheter, the robot can navigate the target point accurately, just like a doctor's hand. Besides, a master manipulator based on MR fluids was used to realize the force feedback by generating tactile force acting on the doctor's hand, which can improve the safety of the system. Finally, the cooperation performance and safety performance of the system have been verified by the experiments in "Vitro".

TABLE I
THE CURRENT RESEARCH STATUS REGARDING ROBOTIC TECHNOLOGIES

Authors \ Contributions	The developed robot-assisted systems: Research purposes	Research approaches
X. Yin, et al [6]-[8]	✓Achieve haptic force feedback ✓Improve the system safety	Developed a master manipulator based on MR fluid properties
X. Bao, et al [9][10]	✓Improve the operation accuracy ✓Reduce the X-rays radiation risk	Proposed a remote-controlled vascular interventional robot
X. Zhou, et al [11]-[13]	✓Analyze the natural behaviors ✓Identify the motion patterns	Proposed a HMM-based analysis and classification framework
G. Dagnino, et al [14]	✓Maintain the natural bedside skills	Developed a system integrated the visual and haptic feedback
K. H. Lee, et al [15]	✓Realize robot-assisted intracardiac catheterization in MRI environment	Developed a robotic manipulator based on hydraulic fluid drive
K. Wang, et al [16][17]	✓Manipulate intervention devices ✓Deploy the stents	Developed a distributed control system with multi-manipulators
J. Sikorski, et al [18][19]	✓Achieve the magnetic actuation of flexible catheters in large workspace	Proposed an advanced robotics for magnetic manipulation
J. Woo, et al [20]	✓Shorten the task-time ✓Reduce the contact force	Developed a robotic system that can manipulate steerable catheter
A. Azizi, et al [21][22]	✓Navigate the tethered instruments in deeper blood vessel regions	Proposed the concept of FFN in clinical MRI scanner

The remained of this paper is organized as follows: In section II, we first introduce the concept of the robot system, the master manipulator, and the slave manipulator. The design principle of slave manipulator, the realization method of force feedback and the robot kinematics analysis are introduced in section III. The experiments for characterizing the performance of the proposed robot-assisted system are conducted in Section IV and discussed in Section V. Finally, the conclusion is drawn in Section VI.

II. SYSTEM DESCRIPTION

As shown in Fig.1, it is the developed guidewire and catheter collaborative operating system. The concept of a robotic system developed in this paper can be described as the doctor operating the master manipulator at the master side, controlling the slave manipulator at the slave side to perform the operation. The force sensor on the slave manipulator can detect the force information between the catheter/guidewire and the vascular environment in real time and feed back to the master side. Moreover, the master manipulator will generate the haptic force acting on the doctor's hand to form the haptic force feedback, an IP (internet protocol) camera is used to monitor the surgical scene of the slave side in real time, and feed back to the master side through the network to form the visual feedback. The role of the force feedback and visual feedback in the tactile sensing robot-assisted system is to improve the safety of the operation.

A. Master Manipulator

The master manipulator was developed based on the previous works of our team [6]–[8], it mainly includes 3 parts, the motion reading and transmitting unit, the haptic interface

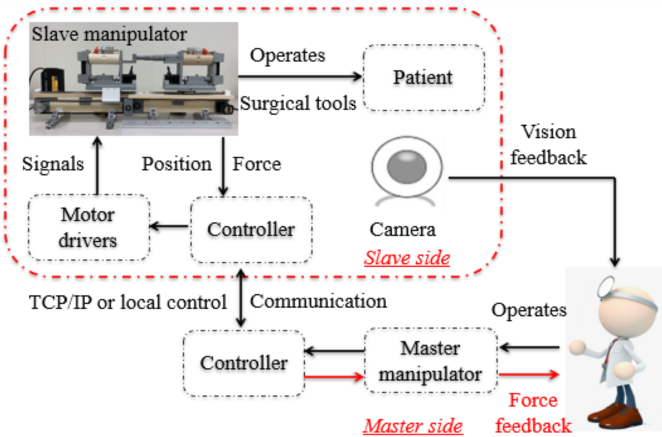

Fig. 1. The developed guidewire and catheter collaborative operating system.

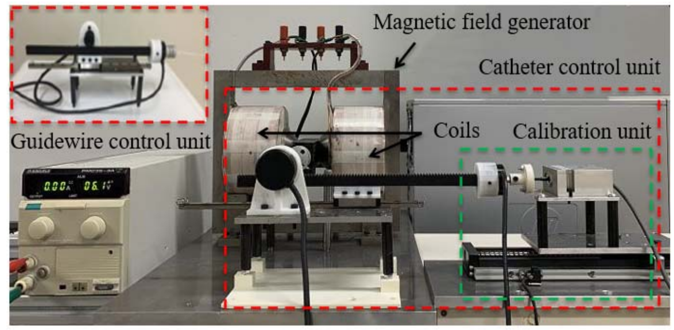

Fig. 2. The master manipulator based on MR fluids [6]–[8].

TABLE II
THE RELATED PARAMETERS OF THE MAGNETIC FIELD GENERATOR [8]

Parameter item	Values
Copper wire diameter (mm)	1.6
Inner diameter of the coil (mm)	30
Outer diameter of the coil (mm)	120
Height of each coil (mm)	68
Coil turns (T)	1200

unit, and the calibration mechanism unit, the haptic interface unit is the main source of providing haptic force feedback to the doctor. So, the design of the magnetic field generator for MR fluids is of great significance. TAB.II shows the relevant design parameters of the magnetic field generator, and Fig.2 shows the developed master manipulator based on MR fluids. The magnetic field generator consists of two symmetrical coils, two iron cores (cylinder with circular truncated cone made of SS400 steel, JIS), and a frame supporting them, the coil of magnetic field generator is made of copper wire with a diameter of 1.6 mm. It has the outer diameter of 120 mm, the inner diameter of 30 mm, the height of 68 mm and the turns of 1200 T. The magnitude of magnetic fields will change with the magnitude of input current, and the properties of the MR fluid will change with the magnitude of the magnetic field, thereby realizing the doctor's haptic force feedback.

