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Design and Evaluation of a Novel Slave Manipulator for the Vascular Interventional Robotic System

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***Abstract* - In this study, we proposed a novel master-slave vascular interventional robotic system. This paper mainly designed the novel slave manipulator which can complete the vascular intervention surgery under doctor's remote control. The slave manipulator comprises four units, including three movable units and one stationary unit. These four units mimic the hands of the doctor in traditional vascular interventional surgery, and the four units work together to complete the push and rotation of the surgical catheter and guide wire. The proposed slave manipulator also can measure the resistance experienced during catheter and guide wire intervention in real time. We conducted three experiments to verify that the proposed slave manipulator can meet the requirements of vascular interventional surgery. The experimental results show that the proposed slave manipulator can accurately push and rotate the catheter and guide wire and can accurately measure the resistance of the catheter and guide wire during operation.**

Index Terms – slave manipulator; vascular interventional surgery; grasping force; force measurement.

I. INTRODUCTION

In recent years, the number of patients with high blood pressure is also increasing year by year. It is estimated that by 2030, the number of deaths caused by myocardial infarction will reach about 20 million, and the number of deaths caused by stroke will reach about 30 million [1]. Sufficient to see that it seriously threatens the survival and health of human beings. Vascular interventional surgery has more than 80 years of research history [2]. Vascular intervention has saved more and more patients with cardiovascular and cerebrovascular diseases. Under the guidance of medical imaging, the doctor directly manipulates the surgical catheter and guide wire, sends it to the lesion site, and then performs a series of diagnosis and treatment [3][4]. Compared with traditional surgery, vascular intervention has the advantages of small wound, fast recovery and high reliability. However, because the operation time is too long, the doctor is exposed to X-rays for a long time, which will affect the doctor's own health.

With the continuous development of robot technology, many organizations have developed robots that can be applied to vascular interventional surgery, and the clinical application prospects are very broad [5-7]. Vascular interventional surgery robot is composed of master side and slave side. During the surgery, the slave replaces the doctor's hands to deliver the catheter and guide wire. The doctor operates master manipulator with the help of medical images, and the slave follows the action of the master to perform the operation. Vascular interventional robots can prevent the effects of radiation on the health of the doctor, and robotic operations are more stable than manual operations. Therefore, it's very helpful for doctors or patients with cardiovascular disease.

Vascular interventional surgery robot is a hot topic for many scholars. Hao Su et al proposed a remote operating system that is compatible with MRI, including a force sensor based on Fabry-Perot Interferometry for measuring the force of the catheter during operation and a pneumatically driven tactile feedback device.[8]. Zhenqiu Feng et al proposed a master-slave proportional tracking control strategy, which scales down from the slave to track the displacement of the master, and the master scales the force measured from the slave[9]. Barbara Bortolani et al proposed a remote catheter navigation system called CathROB that enables automatic navigation and safety warnings for catheters.[10]. BJ Yi et al designed a master-slave interventional robot for cardiac ablation that allows the catheter to be bent and the master manipulator uses a motor to achieve force feedback.[11].

There are two problems with the slave manipulators of vascular interventional robots in many studies. The first is the lack of ability to control the catheter and guide wire at the same time. Because the guide wire plays a guiding role in the

