# A Novel Robotic Platform for Endovascular Surgery: Human–Robot Interaction Studies

Xiaoliang Jin, *Member, IEEE*, Shuxiang Guo, *Fellow, IEEE*, Aiguo Song, *Senior Member, IEEE*, Peng Shi, *Member, IEEE*, Xinming Li, *Graduate Student Member, IEEE*, and Masahiko Kawanishi

***Abstract*— Robot-assisted vascular interventional surgery (RVIS) is an emerging technology for the treatment of vascular diseases. It has obvious advantages over traditional manual operation, such as increased accuracy, reduced fatigue, and reduced tremor. However, current research suggests that natural human–robot interaction in RVIS is still a challenge that needs to be addressed. In this article, we developed a novel robotic platform that realized magnetorheological (MR) fluids-based haptic feedback to improve the interventionist's tactile presence. In addition, we proposed a force sensing method to accurately detect the real-time force of the flexible instrument and a collaborative operation method of the guidewire and the catheter to assist the flexible instruments in selecting the target blood vessel branch and reduce the operation difficulty of the interventionist. To verify the developed robotic platform and the proposed methods, we conducted the performance evaluation experiments in a blood vessel model and an endo vascular evaluator. The results indicated that the developed robotic platform and the proposed methods have great potential to improve the natural human–robot interaction in RVIS and guarantee safety.**

***Index Terms*— Collaborative operation method, guidewire and catheter, haptic feedback, natural human–robot interaction, robotic platform, safety performance.**

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Xiaoliang Jin is with the State Key Laboratory of Digital Medical Engineering, Jiangsu Key Laboratory of Remote Measurement and Control, School of Instrument Science and Engineering, Southeast University, Nanjing 210096, China, and also with the Graduate School of Engineering, Kagawa University, Takamatsu 761-0396, Japan (e-mail: jinxiaoliang@seu.edu.cn).

Shuxiang Guo is with the Department of Electronic and Electrical Engineering, Southern University of Science and Technology, Shenzhen 518055, China, and also with the Key Laboratory of Convergence Medical Engineering System and Healthcare Technology, Ministry of Industry and Information Technology, Beijing Institute of Technology, Beijing 100081, China (e-mail: guo.shuxiang@sustech.edu.cn).

Aiguo Song is with the State Key Laboratory of Digital Medical Engineering, Jiangsu Key Laboratory of Remote Measurement and Control, School of Instrument Science and Engineering, Southeast University, Nanjing 210096, China (e-mail: a.g.song@seu.edu.cn).

Peng Shi is with the School of Medical Technology and Engineering, Henan University of Science and Technology, Luoyang 471000, China, and also with the Graduate School of Engineering, Kagawa University, Takamatsu 761-0396, Japan (e-mail: shipeng@haust.edu.cn).

Xinming Li is with the Graduate School of Engineering, Kagawa University, Takamatsu 761-0396, Japan (e-mail: s21d504@kagawa-u.ac.jp).

Masahiko Kawanishi is with the Department of Neurological Surgery, Faculty of Medicine, Kagawa University, Takamatsu 761-0793, Japan (e-mail: mk@med.kagawa-u.ac.jp).

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## I. Introduction

IN RECENT years, vascular disease has become a typical disease that affects human health. It is characterized by rapid morbidity and high mortality. Due to the rapid development of medical technology, vascular interventional surgery (VIS) has become an effective way to treat vascular disease [1], [2]. The procedure of VIS is shown in Fig. 1. The main flexible instruments used in VIS are guidewires and catheters. In manual operations, interventionists must wear heavy protective clothing in the operating room with X-rays for a long time to operate the flexible instruments to the patient's lesion site for diagnosis and treatment. However, this can be a considerable challenge to the endurance and concentration of interventionists. Some recent publications have reported an increased risk of developing cancerous tumors, eye diseases, and bone diseases among individuals who are regularly exposed to X-rays [5], [6], [7]. In contrast, the emerging robot-assisted VIS (RVIS) has several obvious advantages, such as reduced fatigue, reduced tremor, and increased accuracy. It can also protect interventionists from X-rays. So, the emerging RVIS has attracted the attention of people from all walks of life and many researchers. Some research teams have achieved important results.

### A. Current Research Status

From the perspective of clinical operations, interventionists must wear heavy protective clothing to protect themselves from X-rays in the operating room. Whether it is the damage caused by X-rays or the inconvenience caused by heavy protective clothing, it will bring great challenges to interventionists. To solve this challenge, some studies focus on the development of a novel leader-follower robotic platform for VIS [8], [9], [10], [11], [12], [13], [14]. The haptic feedback function during the operation was achieved in different ways, including magnetorheological (MR) fluid-based [15], [16], [17], electromagnetic induction-based [18], spring-based [19], haptic device-based [10], [11], and linear motor-based [13], [14]. During the procedure of RVIS, the force sensing of flexible instruments in blood vessels was achieved by embedding the conductive liquid on the tip of the catheter [20] or integrating the force sensor based on the sensitive material [21] or the fiber Bragg grating [22], [23] into the flexible instrument. However, a recent publication also pointed out that integrating force sensors into flexible instruments may negatively affect their structural properties [24]. Sensorless

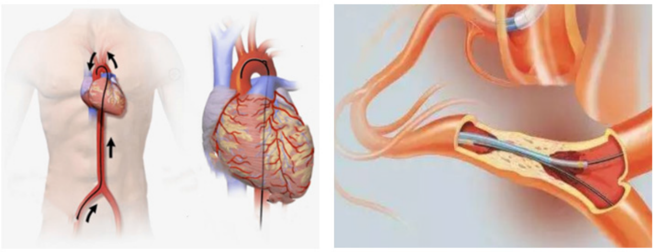

Fig. 1. Procedure of VIS [3], [4].

solutions, such as numerical finite element modeling and image feedback [25], kinetic modeling [26], and deep learning [27], have the potential to solve the limitations of the above methods. However, sensorless solutions are challenging to guarantee the accuracy of the force sensing in RVIS.