The calibration mechanism is used to conduct the calibration experiment of MR fluids. The mathematical relationship of the force and input current is obtained. The calibration mechanism is mainly including a load cell (TU-UJ5N, TEAC, Japan) and a linear screw with the length of 400 mm. The experiment setup and results will be introduced in the part C of section III.

The motion reading and transmitting unit mainly consists of four encodes (MTL, MES020-2000P, Japan), the encode is used to detect and transmit the motion information of the guidewire and the catheter at the master side, two encodes are used for the linear motion of the guidewire and catheter, and the other two encoders are used for the rotation motion of the guidewire and catheter. All motion information will be transmitted to the slave side by the controller (Arduino, Mega 2560, China).

B. Slave Manipulator

The novel slave manipulator developed in this paper is shown in Fig.3, including a guidewire manipulation unit and a catheter manipulation unit. The stepping motor (ASM46AA, ORIENTA L MOTOR, Japan) is used for the linear and rotation motion of the guidewire and catheter with a resolution of 0.36 degrees. To improve the efficiency of motion transmission, the synchronous belt is employed to complete the motion transmission. Two load cells (TU-UJ5N, TEAC, Japan) are used to detect the axial force (includes the insertion and retraction force) information of the guidewire and catheter, respectively, and then feed back to the master side. The detection range of the load cell is from -5N to 5N. And two torque sensors are used to detect the radial torque information of the guidewire and catheter respectively, and then feed back to the master side. It is worthy to emphasize that the joint between the guidewire and the catheter is easy to bend and broke during the operation, in order to prevent this phenomenon, a telescopic tube is designed and printed. The length of the slave manipulator is 92 cm, the maximum effective range of motion of the guidewire or catheter is 40 cm.

III. PRINCIPLES AND METHODS

A complete guidewire and catheter operating system need to fully consider the following challenges from the perspective of the doctor's operating skills [23]–[25]. (1) Grasper device. It can simulate the doctor's hand clamping or releasing the guidewire and catheter and cannot damage the guidewire and catheter due to excessive clamping force. (2) Force detection mechanism for guidewire and catheter. It provides an important reference basis reproducing the haptic force of the master manipulator. So, the force detection mechanism needs better detection accuracy. (3) Good safety performance of the whole system. The function of the system force feedback is used to enhance the doctor's tactile tele-presence. In the absence of force feedback, the blood vessel wall may be perforated due to excessive insertion force. So, the function of haptic force feedback is so necessary. (4) Universal applicability. The type of the catheter is different; therefore, the slave manipulator should be applicable for different sizes of the catheters.

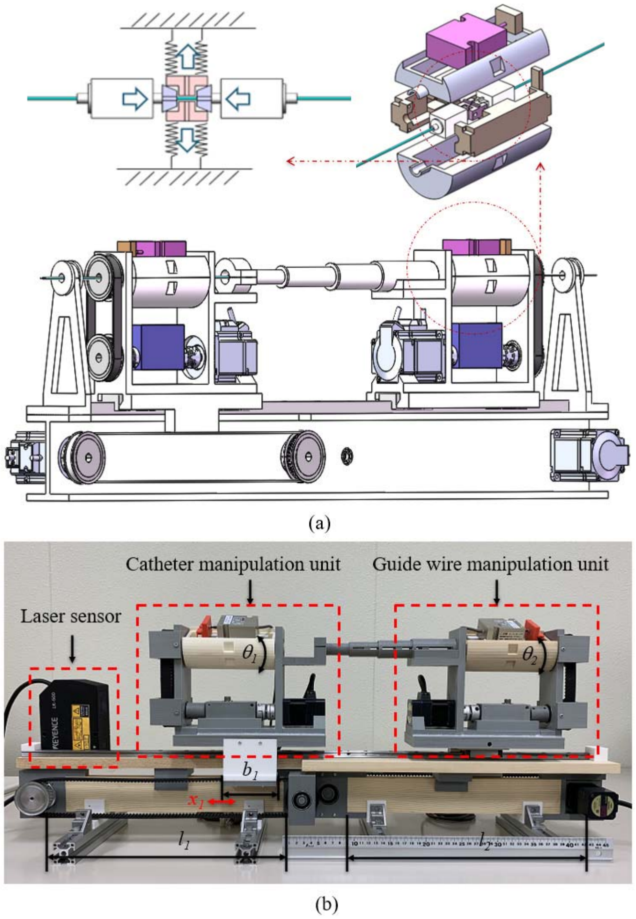

Fig. 3. The slave manipulator. (a) Schematic structure. (b) The developed device.

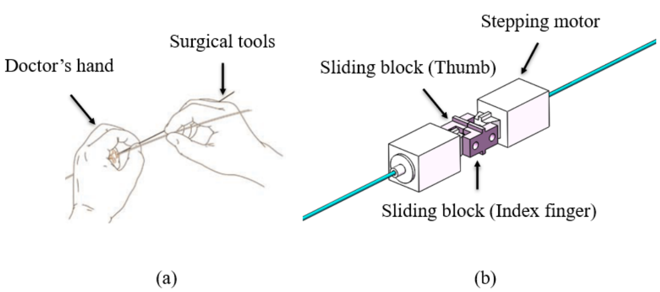

Fig. 4. The developed grasper device. (a) The schematic diagram of the surgeon operating surgical tools [28]. (b) The 3D structure of grasper device [26].