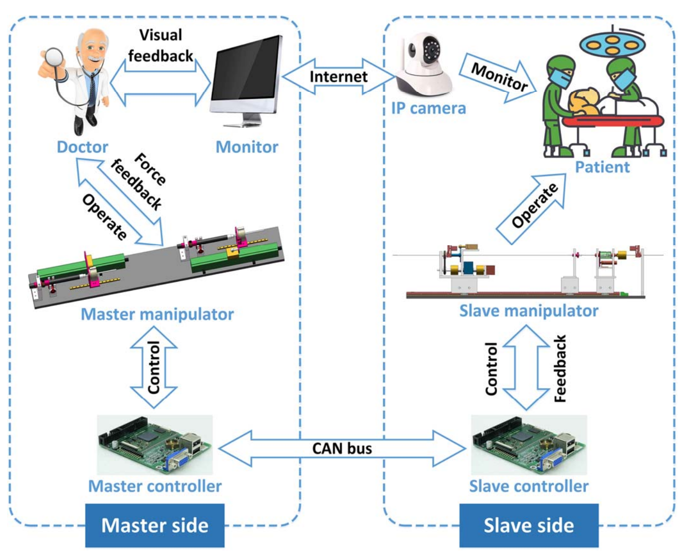

Fig. 1 Schematic diagram of the master-slave teleoperation system

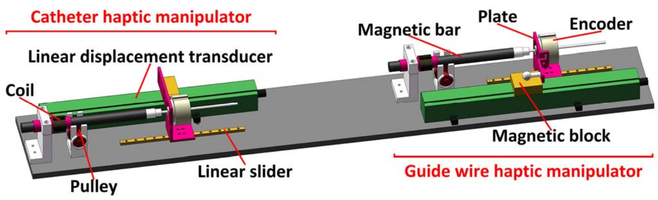

Fig. 2 Mechanical structure of the master manipulator

manual surgery, catheters and guide wires are medical equipment that doctors must use. The second is the lack of measurement of the force applied to the catheter and guide wire during operation. The measurement of force is the premise of force feedback, and accurate force feedback can improve the safety of surgery. In this study, we designed a novel slave manipulator that can solve the above two problems. Fig. 1 shows the schematic diagram of the master-slave teleoperation system. The force data measured from the slave manipulator is ultimately fed back to the haptic device of the master manipulator, which enhances the physician's tactile feel. Fig. 2 shows mechanical structure of the master manipulator. The master manipulator includes a catheter haptic manipulator and a guide wire haptic manipulator. The doctor operates the two parts with both hands to control the slave manipulator. The master manipulator can also provide tactile feedback to the doctor.

In this paper, design of the slave manipulator is described in Section II, including mechanical structure, clamping principle and principle of force measurement. We conducted three experiments to evaluate the feasibility of the slave manipulator proposed and we introduce them in Section III. In Section IV, the results of the three experiments are analyzed and discussed. In Section V, the conclusions of this study are given.

II. Design Of The Slave Manipulator

A. Overview of the mechanical structure

Fig. 3 shows the mechanical structure of the slave manipulator. The slave manipulator comprises four units. Unit 1, Unit 2 and Unit 3 are capable of axial movement and they can advance and retreat on the linear motion platform which consists of two linear sliders, one helical rack, three helical gears, three motors, six support brackets and two proximity switches. Each motor is separately fixed with a helical gear and two support brackets by a shaft. Each motor can drive a helical gear and two support brackets to move on the helical rack and the linear sliders. The proximity switches are used to prevent units from moving beyond the range of the linear sliders and the helical rack. The Unit 4 is fixed to the bottom plate and cannot be freely moved. Each unit has a grasper on which Grasper 1, Grasper 3 and Grasper 4 are electrical clamps that can be controlled by the motor. Grasper 1 is used to clamp or release the catheter, and Grasper 3 and 4 are used to clamp or release the guide wire. Grasper 2 is always in a clamped state, and its function is to clamp the tail of the catheter so that the tail of the catheter can move synchronously with the head, and a stable catheter tail helps the insertion of the guide wire. The function of the motor 1 is to rotate the catheter. When Grasper 1 clamps the catheter, the motor 1 is enabled, and Grasper 1 is rotated by the timing belt to achieve the purpose of rotating the catheter. The function of the motor 2 is to rotate the guide wire. When Grasper 3 clamps the guide wire, the motor 2 is enabled, and Grasper 3 is rotated together by the gear transmission to achieve the purpose of rotating the guide wire.

It’s necessary to control catheter and guide wire separately or simultaneously during vascular interventional surgery, therefore the four graspers from the slave manipulator proposed need to cooperate to control the catheter and guide wire. As shown in Fig. 4, the cooperation of the graspers, the red arrow indicates the grasper in the clamped state, and the gray arrow indicates the grasper in the released state. The process (1) is an initial state before the start of the operation. Grasper 1 clamps the catheter, Grasper 2 clamps the tail of the catheter, Grasper 3 clamps the guide wire and Grasper 4 is in a state of releasing the guide wire. The process (2) is the process of pushing and rotating the guide wire. When Grasper 3 advances, the guide wire is pushed, and when Grasper 3 is rotated, the guide wire can be rotated. The process (3) describes that when the movement range of the Unit 3 reaches the limit and the guide wire still needs to be pushed, Grasper 3