Safe operation is a topic that cannot be overlooked in RVIS. In recent years, advanced control algorithms have been developed to improve the performance of the robotic platform. For instance, an active disturbance rejection control [28], a simplified piecewise linear model [29], and an adaptive backlash compensation control [30] were proposed to improve the tracking accuracy and reduce the hysteresis of the robotic platform. A generalized predictive control [31] was proposed to inhibit the effect of the time-varying delay. Besides, a generative adversarial imitation learning [32] and a supervised semi-autonomous control [33] were proposed to automate the robotic platform. These algorithms are developed to improve the robotic platform's own performance, but few studies have focused on the improvement of the human–robot interaction in the procedure of RVIS.

### *B. Challenges and Contributions*

The main purpose of this article is to address the challenges of natural human–robot interaction in the procedure of RVIS through the studies of haptic feedback, the force sensing method, and the collaborative operation method of the catheter and the guidewire. The main contributions are listed as follows.

1) Based on our team's previous work on haptic feedback using MR fluid, a novel robotic platform for VIS was developed. The haptic feedback function of the robotic platform improves the interventionist's tactile presence.
2) The force sensing method was achieved by integrating a force sensor into the robot platform. This addresses the limitations of existing methods, such as the difficulty of integrating a force sensor into a flexible instrument without affecting its structural properties and the limited accuracy of sensorless solutions.
3) The collaborative operation method was proposed to assist the flexible instrument in correctly selecting the target blood vessel branch. This method simulates the interventionist's operation of flexible instruments in clinical surgeries and collaboratively delivers the guidewire and catheter with good flexibility. This can reduce the interventionist's operation difficulty and avoid the risk of puncture.

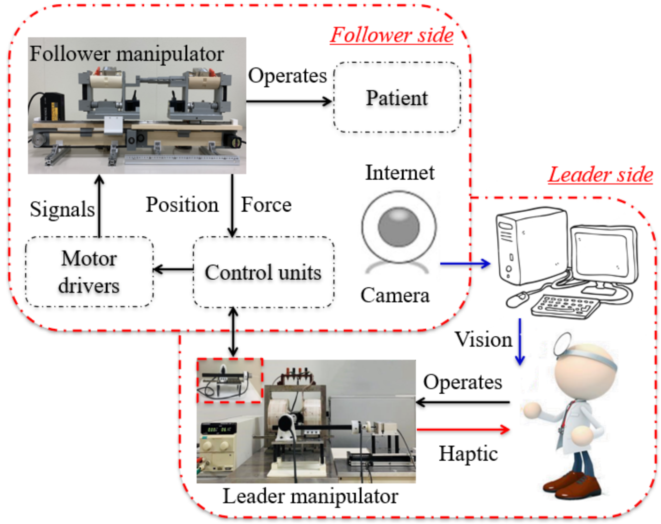


Fig. 2. Concept of RVIS.

4) A series of performance evaluation experiments were carried out in a blood vessel model and an endo vascular evaluator. The results indicated that the developed robotic platform and the proposed methods have great potential to improve human–robot interaction in the procedure of RVIS and guarantee safety.

Finally, the rest of this article is organized as follows: Section II describes the concept, structure, principle, and method of the robotic platform. Section III presents the validation experiments, mainly including the positioning ability of the follower manipulator, the collaborative operation performance of the robotic platform, the haptic feedback performance of the robotic platform, and the subjective evaluation of the novel robotic platform. Section IV summarizes the obtained results and discusses the limitations of the current research. Section V concludes this article and discusses the future work.

## II. Novel Robotic Platform

### *A. Description*

RVIS is a research hot spot in the intersection of medicine and engineering and has obvious advantages over traditional manual operation. The concept of RVIS is shown in Fig. 2. Generally, the robotic platform is developed in a "leader-follower" structure to protect interventionists from X-rays. During the surgery, the leader manipulator captures the interventionist's surgical actions, controls the delivery of surgical instruments from the follower manipulator, and provides haptic guidance to the interventionist. The follower manipulator delivers surgical instruments in the operating room instead of the interventionist and provides position information and force information of surgical instruments. The medical imaging system provides real-time visual feedback to the interventionist. RVIS is performed under haptic and visual guidance.

### *B. MR Fluids-Based Leader Manipulator*

The MR fluids-based leader manipulator is developed based on our previous studies, and its structure is shown in Fig. 3.

