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Performance Evaluation of a Collaborative Vascular Interventional Robot in Glass Blood Vessel

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***Abstract* – Robot-assisted vascular minimally surgery (VIS) always has significant values of medical application and commercial exploitation to accomplish purposes of assisting the surgeon operation and improving the surgical safety. We developed a novel collaborative vascular interventional robot in our recent study. Two types of independent operating handles and magnetically controlled haptic feedback were used on master side. This kind of robot has multiple operating modes due to the collaborative design. This paper shows the structure of master device, introduces the achieving mechanism of haptic feedback, and analyzes collaborative operating mechanisms. The performance of this robot was evaluated by comparative experiments in a glass blood vessel with dissimilar environments. Experimental results indicate that the developed collaborative vascular interventional robot has good display in glass blood vessel with and without simulated blood. This study also has potential influence and reference value for the design and development of co-operating robots in the field of master-slave robotics.**

Index Terms* – *Vascular interventional robot, Collaborative operation, Master-Slave structure, Haptic feedback.

I. Introduction

Recently, cardiovascular disease is still a medical challenge due to injury and randomness for both of patients and surgeons [1]. Vascular interventional surgery (VIS) is undergoing a rapid growth, which is a treatment method with some advantages including minimal invasive, less intraoperative pain, and fast postoperative recovery. Particularly, robot-assisted VIS is an advanced method to address the problem of prolonged radiation exposure for doctors. And also, robot-assisted VIS has benefits in several aspects including remote operation, safe surgery, highly accurate digital control, and decreasing workload [2]. The structure of master-slave makes it possible to develop teleoperation technology and expert intervention [3], which would be a huge step for teletherapy in inconvenient areas.

In the past decade, related studies mainly focus on structure design for master-slave robotic system [4]-[6] and improvement of safety performance for operation [7]-[9]. Robot-assisted surgeries have been popularized in the field of medical procedures, especially in minimally interventional surgeries. To ensure the safety of robot-assisted VIS, a great deal of researchers pay attention to a high level of stability and transparency for EC robotic systems. Robust mechanical design for EC robots, high precision force feedback structure, and smooth interventional navigation system have witnessed the rocket development of robot-assisted technology. A novel smart material named magnetorheological (MR) fluid was used to provide haptic feedback in an endovascular catheterization system [10]. Meanwhile, this system has the ability to offer flexible and effective insertion and extraction for guidewire/catheter. In Beijing Institute of Technology (BIT), a "Master-Slave" VIS robot based on two phantoms and a salve manipulator was proposed to realize remote operation for vascular intervention [11]. In addition, this research team also designed an isomorphic interactive device to replicate doctor's natural operation [12]. In Imperial College London, D. Kundrat et al. adopted a MR-safe remotely operated robotic system [13] to improve the surgical performance with a success rate of 90% to 100%, which is a meaningful study for continuous operation and reduced equipment footprint. In University of Hongkong, L. Kit-Hang et al. designed an intelligent manipulator robot to find visualize lesions under magnetic resonance imaging (MRI) environment based on high-quality medical images [14]. The research team of Yanshan University presented a novel VIS robot based on force feedback and flexible clamping regulation [15]. Moreover, Naveen. K et al. proposed an endovascular robotic system (ERS) to capture the information of proximal force and offer effective haptic feedback based on a novel force calibration methodology. On the basis of current and latest efforts of vascular interventional robot such as magnetically driven navigation [16]-[18], machine vision detection [19]-[20], new types of steerable surgical instruments [21]-[22], location and morphological study [23] are embracing a significant hotspot to increase the patient's comfort and improve the operator's surgical environment.

In our previous research, a tactile sensing robot-assisted system was developed to reduce the burden of surgeons [4]. Besides, we analyze the total force between surgical instruments and vessel of patient for the purpose of ensuring safety [6]. For the study of master side, a haptic robot-assisted system based on a novel spring haptic force interface and collision protection function was proposed [5]. Among these robotic systems, we developed a collaborative vascular interventional robot based on two separate handles to operate guidewire and catheter, respectively. We introduce detailed master structure, achieving mechanism of haptic feedback by a magnetically controlled haptic feedback on master side, and analyzes the operating mechanisms under different operator's modes. At last, experimental results in a glass blood vessel with simulated blood or not show the performance of the developed vascular interventional robot. This paper explores the force information in glass blood vessel under different environments.