A. Grasper Device

The grasper device, like a doctor's hand, which can clamp and release the guidewire and catheter. So, from the perspective of simulating the doctor's hand, a grasper device for the guidewire and catheter collaborative operating system was developed, and the structure is shown in Fig.4. Besides, the shell of the grasper device was printed by a 3D printer, with the length of 11cm, the width of 3cm, and the height of 3cm.

Fig.5 shows the working principle of the grasper device. It can be described as in the initial state, the guidewire and the catheter are clamped by the sliding block (Thumb) and the

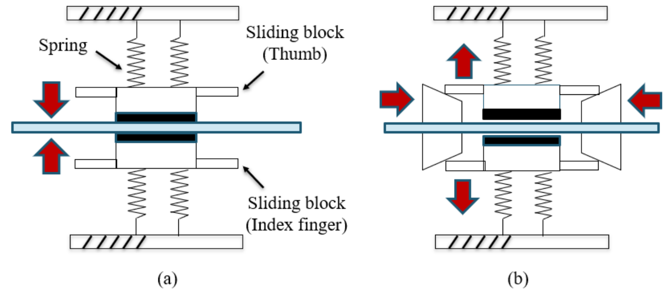

Fig. 5. The working principle of grasper device. (a) Clamping. (b) Releasing.

sliding block (Index finger) due to the elastic force of springs. To increase the friction between the surgical instruments and the grasper device, and prevent excessive clamping force from damaging the guide wire and catheter, the part where the inner surface of the sliding block in contacts the outer surface of the guidewire and catheter are filled with rubber. The release of the guidewire and catheter is achieved by two stepping motors (LIKO MOTOR, 20BYGH 30-0604A-ZK3M5). The stepping motor provides the thrust of the sliding block, when the thrust is greater than the elastic force of springs, the guidewire and the catheter can be released by the grasper device. We have completed the simulation experiment of the grasper device in Ref. [26]. Compared with the previous design [27], the clamping effect is better.

B. Force Detection Mechanism

The principle of force detection mechanism for the guidewire or catheter is show in Fig.6. Fig.6 (a) is the principle of the axial force detection mechanism for the catheter or guidewire, Fig.6 (b) is the principle of torque detection mechanism for the guide wire or catheter. As shown in Fig.6 (a), a load cell is adopted to detect the axial force between the guidewire or catheter and the vascular environment in real time. The output shaft of the load cell is connected to the grasper device, and the linear sliding rail is installed on the bottom of the grasper device. This design can transmit the axial force of the guidewire or catheter to the load cell, when the slave manipulator moves in linear direction, once the guidewire or catheter is subjected a force, the grasper device will collide with the output shaft of load cell, the load cell will output axial force information. The load cell used in this paper can detect forces in the range of -5N to 5N.

Fig.6 (b) is the principle of torque detection for the guidewire or catheter. A dynamic torque sensor is used to detect the force of the guidewire or catheter in real time when the guidewire or catheter rotates. Due to the influence of the blood flow rate and viscosity, a force will be generated when the slave manipulator rotates in the radial direction. The force will be collected by the dynamic torque sensor through the synchronous belt. Then, the dynamic torque sensor will output radial force information.

To verify the effectiveness of the developed force detection mechanism, we completed the calibration experiment for many times. Experimental setup is shown in Fig.7, there are two

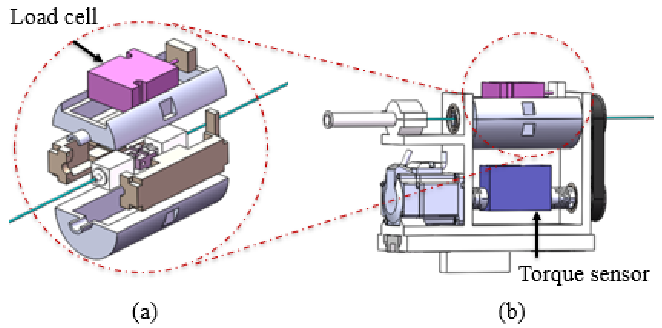

Fig. 6. The principle of force detection mechanism for the catheter or guidewire. (a) The axial force detection. (b) The torque detection.

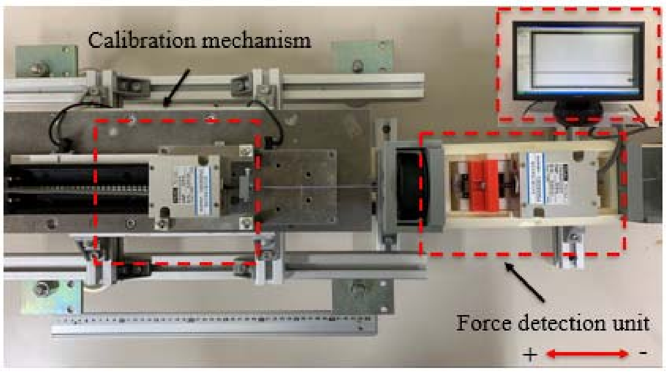

Fig. 7. The calibration experiment for force detection mechanism (t = 0s).

force sensors, one is installed on the force detection unit, the other is installed on the calibration mechanism. The force detection unit and the force sensor on calibration mechanism are connected by a catheter. Then, we pulled and pushed the catheter through the calibration mechanism, the plus and minus signs in Fig.7 are the direction of catheter movement.