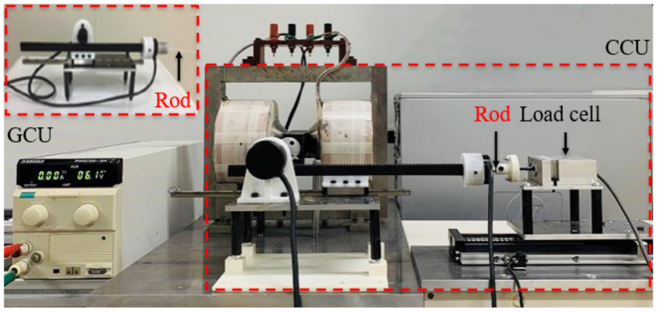


Fig. 3. Structure of the MR fluids-based leader manipulator (GCU has not yet incorporated haptic feedback, and CCU has incorporated haptic feedback).

TABLE I
PARAMETERS OF THE MR FLUIDS (LORD. CORP.) [34]

| MRF-122EG | |
|---|---|
| Appearance | Dark gray liquid |
| Viscosity (Pa s at 40˚C) | 0.042±0.020 |
| Density (g/cm$^3$(lb/gal)) | 2.28 (2.48) |
| Solids content by weight (%) | 72 |
| Flash point (˚C) | >150 |
| Operating temperature (˚C) | -40 to 130 |

The GCU is the guidewire control unit, and the CCU is the catheter control unit. The MR fluids-based leader manipulator is easy to operate and has the function of haptic feedback. The capture of surgical actions, mainly including the insertion, retraction, and rotation of the operating rod, is realized by encoders (MTL, MES020-2000P, Japan). The haptic feedback is achieved based on MR fluids. The characteristics of MR fluids can be simply understood as follows, when there is no external magnetic field applied, it behaves as a “Newtonian” fluid with low viscosity; when an external magnetic field applied, it behaves as a “Bingham” fluid with high viscosity and low fluidity. MR fluids are often used to design and develop dampers because of their active properties. The parameters of the MR fluids used in this article are shown in Table I.

*1) Realization of Haptic Feedback:* As mentioned before, the haptic feedback of RVIS is achieved based on the characteristics of MR fluids. The viscosity of MR fluids depends on the intensity of the magnetic field. During the operation, the interventionist operates the GCU and CCU of the leader manipulator to control the follower manipulator to deliver the guidewire and catheter to the target position for diagnosis and treatment. When the catheter is subjected to force, the electric current connected to the magnetic field generator will be changed in response. The force generated by the MR fluids will be transmitted to the interventionist’s hand through the operating rod. The method of providing the magnetic field is shown in Fig. 4. It is inspired and constructed according to the principle of electromagnetism. The parameters of each coil are as follows, the inner and outer diameters are 30 and 120 mm, respectively, and the number of turns is 1200 T. To increase the intensity of the magnetic field, an iron core is inserted into the center of the coil.

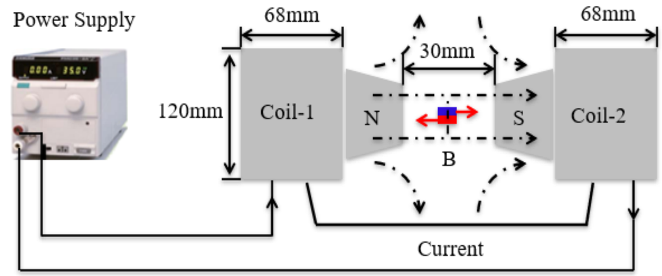


Fig. 4. Method of providing the external magnetic field.

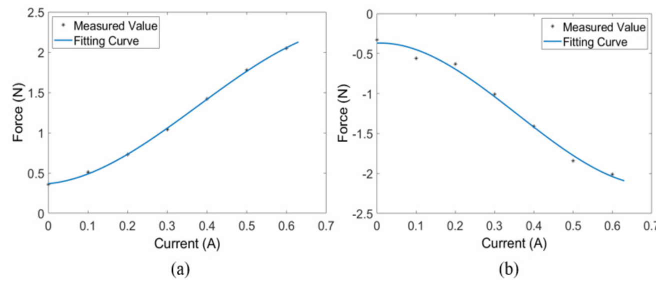


Fig. 5. Relation between the haptic force generated by the MR fluids and the electric current. (a) Tension. (b) Thrust.

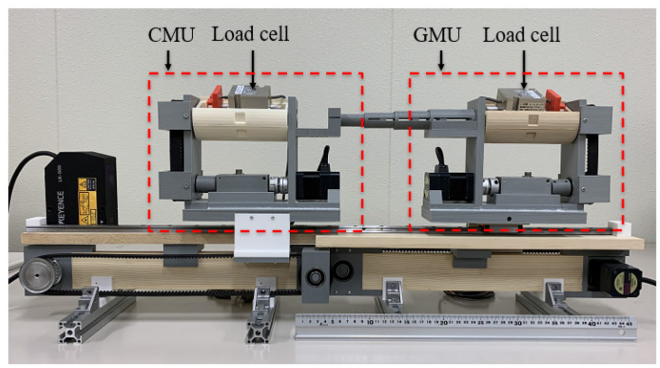


Fig. 6. Structure of the follower manipulator.

*2) Calibration of Haptic Feedback:* Experimental setup for the calibration of haptic feedback is shown in the CCU of Fig. 3. A load cell with a measurement range of −5–5 N (TU-UJ5N, TEAC, Japan) was installed on a lead screw connected to a stepping motor with a resolution of 0.36° (ASM46AA, ORIENTAL MOTOR, Japan). The operating rod in the CCU was pushed and pulled by the stepping motor, which ran at a constant speed. The electric current connected to the magnetic field generator was increased from 0 to 0.7 in steps of 0.1. The relationship between the haptic force generated by the MR fluids and the electric current is shown in Fig. 5. The points are the measured values, and the line is the fitting curve fit by MATLAB. Therefore, the haptic force that the leader manipulator fed back to the interventionist during the operation can be calculated.