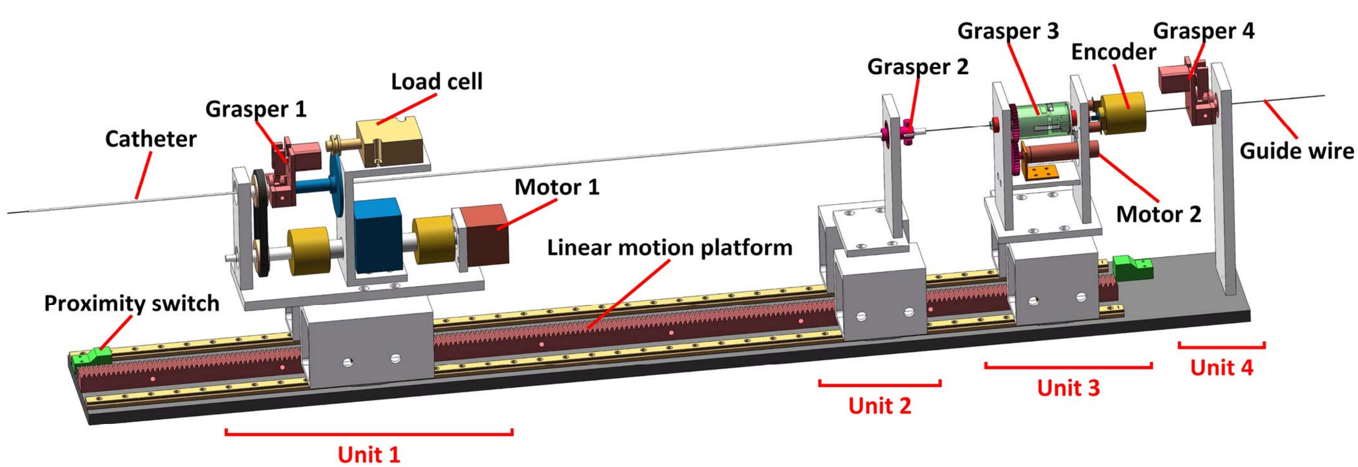

Fig. 3 Mechanical structure of the slave manipulator

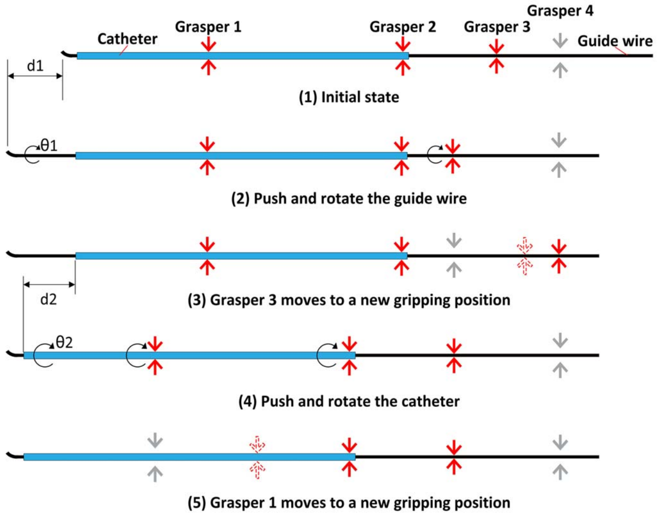

Fig. 4 Cooperation of the graspers

needs to move to a new gripping position in the state of releasing the guide wire, and then the guide wire is clamped for a new round of pushing. The red dotted arrow in Fig. 4 indicates the new gripping position. During the process (3), Grasper 4 is always in the state of clamping the guide wire in order to prevent the guide wire from slipping during the retraction of Grasper 3. The process (4) is the process of pushing or rotating the catheter. When Grasper 1 and Grasper 2 are simultaneously advanced, the catheter is pushed, and when Grasper 1 and Grasper 2 are simultaneously rotated, the catheter can be rotated. The process (5) is similar to process (3) and is the retraction process of Grasper 1.

According to the above description, by the slave manipulation, the doctor can operate the catheter or the guide wire separately, or can simultaneously operate the catheter and the guide wire, in accordance with the requirements of the vascular interventional surgery.

B. Grasping mechanism

In the design of a vascular interventional surgical robot, the design of the graspers is very important because the graspers must clamp the catheter and the guide wire without causing damage to the surfaces of them. If the surgical catheter or guide wire is displaced relative to the graspers, it will have a large impact on the accuracy of the surgery. Catheter and guide wire with damaged surfaces are prone to vascular occlusion, which is harmful to the safety of the surgery. Therefore, it's necessary to design a grasper that can clamp the catheter and guide wire without damaging their surfaces.