The results of calibration experiment are shown in Fig.8. The error is unavoidable and may be caused by the loss of the sliding rail, and the deformation of the printed grasper device inside the force detection mechanism. The deformation is mainly caused by the spring of the grasper device, which will offset part of the force acting on the load cell and resulting in the measured force being inconsistent with the actual force. Besides, the developed slave manipulator is manufactured by the 3D printing material with low stiffness. The deformation of the low stiffness material will also cause errors. The results showed that the average error between these two forces is 8.42%. According to the analysis in Ref.[9], the perceptual resolution in the force discrimination, as measured by JND (just noticeable difference), is 7-10% over a range of 0.5N-200N. So, we believe that the force detection unit has enough sensitivity to detect small changes in force.

C. Force Feedback

The force feedback function plays an important role in guide wire and catheter operating system. It uses a master manipulator to reproduce the force of the slave side on the master side, and apply it to the doctor's hand, so as to give a tactile reminder and avoid danger. As for force feedback,

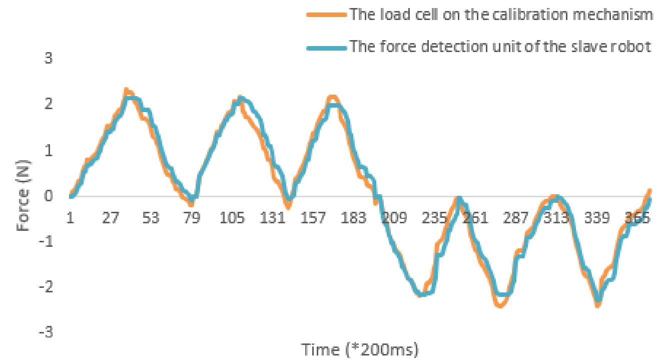

Fig. 8. The result of calibration experiment for force detection mechanism.

the researchers in our team were inspired through a special material -MR fluids [6]–[8]. MR fluids is a suspension composed of small soft magnetic particles with high permeability, low hysteresis, and non-magnetic liquid. The rheological properties of MR fluids will change drastically under the action of magnetic fields. This interacting magnetized particle forms a chain-like structures arranged in parallel to the applied magnetic field. In addition, the kind of rheological state can be changed from the free flow state into the semi-solid state in several milli-seconds. Based on this characteristic, the master manipulator based on MR fluids was developed, it is shown in Fig.2. The total haptic force mainly consists of two parts, one is controllable force, the other is uncontrollable force. And it was described in detail in Ref. [29] and Ref. [30], the magnitude of the controllable force is determined by the magnetic fields, and the intensity of the magnetic fields is determined by the current of the coil. Finally, the uncontrollable force also has 2 parts, one is viscous force, the other is friction force, the magnitude of the uncontrollable force can be measured through the experiments for many times. So, the calibration experiment is necessary.

The calibration experiment setup is shown in the calibration mechanism in Fig.2, a stepping motor connected to a lead screw with the length of 400 mm. The output shaft of the load cell is connected to the catheter, under the action of the stepping motor, the uniform linear motion of the catheter is completed.

The calibration experiment results of the master manipulator are shown in Fig.9 and Fig.10. And the relationship between the haptic force (including the tension and thrust) and input current was obtained. Fig.9 is the relationship between the tension and input current. And Fig.10 is the relationship between the thrust and input current. The fitting equations is obtained by the cftool toolbox of MATLAB. In the fitting equations, f_{te} represents the haptic force (tension), f_{th} represents the haptic force (thrust), and i represents the input current, the range is from 0A to 0.7A.

D. Robot Kinematics and System Analysis

To realize the collaborative operating of the catheter and the guidewire, the developed slave manipulator adopts two similar manipulation units, the movements of those two manipulation units do not interfere with each other. As shown in Fig.3,

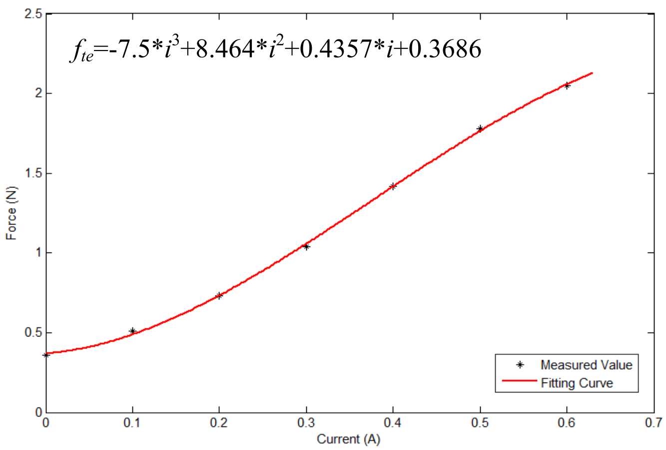

Fig. 9. The relationship between the haptic force (tension) and the input current.

it can be described by joint status [31], that is, mi with $i = \{1,2\}$. The catheter manipulation unit is described by $m_1 = (x_1, \theta_1)^{\mathrm{T}} \in \mathrm{R}^2$. Similarly, the guidewire manipulation unit is described by $m_2 = (x_2, \theta_2)^{\mathrm{T}} \in \mathrm{R}^2$. So, the joint status of the slave manipulator can be described as follows.