## C. Follower Manipulator

The structure of the developed follower manipulator is shown in Fig. 6. The CMU is the catheter manipulation unit, and the GMU is the guidewire manipulation unit. These two manipulation units are similar in structural design. The linear

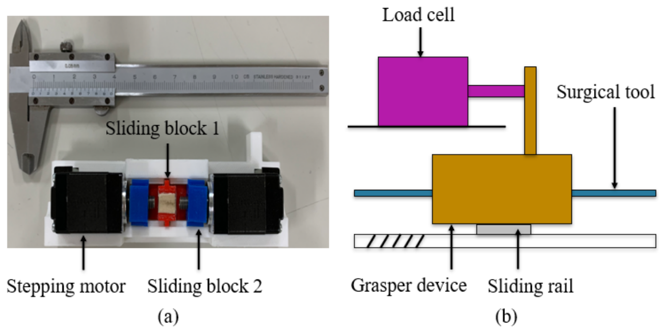


Fig. 7. Grasper device and the force sensing method. (a) Grasper device. (b) Proposed force sensing method of the flexible instrument.

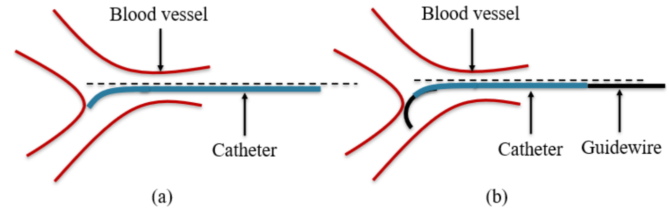


Fig. 8. Concept of two operating methods. (a) Method of only operating the catheter. (b) Concept of the collaborative operation of the guidewire and the catheter.

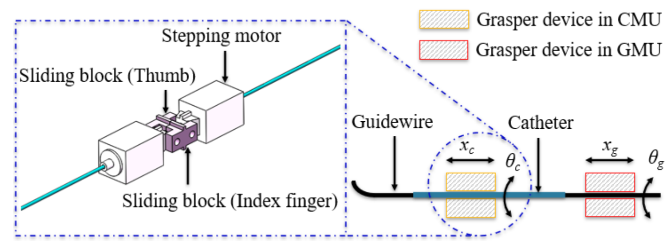


Fig. 9. Operation process of using two grasper devices to perform the delivery of the guidewire and the catheter.

motion and the rotation motion of the guidewire and the catheter are both driven by the stepping motor. The total force of the catheter and the guidewire is detected by the load cell when the follower manipulator is doing the linear motion. The torque of the guidewire and the catheter is detected by the torque sensor when the follower manipulator is doing the rotation motion (the specifications of the stepping motor and the load cell are described in the section "*the calibration of hapticfeedback*").

*1) Grasper Device:* The grasper device is developed to clamp flexible instruments for the linear motion and the rotation motion, just like the interventionist's hand. The structure of the grasper device is shown in Fig. 7(a). The guidewire or the catheter can be clamped by two *sliding blocks 1* under the elastic action of the spring. Two hollow stepping motors (20BYGH30-0604A-ZK3M5, LIKO MOTOR, China) are used to adjust the relative distance of two *sliding blocks 2*, achieving the clamping and releasing of the guidewire or the catheter. Rubber is attached to the contact surface of the *sliding block 1* to improve the clamping effect of the grasper device on the flexible instrument.

*2) Force Sensing Method:* In the traditional manual operation, interventionists rely on their surgical experience to estimate the force on the ends of the guidewire and the catheter, which can be difficult and error-prone. In contrast, RVIS uses a novel robotic platform that integrates force sensors to accurately obtain the force of flexible instruments. This can reduce the operation difficulty for interventionists. This study proposes a force sensing method. As shown in Fig. 7(b), a sliding rail is installed on the bottom of the grasper device. The output shift of the load cell is mechanically connected to the grasper device. During the operation, when the surgical instrument is subjected to a force in the patient's blood vessel, the grasper device will move slightly under the action of the small sliding rail. The load cell will output the force value. For the GMU, if the load cell outputs a positive value, the guidewire is inserting. If the load cell outputs a negative value, the guidewire is retracting. For the CMU, if the load cell outputs a positive value, the catheter is retracting. If the load cell outputs a negative value, the catheter is inserting.

The collaborative operation of the guidewire and the catheter is an important method in RVIS. In clinical surgeries, the complex distribution of blood vessels in the human body makes it difficult for interventionists to deliver the catheter to the target position without the guidance of a guidewire. This study also proposes a collaborative operation method to reduce the operation difficulty of interventionists during RVIS. As shown in Fig. 8, the method of only operating the catheter is shown in Fig. 8(a). In this case, the selection of the target blood vessel branch is achieved by the elastic force of the blood vessel on the catheter and the deflection of the catheter tip. However, this method is easy to damage the blood vessel, resulting in puncture. The concept of collaborative operation method of the guidewire and the catheter is shown in Fig. 8(b). The selection of the target blood vessel branch can be achieved through the guidance of the guidewire. In contrast, the collaborative operation method is more flexible and can reduce the operation difficulty of interventionists.