In our previous work, we have designed a grasper that meets the medical requirements [12]. From Grasper 1 and Grasper 4 on the slave manipulator, we continue to use the previously designed grasper architecture because it clamps the catheter and guide wire and does not damage the surface of the catheter and guide wire. Grasper 2 is a non-electric grasper with a simple structure. During operation, Grasper 2 is always in the state of clamping the tail of the catheter by means of two screws. Grasper 3 is a newly designed grasper that clamps

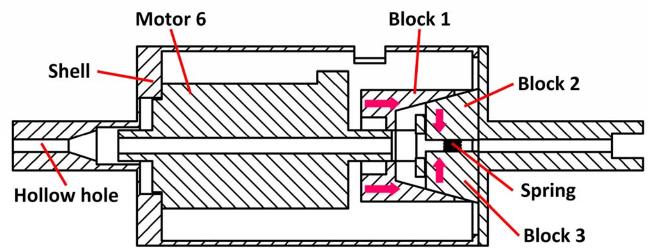

Fig. 5 Section view of Grasper 3

or releases the guide wire.

Fig. 5 shows the section view of Grasper 3. Grasper 3 clamps or releases the guide wire to be controlled by the motor 6. The shaft of the motor 6 is hollow and has external threads on the shaft. The guide wire can pass through the motor shaft from the hollow hole and then through the entire Grasper 3. The block 1 has an internal thread that cooperates with an external thread on the motor shaft. When the motor shaft rotates, the block 1 can move forward or backward. When the block 1 moves forward, the block 2 and the block 3 will approach each other, and finally the guide wire will be clamped. When the block 2 moves backward, under the elastic force of the spring, the block 2 and the block 3 will move away from each other, and finally the guide wire is released. On the block 2 and block 3, we put on a layer of flexible material, in order to increase the contact area between the grasper and the guide wire. This can increase the clamping force while avoiding damaging the surface of the guide wire.

C. Force Measurement

Force feedback is the focus of research on vascular interventional surgery robots. Whether providing the physician with visual feedback of the catheter and guide wire force information or tactile feedback, the slave manipulator can accurately measure the force experienced by the catheter and guide wire during the procedure and is the basis for providing force feedback. Accurate force feedback can greatly help doctors perform surgery and improves the safety of the operation. The force on the catheter and guide wire during vascular intervention is very small and requires a special force measurement mechanism to measure.

In our previous work, we have introduced the force measurement method of catheter in Unit 1 [13]. In this section,

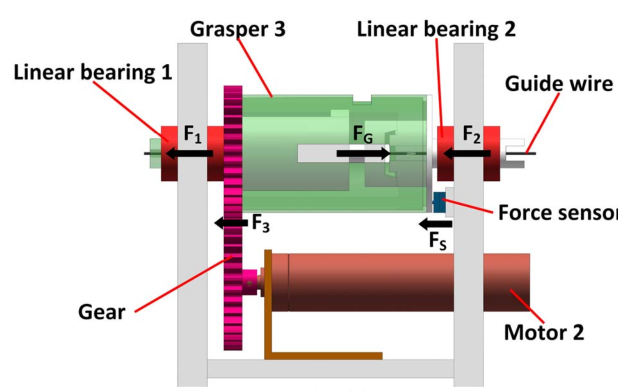

Fig. 6 The principle of force measurement

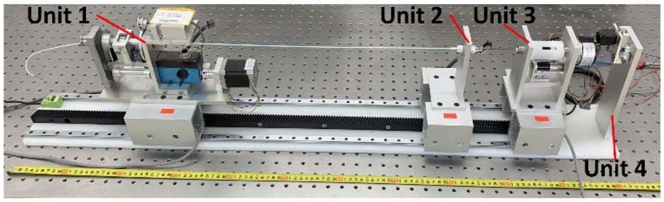

Fig. 7 Prototype of the slave manipulator

we introduce the newly proposed guide wire force measuring mechanism. The static connection of the force sensor and the transmission device is currently a better way to measure the force, because the catheter or the guide wire does not slip relative to the transmission device during static connection with respect to the dynamic connection. Grasper 3 is used to grasper the guide wire in a static manner. Fig. 6 shows the principle of force measurement. Grasper 3 is supported by two linear bearings so that it can be moved back and forth and rotated. Grasper 3 and the front end of the force sensor are infinitely close. The force of the guide wire can be obtained by:

$$F_G = F_S + F_1 + F_2 + F_3 \tag{1}$$

where F_G is the force of guide wire, F_S is the measured force of force sensor, F_1 is the friction force generated by the linear bearing 1, F_2 the friction force generated by the linear bearing 2, and F_3 is the friction force generated by the gearing. In

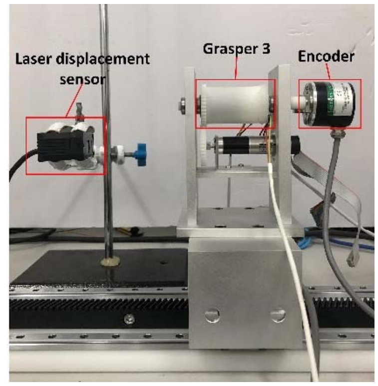

Fig. 8 Experimental set-up for motion evaluation of Unit 3

order to reduce the influence of friction, the key parts are well lubricated. Since the friction can be considered as a constant, we can accurately measure the force of the guide wire.