$$m = (m_1, m_2)^T \in \mathbb{R}^4 \tag{1}$$

The kinematic parameters of the slave manipulator are shown in Fig.3. Where, l_1 represents the effective movement stroke of the catheter manipulation unit, x_1 represents the insertion stroke of the catheter manipulation unit, and b_1 represents the width of the connecting element between the catheter manipulation unit and the synchronous belt. In the same way, we can know that l_2 represents the effective movement stroke of the guidewire mani pulation unit, x_2 represents the insertion stroke of the guidewire manipulation unit, and b_2 represents the width of the connecting element between the guidewire manipulation unit and the synch ronous belt. Therefore, during the insertion of the catheter and guidewire, the joint stroke can be described as follows.

$$\begin{cases} s_{cat,ins} = x_1 \\ s_{gw,ins} = x_2 \end{cases} \tag{2}$$

where, $s_{cat,ins}$ and $s_{gw,ins}$ represent the insertion stroke of catheter and guidewire, respectively. During the catheter and guidewire retraction, the joint stroke can be described as follows.

$$\begin{cases} s_{cat,ret} = l_1 - (x_1 + b_1) \\ s_{gw,ret} = l_2 - (x_2 + b_2) \end{cases} \tag{3}$$

where $s_{cat,ret}$ and $s_{gw,ret}$ represent the retraction stroke of catheter and guidewire respectively. In addition, the boundary condition of x_1 and x_2 can be described as follows.

$$\begin{cases} b_1 \le x_1 \le l_1 \\ b_2 \le x_2 \le l_2 \end{cases} \tag{4}$$

It is worthy to emphasize that the rotation strokes of the guide wire manipulation unit and the catheter manipulation unit of the slave manipulator are infinite. However, they cannot be rotated excessively to avoid damaging the catheter and guidewire.

Based on the previous study [6], the developed guidewire and catheter collaborative operating system can achieve the transfer of information between the doctor and the surgical environment. The main process is that the doctor's operation information is transmitted to the slave side through the vascular interventional surgery robotic system, and the force information of slave side is also fed back to the master side through the system. Therefore, the robot-assisted system can be regarded as a two-port network, because there is a bi-directional channel between the doctor and the blood vessel environment. The stability and transparency of two-port networks have been proved by the previous work, and the research of this paper is continued on the previous work, so there is no more description.

IV. Experimental Evaluation

In the previous section, we introduced the structure, principle and method of the system. So, in this section, the guidewire and catheter collaborative operating system will be evaluated by the experiments in "Vitro", including the tracking evaluation of the slave manipulator, and the collaborative operation evaluation in cardiovascular. Each experiment consists of experimental setup and experimental results. In addition, we analyzed the results of experiments, and draw the conclusions that the system has good collaborative operation performance, and high safety.

A. The Tracking Performance of the Slave Manipulator

1) Experimental Setup: To verify the developed guidewire and catheter collaborative operating system, it is very important for the slave manipulator to have good tracking performance. A laser displacement sensor (LK 5000, Laser displacement sensor, KEYENCE Corp, Japan) is employed to detect the displacement of the manipulation unit of the slave manipulator. The accuracy of the laser sensor is 50 um/mV. Since we use the synchronous belt to achieve the linear motion. According to the diameter of the synchronous pulley is 46.3 mm, we can easily calculate that when 500 pulses are input to the stepping motor, the theoretical displacement value of the manipulation unit is 18.17 mm. The measurement range of this experiment is from 0 mm to 218 mm. To prevent the occurrence of accidental errors, we conducted the experiment for five times. Also, an encoder (CB-1000LD, LINE SEIKI CO., LTD, Japan) with the accuracy of the encoder is 0.09 degree/pulse is used to detect the rotation angle of the manipulation unit. The stepping motor rotates 45 degrees each time, ranging from 0 degrees to 360 degrees. We also conducted the experiment for five times.

2) Experimental Results: Experimental results are shown in Fig.11, TAB.III, Fig.12 and TAB.IV, Fig.11 is the error of linear motion after the experiment was repeated five times. TAB.III is the statistical result of errors after the experiment was repeated five times in the linear motion. As shown in Fig.11 and TAB.III, the maximum error of the linear motion is less than 2 mm, and the average error of linear motion

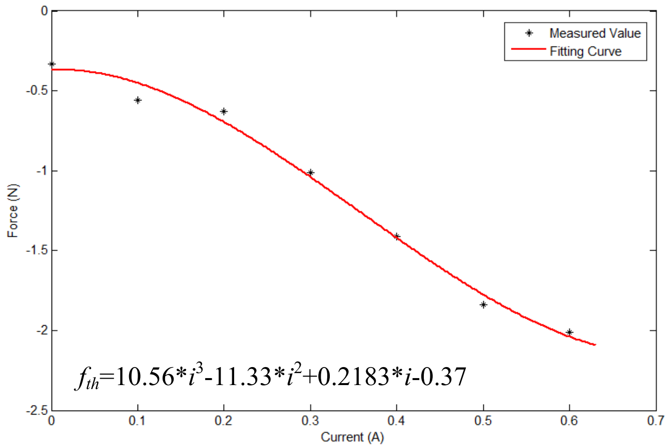

Fig. 10. The relationship between the haptic force (thrust) and the input current.