From the structural design of the robotic platform, the leader manipulator consists of two independent units that do not interfere with each other: the GCU and the CCU. The follower manipulator consists of two independent units that do not interfere with each other: the GMU and the CMU. The collaborative operation of the guidewire and the catheter can be described as follows. In RVIS, the interventionist operates the leader manipulator to control the follower manipulator. The grasper device clamps the guidewire and the catheter and then selectively completes the independent delivery of the guidewire, the independent delivery of the catheter, and the simultaneous delivery of the guidewire and the catheter. The operation process of using two grasper devices to perform the delivery of the guidewire and the catheter is shown in Fig. 9, $x_c$ and $x_g$ represent the translations of the guidewire and the catheter, respectively, and $\theta_c$ and $\theta_g$ represent the rotations of the catheter and the guidewire, respectively.

### *D. Console*

The motion commands of the leader side are transmitted to the actuator of the follower side through two Arduino

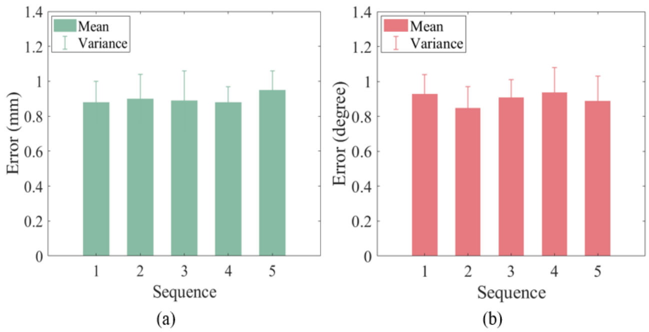


Fig. 10. Mean and variance of the difference between the theoretical and the actual measured values. (a) Linear motion. (b) Rotation motion.

controllers. One controller is used to record the operating information of the GCU and achieve the control of the GMU. The other controller is used to record the operating information of the CCU and achieve the control of the CMU. The total force of the flexible instrument is detected by the load cell equipped on the follower manipulator and then transmitted to the computer through an acquisition card (AD 16-16U, CONTEC, Japan). The control software is realized using C++.

## III. Experiments and Results

The performance evaluation experiment of the robotic platform will be designed and completed in this section. The positioning ability of the follower manipulator will be verified in Section III-A, the collaborative operation performance of the robotic platform will be verified in Section III-B, the haptic feedback performance of the robotic platform will be verified in Section III-C, and the subjective evaluation of the robotic platform will be completed in Section III-D.

### A. Positioning Ability of the Follower Manipulator

*1) Experimental Setup:* To verify the performance of the follower manipulator in positioning the target position, the linear motion and the rotation motion of the follower manipulator were evaluated five times each. Both the linear motion and the rotation motion were driven by the synchronous belt, and the diameter of the two synchronous pulleys was 46.3 mm. So, the transmission ratio was 1:1. For the evaluation of the linear motion, the motion range was set from 0 to 218 mm. The stepping motor rotated 45° at a time, and a laser sensor with an accuracy of 50 $\mu$m/mV (LK-5000, KEYENCE Corporation, Japan) was used to measure the displacement. For the evaluation of the rotation motion, the motion range was set from 0° to 360°. The stepping motor rotated 45° at a time, and an encoder with an accuracy of 0.09°/pulse was used to measure the rotation angle.

*2) Experimental Results:* The results are shown in Fig. 10. In Fig. 10(a), the mean of the difference between the theoretical and measured values was 0.88, 0.90, 0.89, 0.88, and 0.95, respectively. The variance of the difference between the theoretical and actual measured values was 0.12, 0.14, 0.17, 0.09, and 0.11, respectively. In Fig. 10(b), the mean of the difference between the theoretical and actual measured values was 0.93, 0.85, 0.91, 0.94, and 0.89, respectively. The variance of the difference between the theoretical and actual measured values was 0.11, 0.12, 0.10, 0.14, and 0.14, respectively. In addition, the maximum difference in each group of data for the linear motion evaluation was less than 2 mm, and the maximum difference in each group of data for the rotation motion evaluation was less than 2°.

### B. Collaborative Operation Performance of the Developed Robotic Platform

*1) Experimental Setup:* To verify the performance of the novel robotic platform in collaborative operation of the catheter and the guidewire, the evaluation was carried out in a blood vessel model. As shown in Fig. 11(a), the inner and outer diameters of the blood vessel model are 5 and 7 mm, respectively. The catheter and the guidewire were delivered by the follower manipulator from position A to position C, where position C was the target position. To highlight the advantages of the collaborative operation method, the validation experiment was conducted in two different conditions: one in which the catheter was operated alone and the other in which the collaborative operation method was used. The flexible instruments used in this experiment mainly included a guidewire with a tip angle of 45° and a catheter with the specification of 4 Fr ($\Phi \approx 1.333$ mm).