The remaining structure of this paper is shown as bellow. The description of vascular interventional robot is presented in Section II. The mechanism of haptic feedback and operating mechanisms are exhibited in Section III. Experimental results and analysis are revealed in Section IV. Finally, Section V summaries conclusion and future work.

II. Developed Vascular Interventional Robot

The entire vascular interventional robot generally consists of master device and slave manipulator. A novel vascular interventional robot was introduced in this paper. The research purposes of developed VIS robot are providing better radiation protection, higher surgical safety, and less continuous working pressure for robot-assisted technology.

A. Overview

The developed vascular interventional robot is shown in Fig. 1. The doctors operate master device to drive slave manipulator conducting a robot-assisted VIS, which is a safer and more effective method to perform remote surgery. The master device is used to capture operating signals including linear motion and rotation motion of surgical instruments. Meanwhile, the master device has ability to offer a resistance sense of haptic feedback that can improve safety of procedure. Correspondingly, the underlying function of slave manipulator is accurately and flexibly control insertions of surgical instruments (guidewire and catheter in this study) into patient's lesion vessel. The slave manipulator was presented by our previous study [4]. Guidewire manipulator unit and catheter manipulator unit are proposed to clamp and delivery surgical instruments stably and safely. In addition, this kind of master manipulator also could detect proximal forces of guidewire and catheter in real time and record the position of surgical instruments and the position of corresponding manipulators when conducting surgeries.

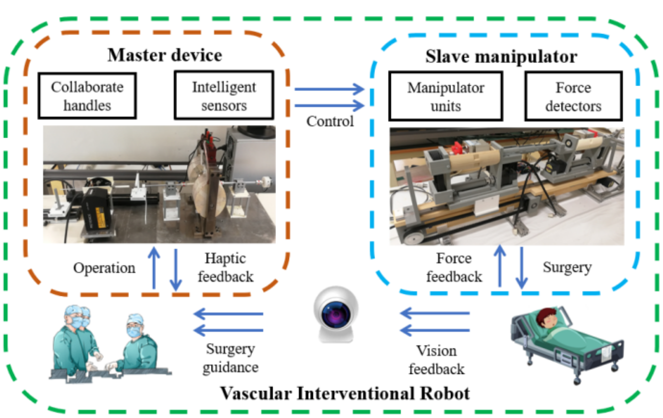


Fig. 1 Conceptual diagram of the developed vascular interventional robot.

B. Structure of Master device

The details of designed master device are shown in Fig. 2. The master device is planning to mount on a separate and radiation-free operating room, which is a significant protective measure for interventional surgeons. We proposed a collaborative vascular interventional robot using two independent handles and a magnetically controlled haptic feedback structure.

As shown in Fig. 2, guidewire handle and catheter handle are adopted to measure individual operating information of surgical instruments. Two ball splines (THK, SLT 006-T2-N5) are used to support the guidewire handle, and an encoder (MES020-2000P) with the accuracy of 0.09 degree/pulse is utilized to detect rotation signal. Moving data of guidewire is obtained by a laser sensor (KEYENCE, LK-2500). Moreover, an advanced integrated photoelectric sensor has a great advantage to measure motion signal and rotation signal of catheter handle simultaneously, which can shorten operating space. Besides, we also designed two resetting components based on stepping motor (ASM46AA, ORIENTA) to implement the function of automatic recovery, more details please see Ref. [2]. The operating positions for both of guidewire handle and catheter handle are set in the right side of two different handles. In addition, the haptic feedback is provided by a friction-contact structure under magnetic control.