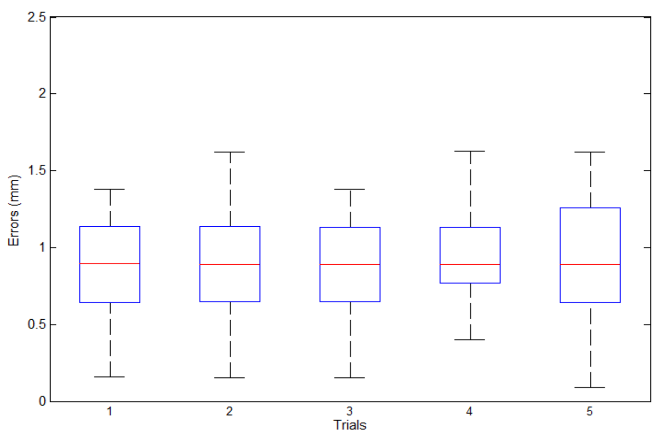

Fig. 11. The error of linear motion after the experiment was repeated five times.

is 0.878 mm, which can satisfy the requirement of operation. In traditional surgery, the surgeon with well skills will produce the motion error greater than 2 mm when operating the catheter [32]. And Fig.12 is the error of rotation motion after the experiment was five times. TAB. IV is the statistical result of errors after the experiment was repeated five times in the rotation motion. The maximum error of rotation motion is less than 2 degree, and the average error of rotation motion is 0.920 degrees. The rotation motion is just to adjust the direction of the tips of the guidewire and catheter, and the risk of damaging the blood vessel is small during the operation. Therefore, we believe that the developed robot-assisted system is satisfy the requirement of the surgery.

B. The Collaborative Operation Performance of the System

The purpose of this experiment is to prove that the guidewire and catheter collaborative operating system has higher accuracy in choosing vascular branches. The blood vessel of human body is intricate. The left subclavian artery, the left common carotid artery and the innominate artery are very close to each other. It is very important to choose the correct vascular branch. Besides, the dislodgement of aortic plaques easily leading to the risk of stroke. Therefore, to navigate the target

TABLE III
THE STATISTICAL RESULT OF ERRORS IN THE SYSTEM LINEAR MOTION

Trials	Average (mm)	Variance (mm)	Maximum (mm)	Minimum (mm)
1	0.88	0.13	1.38	0.16
2	0.85	0.14	1.62	0.15
3	0.86	0.13	1.87	0.15
4	0.91	0.13	1.63	0.08
5	0.89	0.17	1.62	0.09

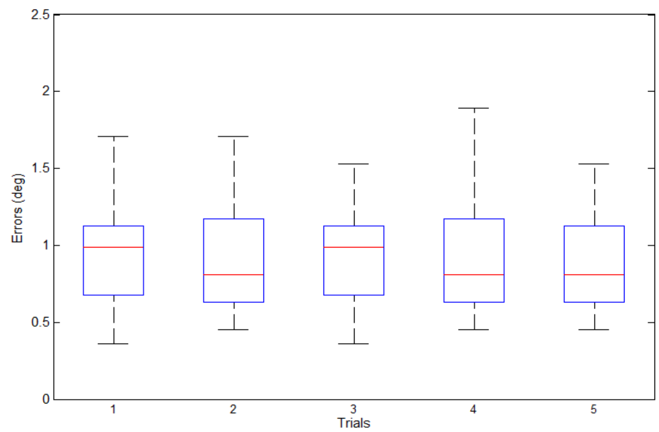

Fig. 12. The error of rotation motion after the experiment was repeated 5 times.

position accurately and smoothly, the collaborative operation of the guidewire and the catheter is necessary.

1) Experimental Setup: Generally, vascular interventional surgery is performed with the collaborative operating of guidewires and catheters. A slave manipulator with good performance is the key to complete the operation. So, the collaborative operating experiment of a guide wire and catheter was carried out in the endo vascular evaluator (EVE: Fain-biomedical, Nagoya, Japan). A bellows pump (KB- 4N, Tokyo, Japan) was used to circulate the fluids injected into the EVE model, the purpose of this is to make the environment closer to the real blood pressure of human beings. Experimental setup is shown in Fig.13. Fig.13 (a) is the master side, including a master manipulator based on MR fluids, a power supply, and a monitoring interface of slave side. And Fig.13 (b) is the slave side, including a slave manipulator, an IP camera, and an EVE model. Among them, the function of the camera is to feed back the surgical scene to the master side to achieve visual feedback of the system. Through the combination of the force and visual feedback, the safety of the system can be improved. The starting point and the target point of this experiment are shown in Fig.13 (c), the starting point was set in the arcus aortae, the target point was set in the left subclavian artery. The guidewire used in this experiment is a long guidewire with an angle type of 45 degrees and the catheter is a 5Fr catheter (JB2-125, Saitama, Japan).

Five participants with research experience in robotic systems for vascular interventional surgery under the age of 25-30 were asked to complete the experiment in the

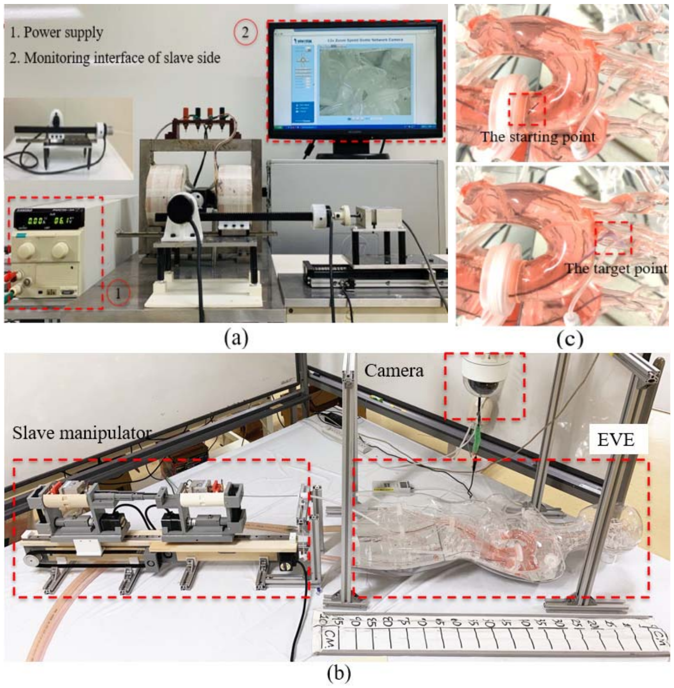

Fig. 13. Experimental setup. (a) The master side. (b) The slave side. and (c) The starting and target point of the experiment in EVE model.