*2) Experimental Results:* The results are shown in Figs. 11(b)–(e) and 12. Fig. 11(b) and (c) shows the operation process under the method of only operating the catheter, which is a failed sample of locating the target blood vessel branch. Fig. 11(d) and (e) shows the operation process under the method of collaborative operating the catheter and the guidewire, which is a successful sample of locating the target blood vessel branch. In the failed sample, the correct path should be A–B–C. However, without the guidance of the guidewire, the catheter cannot correctly enter the target blood vessel branch. To avoid the failure of the experiment due to lack of operation experience, the catheter was retreated to the starting position A, and the experiment was performed once again, but it still failed to enter the target blood vessel branch. The main reason may be that the corner at position B was too large, and the tip of the catheter was not as flexible as the guidewire, resulting in the catheter being difficult to choose the target blood vessel correctly. In contrast, with the proposed collaborative operation method, the catheter can select the target blood vessel branch correctly. In the successful sample, the guidewire was first inserted into the target blood vessel branch due to the flexibility of its tip, and then, the catheter passed through the corner at position B along the path of the guidewire. Finally, the catheter located the target blood vessel branch successfully.

The force of the flexible instrument during the surgery is shown in Fig. 12. The force obtained under the method of only operating the catheter is shown in Fig. 12(a), and the force obtained under the collaborative operation method is shown in Fig. 12(b). In Fig. 12(a), as the catheter was pushed, the area of contact between the catheter and the blood vessel model increased, and the maximum force was −0.84 N. At $T = 5$ s, the catheter was retracted, and the direction of the force was

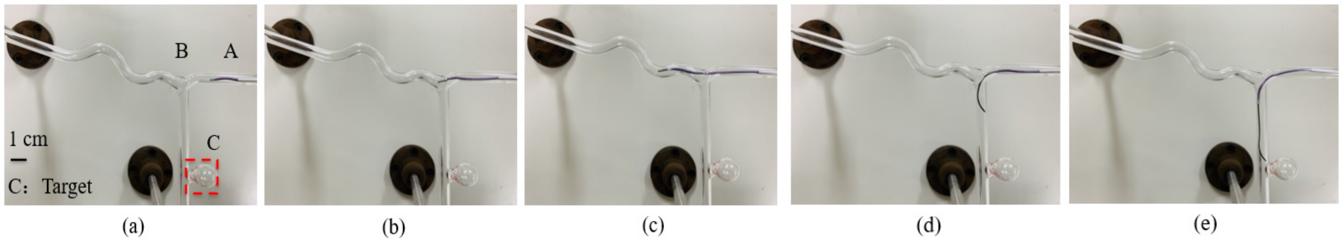


Fig. 11. Operation process of two operation methods for locating the target blood vessel. (a) Experimental setup. (b)–(c) Failed sample. (d) and (e) Successful sample.

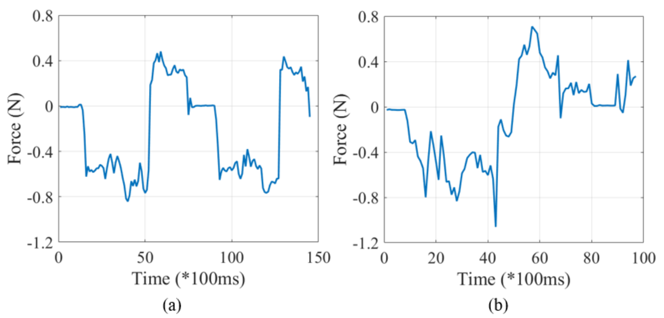


Fig. 12. Real-time force of the flexible instrument during the operation. (a) Failed sample. (b) Successful sample.

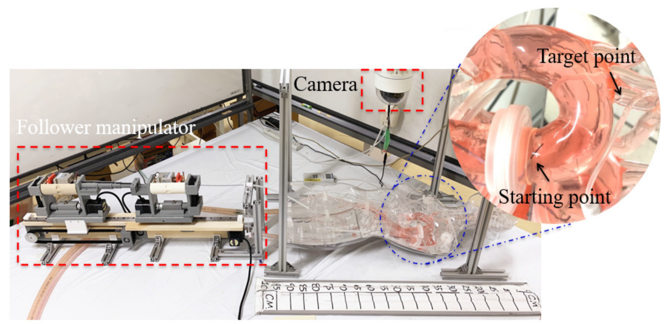


Fig. 13. Experimental setup in EVE model (pressure: 120/80 mmHg).

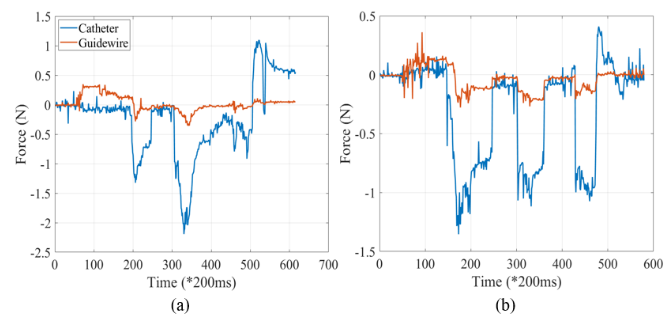


Fig. 14. Real-time force of the flexible instrument during the operation. (a) Without haptic feedback. (b) With haptic feedback.

changed, and the maximum force was 0.48 N. The operation process was completed twice, so there are two similar data segments. In Fig. 12(b), the catheter was pushed along the path of the guidewire. At $T = 4.3$ s, the catheter reached the target position, and the maximum force was $-1.06$ N. Then, the catheter was retracted, the direction of the force was changed, and the maximum force was 0.71 N.