III. Experiments And Results

A. *Prototype of the slave manipulator*

Fig. 7 shows the prototype of the slave manipulator. The slave manipulator has a length of 112 cm, a width of 13 cm and a height of 22 cm. It can mimic the doctor's hands to push and rotate the catheter and guide wire. It can not only operate the catheter and guide wire separately or simultaneously, but also accurately measure their force during operation. Most of

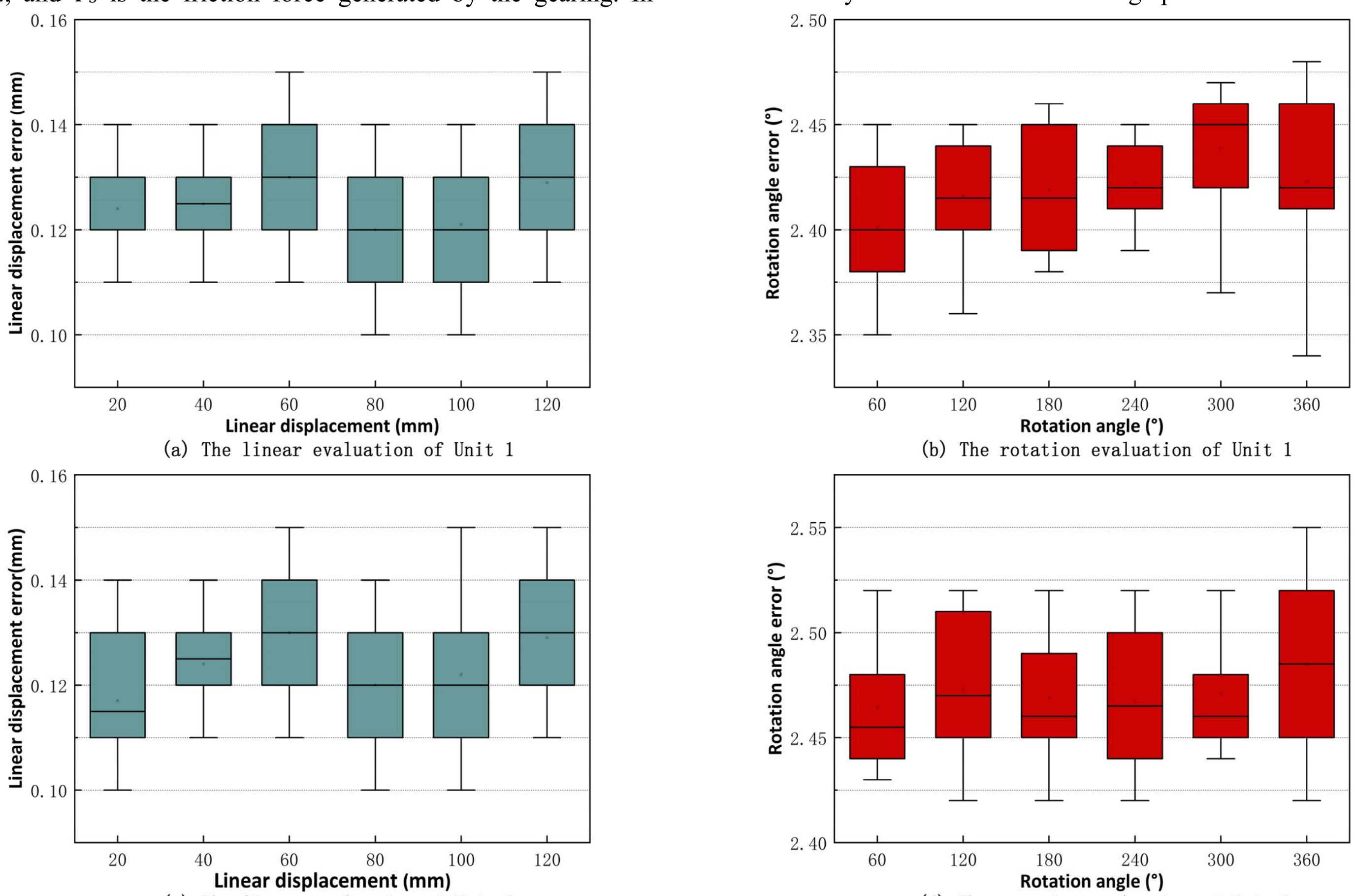

Fig. 9 Error of the motion evaluation

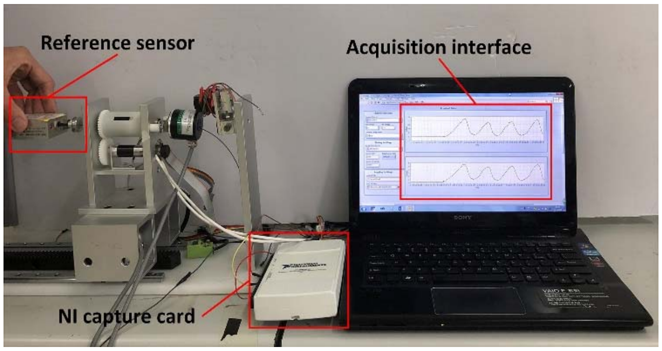

Fig. 10 Experimental set-up for force measurement of Unit 3

the structure of the slave manipulator is made of aluminum alloy.

B. Experiment for motion evaluation

To demonstrate that the proposed slave manipulator can accurately manipulate the catheter and guide wire, we evaluated the linear and rotational motion of Unit 1 and Unit3.

Fig. 8 shows the experimental set-up for motion evaluation of Unit 3. In order to evaluate the linear displacement accuracy of Unit 3, the motor 5 was controlled to advance by different distances (20 mm-120 mm), and performed ten experiments per distance. In this experiment, a laser displacement sensor was used to measure the displacement of Unit 3. In order to evaluate the rotation accuracy of Unit 3, the motor 2 was controlled to rotate different distances (60°-360°), and performed ten experiments for each distance. In this experiment, the distance the guide wire rotates is measured with an encoder. In order to verify the accuracy of the motion of Unit 1, the same experiments were carried out.

Error of the motion evaluation is shown in Fig. 9, (a) is the linear displacement error of Unit 1, (b) is the rotational distance error of Unit 1, (c) is the linear displacement error of Unit 3, and (d) is the rotational distance error of Unit 3. The linear displacement maximum error of the slave manipulator proposed is 0.16 mm and the rotation angle maximum error is 2.6°. The average value of the linear displacement error of Unit 1 is 0.12 mm, and the average value of the rotation angle error is 2.47°. The average value of the linear displacement error of Unit 3 is 0.12 mm, and the average value of the rotation angle error is 2.42°. From the experimental results, the error is within the expected specifications.