EVE model. Before the experiment, each participant was trained for 10 minutes, and the training includes operating the developed master manipulator to control the slave manipulator to complete the linear and rotation motion of the guidewire and catheter, the tactile force provided by the master manipulator to the participants when the catheter is inserted into the blood vessel. We will evaluate the guidewire and catheter collaborative operating system from the following two metrics: (1) the safety performance of the system under the operation without or with force feedback, we defined the forces with absolute value greater than 1.0 N as unsafe factors. And (2) the completion time of the surgical tasks under the operation with or without force feedback.

The cooperation process of the guidewire and the catheter is shown in Fig.14. Fig.14 (a) is the operation process of the guide wire, Fig.14 (b) is the operation process of the catheter. And the grasper device plays an important role, likes a doctor's hand, its function is to push the guidewire and catheter step by step.

2) Experimental Results: Experimental results are shown in Fig.15, the real-time force measurement results of the guidewire and the catheter in cardio vascular. Fig.15 (a) is the operation without force feedback, and Fig.15 (b) is the operation with force feedback. The blue one is the real-time force information of the guidewire, the green one is the real-time force information of the catheter. It is worthy to emphasize that there is a friction force between the catheter and the guidewire, they will affect each other because the guidewire passes through the catheter. Although this force is small, it does exist. Moreover, the safety threshold of this experiment was set as 1.0 N, and the forces over 1.0 N was regarded as the unsafety force during the surgery. So, it is easy to calculate the degree of danger of Fig.15 (a) is

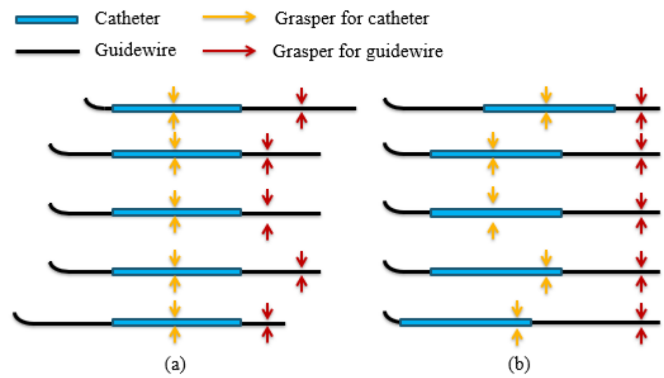

Fig. 14. The cooperation process of a guidewire and catheter. (a) The operation process of guidewire. (b) The operation process of surgical catheter.

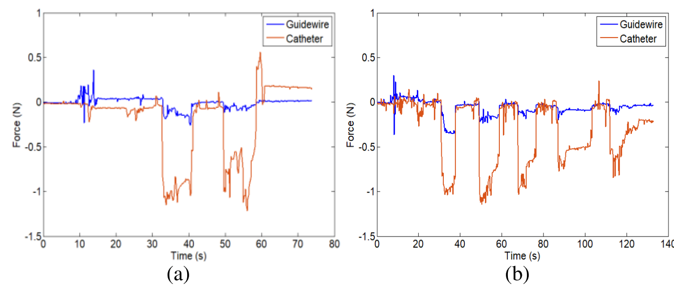

Fig. 15. The real-time force measurement of the guidewire and the catheter. (a) Under the operation without force feedback. (b) Under the operation with force feedback. (**Safety threshold: 1.0 N**).

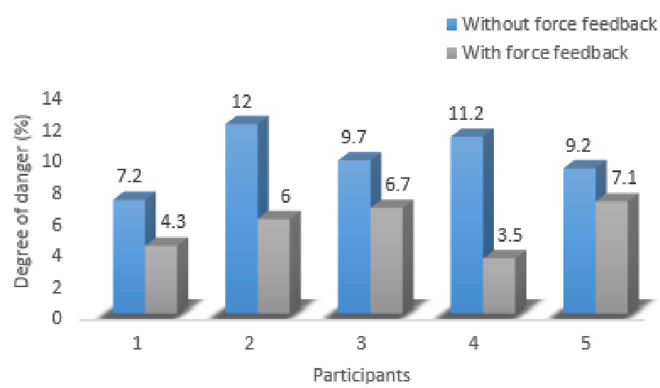

Fig. 16. The safety of the guidewire and catheter collaborative operating system after the operation by five participants.

7.2%, and Fig.15 (b) is 4.3%. Compared with the operation without force feedback, the degree of danger was reduced by 2.9%, indicating that the haptic force feedback can prevent the occurrence of danger, and improve the safety of the robot-assisted system.

As shown in Fig.16, the bar on the left is the degree of danger under the operation without force feedback and the bar chart on the right is the degree of danger under the operation with force feedback. By comparison, it is easy to know that the degree of danger has been reduced by 2.9%, 6.0%, 3.0%, 7.6% and 2.1% respectively, under the operation with force feedback from the participants 1 to 5.