### *C. Haptic Feedback Performance of the Developed Robotic Platform*

*1) Experimental Setup:* To verify the performance of the novel robotic platform in haptic feedback, the evaluation was carried out in an endo vascular evaluator model (EVE Fain-biomedical, Nagoya, Japan). The experimental setup is shown in Fig. 13. To make the experimental environment more realistic, the pressure of the fluid in the EVE model was set to 120/80 mmHg. The starting position and the target position were set in the arcus aortae and the left subclavian artery, respectively. The flexible instrument used in this experiment mainly included a guidewire with a tip angle of 45° and a catheter with the specification of 5 Fr ($\Phi \approx 1.667$ mm).

*2) Experimental Results:* The force of the flexible instrument during the operation is shown in Fig. 14. Fig. 14(a) is obtained under the condition of without haptic feedback, and Fig. 14(b) is obtained under the condition of with haptic feedback. The guide wire and the catheter were delivered to the target point using the collaborative operation method. The force of the catheter is shown in the blue line, and the force of the guidewire is shown in the red line. The guidewire was first pushed; then, the catheter followed the path of the guidewire. In Fig. 14(a), the catheter was pushed twice by the follower manipulator to reach the target position, so there were two significant increases in the force, with maximum values of 1.32 and 2.19 N, respectively. In Fig. 14(b), the catheter was pushed three times by the follower manipulator to reach the target position, so there were three significant increases in the force, with maximum values of 1.35, 1.12, and 1.07 N, respectively. It is obvious that the force of the catheter is relatively small, and the operation is relatively safe under the haptic guidance of the MR fluids-based leader manipulator during the operation. However, the catheter was pushed three times. The reason for this may be that the posture of the catheter was adjusted appropriately under the guidance of the haptic feedback.

### *D. Subjective Evaluation Experiment of the Developed Robotic Platform*

*1) Experimental Setup:* To subjectively evaluate the developed robotic platform for VIS, ten participants with different research experiences in the field of RVIS were recruited to complete the experiment in the EVE model. The settings were the same as in Section III-C. The pressure of the fluid in the

TABLE II
CONTENT OF THE QUESTIONNAIRE

| No. | | The content of the questionnaire |
|---|---|---|
| 1 | Q1 | Is the robotic platform easy to be operated? |
| | Q2 | Is the robotic platform easy to be learned? |
| 2 | Q3 | Does the robotic platform provide haptic force |
| | Q4 | Does the robotic platform has good safety performance? |
| 3 | Q5 | Is the robotic platform easier to locate the target position? |
| | Q6 | Is the grasper device easy to be controlled? |

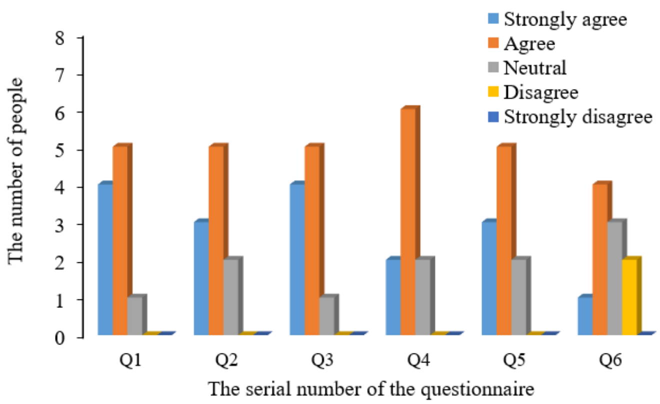


Fig. 15. Statistical results of the question listed in Table II after the experiment was completed in the EVE model.

EVE model was set to 120/80 mmHg, and the starting position and the target position were set in the arcus aortae and the left subclavian artery, respectively. The flexible instrument used in this experiment mainly included a guidewire with a tip angle of 45° and a catheter with the specification of 5 Fr ($\Phi \approx$ 1.667 mm).

This experiment was conducted in the form of a questionnaire. The questionnaire mainly considered the following aspects. The content of the questionnaire is listed in Table II.

1) *The robotic platform design (Q1 and Q2):* Two operating rods were integrated into the MR fluids-based leader manipulator to simulate the flexible instrument. Is the robotic platform easy to be operated and learned?
2) *The haptic feedback (Q3 and Q4):* The MR fluids-based haptic feedback has been achieved. Does the robotic platform provide haptic force and has good safety performance?
3) *The collaborative operation of the guidewire and the catheter (Q5 and Q6)*: Is the robotic platform easier to locate the target position compared to the method of only operating the catheter?

*2) Experimental Results:* The statistical results of the questions listed in Table II after the experiment was completed in the EVE model are shown in Fig. 15. The results indicated that the robotic platform is easy to operate and learn, the realization method of haptic feedback is effective and improves the safety of RVIS to some extent, and the collaborative operation method is helpful for the accurate positioning of the target position. However, for the last question, two participants believed that the control methods of the grasper device should be improved in the future.

## IV. DISCUSSION

RVIS is a research hot spot in the intersection of medicine and engineering. In our team's previous work [15], [16], the MR fluid-based leader manipulator was deeply analyzed, verified, and discussed, providing a solid foundation for this study. In this study, we developed a novel robotic platform for VIS by combining our team's previous work, proposed a force sensing method, and a collaborative operation method for the guidewire and the catheter during operation. We focused on the application research of the robotic platform. Some experiments were carried out in a blood vessel model and an endo vascular evaluator. In this section, we will analyze and discuss the obtained results and the limitations of the current research.