C. Experiment for grasping performance

In our previous work, it has been tested that Grasper 1 is capable of clamping the catheter without causing damage to the surface of the catheter. The maximum static friction between Grasper 1 and the catheter was 3.5 N.

In order to verify that Grasper 3 can clamp the guide wire and not destroy the surface of guide wire, we used a steel rod with a diameter of 0.8 mm instead of the surgical guide wire for the experiment. During the experiment, Grasper 3 was in the state of clamping the guide wire, and a reference sensor was used to push the steel rod from the horizontal position until the steel rod and Grasper 3 were relatively slide. A signal capture card was used to collect the thrust of the reference sensor in real time, and got the maximum thrust value. The maximum thrust value obtained is the maximum static friction of the guide wire relative to the grasper. Through experiments we detected the maximum static friction between Grasper 3 and the guide wire was 5 N.

D. Experiment for force measurement

In order to verify that the slave manipulator proposed can measure the force of the catheter and the guide wire accurately and in real time, we performed a dynamic force experiment on Unit 1 and Unit 3. Figure 10 shows the experimental set-up for force measurement of Unit 3. In the force measurement experiment of Unit 3, the method we used was similar to the method in the grasper performance experiment. We used a steel rod with a diameter of 0.8 mm instead of the surgical guide wire for the experiment. During the experiment, Grasper 3 was in the state of clamping the guide wire. We used a load cell to push the steel rod from the horizontal position, and used the NI capture card to collect the force data of the sensor (FSS015WNSX, Honeywell International Inc., US) in Unit 3 in real time.