TABLE IV
THE STATISTICAL RESULT OF ERRORS IN THE SYSTEM ROTATION MOTION

Trials	Average (deg)	Variance (deg)	Maximum (deg)	Minimum (deg)
1	0.91	0.11	1.71	0.36
2	0.94	0.14	1.71	0.45
3	0.92	0.11	1.53	0.36
4	0.89	0.14	1.89	0.45
5	0.91	0.16	1.98	0.45

TABLE V
THE MAXIMUM FORCE AFTER THE OPERATION BY FIVE PARTICIPANTS

Participants	1	2	3	4	5
With FF (N)	1.14	1.35	1.22	1.13	1.17
Without FF (N)	1.22	2.19	1.36	1.52	1.21

FF: Force Feedback

As shown in TAB.V, it is the statistical result of the maximum force after the operation by five participants, which showed that the maximum force under the surgical task with force feedback was far less than that of without force feedback. The maximum difference is 0.84 N (as shown in the participant 2).

Finally, Fig.17 is completion time of surgical tasks under the operation without or with force feedback. The bar chart on the left is the completion time of surgical tasks under the operation without force feedback, and the bar chart on the right is the time of surgical tasks under the operation with force feedback. The completion time of surgical tasks under the operation with force feedback is longer than that of without force feedback, because each participant needs to change the state of the guidewire and the catheter in real time according to the force feedback during the operation. In the absence of force feedback, the participants completed the surgical tasks based on the visual feedback of the IP camera, only needed to deliver the guidewire and catheter to the target point. Therefore, it takes less time.

V. DISCUSSION

Aiming at the challenges mentioned in Section I. This paper developed a master-slave guidewire and catheter collaborative operating system with the function of force feedback.

To evaluate the developed robotic system, the experiments in "Vitro" were performed. Experimental setup is shown in Fig.13. The evaluation metrics of the experiment include (1) The safety performance of the developed system under the operation with or without force feedback, and the definition of safety has been given in the previous statement. (2) The completion time of the surgical task under the operation without or with force feedback. And experimental results showed that the slave manipulator has valuable performance in collaborative operating the guide wire and catheter, can successfully deliver them to the target position. Five participants under the age of 25-30 were asked to complete the experiments in "Vitro".

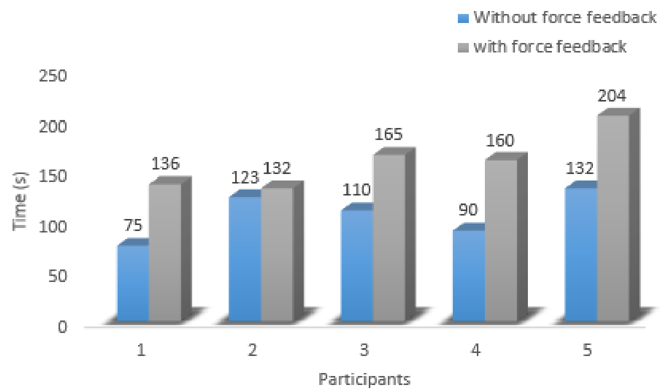

Fig. 17. The completion time of surgical tasks after the operation by 5 participants.

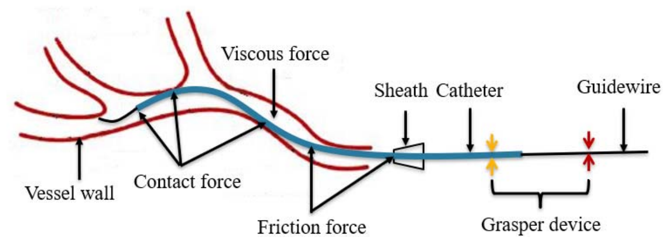

Fig. 18. The force analysis of the guidewire and catheter in surgery [33].

By comparison, we found that from the participant 1 to 5, the degree of danger was reduced by 2.9%, 6.0%, 3.0%, 7.6%, and 2.1%, respectively, under the operation with force feedback. The maximum force between the catheter and environment during the operation with force feedback was far less than that the operation without force feedback (as shown in Fig.16 and TAB.V), but the completion time of the operation is longer (as shown in Fig.17), which may be caused by the need to adjust the posture of the catheter in real time according to the force feedback during the surgery. In addition, the endovascular experience of participants is also an important factor affecting the completion time.

It is worthy to emphasize that the force between the surgical tools and the blood vessel environment detected by the load cell is the sum of all forces. As shown in Fig.18, the force detected by the load cell include the contact force, the viscous force, and the friction force. The friction mainly comes from 3 aspects. For instance, the catheter and the blood vessel wall, the catheter and the catheter sheath, and the inner surface of the catheter and the outer surface of the guidewire. At present, the force detected by the load cell is fed back to the master side to achieve the haptic force feedback. It may be better to use contact force as the basis for force feedback. So, the future work of this study is to extract the contact force between the surgical tools and the blood vessel and improve the system safety.

VI. CONCLUSION

In this paper, a novel tactile sensing robot-assisted system for vascular interventional surgery was developed. This system can accurately deliver the guidewire and catheter to the target point and detect the force information between the surgical tools and the blood vessel environment in real time.

In addition, a master manipulator based on MR fluids was used to generate the haptic force acting on the operator's hand to achieve the force feedback. Finally, the experiments in "Vitro" were completed to evaluate the performance of the system, and experimental results showed that the slave manipulator has good performance in tracking the master manipulator, the maximum error of linear motion is less than 2 mm, the maximum error of rotation motion is less than 2 degrees. And under the guidance of collaborative operation and the function of force feedback, the guidewire and catheter were delivered to the target smoothly, the safety of the operation with force feedback was obviously higher than that of without force feedback. After five participants completed the experiment, the safety increased by 4.32% on average. So, we consider that the developed tactile sensing robot-assisted system is effective.

In the future, the current limitations mentioned in Section V will be overcome, and if possible, the developed robotic system will be verified through the experiments in "Vivo".

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