In Section III-A, the positioning ability of the follower manipulator was verified. The maximum difference in each group of data was less than 2 mm and 2° for both linear motion and rotation motion. This indicates that the follower manipulator has good stability. In Section III-B, the proposed collaborative operation method was preliminarily verified. The catheter was able to successfully enter the target blood vessel branch under the guidance of the guidewire, although the corner at position B [see Fig. 11(a)] was too large. However, this experiment was relatively simple. To further verify the effectiveness of the proposed collaborative operation method, we used this method to complete the experiment in Section III-C. The guidewire and the catheter were still successfully delivered to the target position [see Fig. 13]. This indicates that the proposed collaborative operation method is effective. In Section III-C, the haptic feedback of the developed robotic platform was verified. The maximum force during the operation was significantly lower than that of without haptic feedback. This indicates that the MR fluids-based haptic feedback plays a positive role in improving the safety of RVIS. In Section III-D, the robotic platform and the proposed methods were verified by a subjective evaluation.

It is worthy emphasize that the current limitation of this study is the delay in haptic feedback. Based on our team's previous work [15], [16], we know that the delay in haptic feedback is mainly due to the ferromagnetic elements of the magnetic field generator in the leader manipulator, including the iron core and coil. Little or no hysteresis is observed in the B–H curve of MR fluids [35]. By analyzing the results of "The Calibration of Haptic Feedback," we also found that when the operating state of the operating rod changed from push to pull, the detected haptic force did not reach the maximum value immediately. It would reach the maximum value after about 400–600 ms. Existing research in [36] shows that the limitation of the delay in haptic feedback can be addressed by using an adaptive hysteresis compensation control method. In the future, we will focus on addressing the delay in haptic feedback.

## V. CONCLUSION

This article focuses on the improvement of natural human–robot interaction in RVIS. The main contributions of this article include the development of a novel robotic platform for VIS that realizes MR fluids-based haptic feedback to improve the interventionist's tactile presence during the operation. Additionally, a force sensing method and a collaborative operation method were proposed to accurately detect the real-time force of the flexible instrument and correctly assist the flexible instrument in selecting the target blood vessel. To verify the robotic platform and the proposed methods, a series of experiments were carried out in a blood vessel model and an endo vascular evaluator. The results indicated that the novel robotic platform and the proposed methods have great potential to improve the human–robot interaction between the interventionist and the robotic platform in RVIS and guarantee safety.

The limitations of the current research will be addressed in the future. The robotic platform will be evaluated by an experiment in vivo.

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**Xiaoliang Jin** (Member, IEEE) received the Ph.D. degree in intelligent mechanical systems engineering from Kagawa University, Takamatsu, Japan, in 2022.

He is currently a Post-Doctoral with the State Key Laboratory of Digital Medical Engineering, Jiangsu Key Laboratory of Remote Measurement and Control, School of Instrument Science and Engineering, Southeast University, Nanjing, China. His research interests include medical robotics, force control, and haptic feedback.

**Shuxiang Guo** (Fellow, IEEE) received the Ph.D. degree in mechano-informatics and systems from Nagoya University, Nagoya, Japan, in 1995.

He is currently a Chair Professor with the Department of Electronic and Electrical Engineering, Southern University of Science and Technology, Shenzhen, Guangdong, China, and also a Chair Professor with the Key Laboratory of Convergence System and Healthcare Technology Medical Engineering, The Ministry of Industry and Information Technology, Beijing Institute of Technology, Beijing, China. His research interests include medical robot systems, microcatheter systems, and biomimetic underwater robots.

Prof. Guo has a fellowship of The Engineering Academy of Japan.

**Aiguo Song** (Senior Member, IEEE) received the Ph.D. degree in measurement and control from Southeast University, Nanjing, China, in 1996.

From 1996 to 1998, he was an Associate Researcher with the Intelligent Information Processing Laboratory, Southeast University, where he was an Associate Professor with the Department of Instrument Science and Engineering from 1998 to 2000, and the Director of the Robot Sensor and Control Laboratory from 2000 to 2003. From April 2003 to April 2004, he was a Visiting Scientist with the Laboratory for Intelligent Mechanical Systems, Northwestern University, Evanston, IL, USA. He is currently a Professor with the Department of Instrument Science and Engineering, Southeast University. His research interests include haptic display, robot tactile sensor, and tele-rehabilitation robot.

Prof. Song is a member of the Chinese Instrument and Control Association.

**Peng Shi** (Member, IEEE) received the Ph.D. degree in intelligent mechanical systems engineering from Kagawa University, Takamatsu, Japan, in 2022.

He is currently a Lecturer with the School of Medical Technology and Engineering, Henan University of Science and Technology, Luoyang, China. His research interests include medical robotics, force control, and haptic feedback.

**Xinming Li** (Graduate Student Member, IEEE) received the B.S. and M.S. degrees from the Tianjin University of Technology, Tianjin, China, in 2017 and 2020, respectively. He is currently pursuing the Ph.D. degree with Kagawa University, Takamatsu, Japan.

His research interests include medical robotics, safety operation, and haptic feedback.

**Masahiko Kawanishi** received the B.S. degree from the Faculty of Medicine of Kagawa Medical University, Kagawa, Japan, in 1993.

He is currently an Associate Professor with the Faculty of Medicine, Kagawa University, Takamatsu, Japan. His research interests include surgical techniques of neurosurgical operations and intravascular surgery systems.