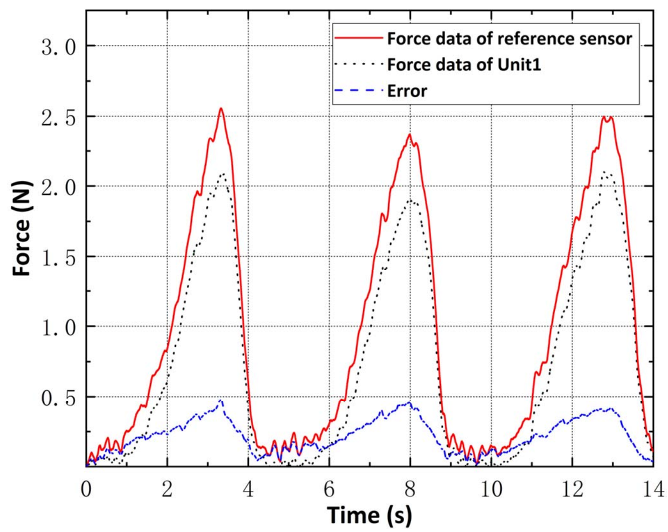

Fig. 11 Result of the force measurement for Unit 1

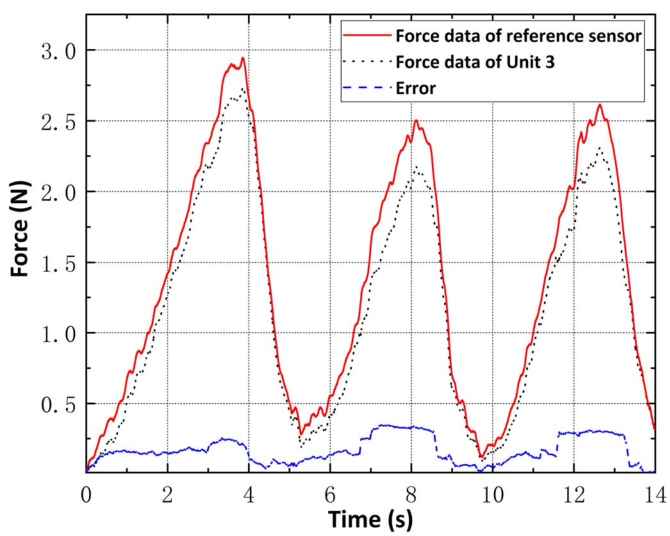

Fig. 12 Result of the force measurement for Unit 3

To evaluate the force measurement of Unit 1, we conducted the similar experiment. A steel rod with a diameter of 1.5 mm was used to replace the catheter.

Result of the force measurement for Unit 1 is shown in Fig. 11, and result of the force measurement for Unit 3 is shown in Fig. 12. The red line represents the sensor used for comparison in the experiments. The black line represents the force value measured by Unit 1 and Unit 3, respectively, and the blue line is the error after comparison. The results show that the force error average value in Fig. 11 is 9.7% relative to the force signal of Unit 1, and the force error average in Fig. 12 is 6.9% relative to the force signal of Unit 3.

IV. DISCUSSION

A. Experiment for motion evaluation

The cause of the error is mainly due to mechanical errors. The linear motion platform uses a rack and pinion structure. Although precision helical gears and helical racks are used, assembly errors are inevitable. The error in the rotational distance comes from the fit between the timing belt and the gear.

B. Experiment for grasping performance

The maximum static friction between Grasper 1 and the catheter was 3.5 N and the maximum static friction between Grasper 3 and the guide wire was 5 N. These two values are greater than 2.5 N which was applied by interventionalists on a catheter [14]. Some sponge is placed in Grasper 3 to increase the contact area with the surface of the guide wire, which can increase the friction and prevent the clamp from damaging the surface of the guide wire.

Therefore, Grasper 1 and Grasper 3 designed meet the requirements of vascular interventional procedures, and the proposed slave manipulator can clamp the catheter and guide wire without damaging the surfaces of them.

C. Experiment for force measurement

The perceptual resolution in force discrimination is 7-10% over a range of 0.5-200 N [15]. Grasper 1 and Grasper 3 are important to measure the force of the catheter and the guide wire. Grasper 1 is made of an aluminum alloy, and Grasper 3 is made of resin in addition to the motor, therefore Grasper 3 is lighter than Grasper 1. Grasper 1 transmits a force signal to the force sensor that needs to pass through a circular disk, the error of which is unavoidable, and Grasper 3 and the force sensor are in direct contact. Therefore, Unit 3 performed better than Unit 1 in the force measurement experiment.

V. CONCLUSIONS

In this study, we proposed a novel master-slave vascular interventional robotic system. This paper mainly designs the novel slave manipulator in the system. The proposed slave manipulator can simulate the doctor's hands to operate the catheter and guide wire and simultaneously operate the them. The graspers we designed can clamp the catheter and guide wire without damaging the surfaces of them. In order to study the force feedback in the future, the designed slave manipulator can accurately measure the force. In the future, we will study the causes of motion and force errors from the slave manipulator and reduce the error by compensating. We also conduct research on the master manipulator to achieve master-slave tracking and force feedback.

ACKNOWLEDGMENT

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REFERENCES

[1] J. Guo, S. Guo, N. Xiao, X. Ma, S. Yoshida, T. Tamiya and M. Kawanishi, “A Novel Robotic Catheter System with Force and Visual Feedback for Vascular Interventional Surgery,” *International Journal of Mechatronics and Automation*, vol.2, no. 1, pp. 15-24, 2012.

[2] J. Guo, X. Jin and S. Guo, “Study of the Operational Safety of a Vascular Interventional Surgical Robotic System,” *Micromachines*, vol. 9, no. 3, pp. 119, 2018.

[3] X. Bao, S. Guo, N. Xiao, Y. Li, C. Yang and Y. Jiang, “A cooperation of catheters and guidewires-based novel remote-controlled vascular interventional robot,” *Biomedical Microdevices*, vol. 20, no. 1, pp.20, 2018.

[4] J. Guo, S. Guo and Y. Yu, “Design and characteristics evaluation of a novel teleoperated robotic catheterization system with force feedback for vascular interventional surgery,” *Biomedical Microdevices,* vol. 18, no. 5, pp. 76, 2016.

[5] J. Guo and S. Guo, “A Marker-based Contactless Catheter-sensing Method to Detect Surgeons' Operations for Catheterization Training Systems,” *Biomedical Microdevices*, vol. 20, no. 3, pp. 76, 2018.

[6] S.Guo, Y. Song, X. Yin, L. Zhang, T. Tamiya, H. Hirata and H. Ishihara, “A Novel Robot-Assisted Endovascular Catheterization System with Haptic Force Feedback,” *The IEEE Transactions on Robotics*, 2019.

[7] M. Tavallaei, D. Gelman, M. Lavdas, A. Skanes, D. Jones, J. Bax and M. Drangova, “Design, development and evaluation of a compact telerobotic catheter navigation system,” *International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 12, no. 3, pp. 442-452, 2016.

[8] H. Su, W. Shang, G. Li, N. Patel and G. Fischer, “An MRI-Guided Telesurgery System Using a Fabry-Perot Interferometry Force Sensor and a Pneumatic Haptic Device,” *Annals of Biomedical Engineering*, vol. 45, no. 8, pp. 1917-1928, 2017.

[9] Z. Feng, G. Bian, X. Xie, Z. Hou and J. Hao, “Design and evaluation of a bioinspired robotic hand for percutaneous coronary intervention,” *Proceedings of 2015 IEEE International Conference on Robotics and Automation*, pp. 5338-5343, 2015.

[10] L. Cercenelli, B. Bortolani and E. Marcelli, “CathROB: A Highly Compact and Versatile Remote Catheter Navigation System,” *Applied Bionics and Biomechanics*, vol. 2017, no. 8, pp. 1-13, 2017.

[11] H.J. Cha, B.J. Yi and J.Y. Won, “An assembly-type master-slave catheter and guidewire driving system for vascular intervention,” *Proc Inst Mech Eng H*, vol. 231, no. 1, pp. 69-79, 2017.

[12] S. Guo, J. Guo, L. Shao, P. Wang, and Y. Wang, “Performance evaluation of the novel grasper for a robotic catheter navigation system,” *Proceedings of 2014 IEEE International Conference on Information and Automation*, 2014.

[13] J. Guo, S. Guo, L. Shao, P. Wang, and Q. Gao, “Design and performance evaluation of a novel robotic catheter system for vascular interventional surgery,” *Microsystem Technologies*, vol. 22, no. 9, pp. 2167-2176, 2015.

[14] Y. Thakur, D. Holdsworth and M. Drangova, “Characterization of catheter dynamics during percutaneous transluminal catheter procedures,” *IEEE Trans Biomed Eng*, vol. 56, no. 8, pp. 2140-2143, 2009.

[15] L. Jones, “Human and Machine Haptics,” By M. Cutkosky, R. Howe, K. Salisbury, and M. Srinivasan, Eds., MIT Press, 2000.