III. Mechanisms Analysis

According to two independent handles for operators, this master device could complete synergistic control of catheter and guidewire, which is an important design that cannot be

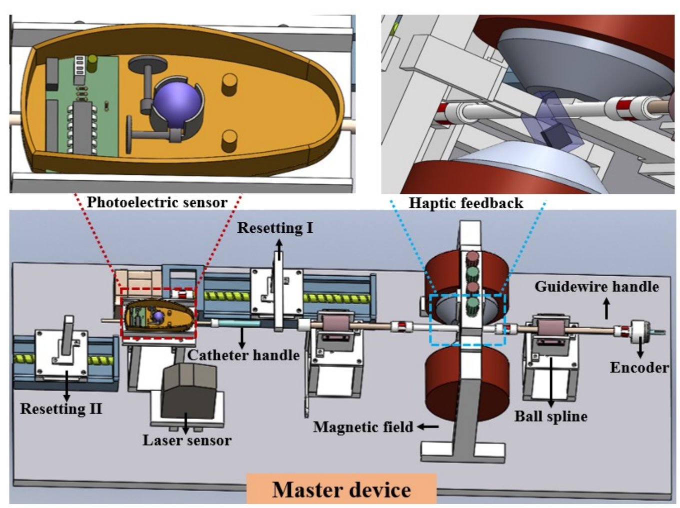


Fig. 2 The master device based on collective operating handles.

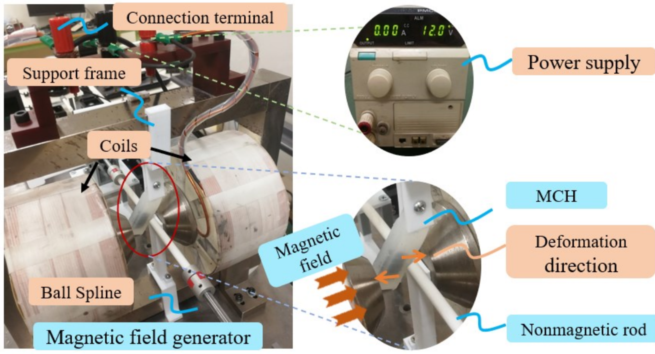


Fig. 3 The installation view and achieving mechanism of haptic feedback.

ignored for experienced interventionalists. We analyzed the achieving mechanism of haptic feedback and operating mechanism of collaboration for this developed vascular interventional robot in this section.

A. Mechanism of haptic feedback

This developed vascular interventional robot uses a novel magnetically controlled hydrogel (MCH). The installation view and achieving mechanism are shown in Fig. 3. An adjustable power supply is used to change the magnetic field by different input voltages or currents. The function of magnetic field generator is providing magnetic fields with different strengths by two coils. The power supply is connected by two sets of different colored terminals.

The MCH is made of smart material, magnetorheological (MR), and transparent hydrogel (Ecoflex^{TM}, 00-20). It was mounted on two big magnetic field generating coils by the support frame. The top part and bottom part of inclined MCH will generate deformations in opposite directions. Then, the contact between nonmagnetic rod and MCH can offer the sense of friction resistance for operators, which makes it possible to reproduce the resistance of surgical instruments when conducting a surgery. In addition, the magnetic field density can be measured by a tesla meter (KANETEC). In this study, the value of stable reference magnetic field density is set to 110 mT, which refer to Ref. [10]. By the designed MCH, master side is able to offer a sense of haptic feedback. The related parameters of the haptic feedback structure are exhibited in Table I.

TABLE I
RELATED PARAMETERS OF HAPTIC FEEDBACK STRUCTURE

Items	Parameters	Values
Magnetic part of MCH	Length	20 mm
	Width	10 mm
	Height	3 mm
Hydrogel part of MCH	Length	50 mm
	Width	14 mm
	Height	10 mm
Nonmagnetic rod	Length	150 mm
	Diameter	7 mm
Magnetic field gap	Distance	27 mm

Actually, the vertical pressure in the direction of contact surface between MCH and nonmagnetic rod is not easy to detect due to irregular deformation of the structure of MCH. We assume that the pressure $F_{pressure}$ with a direction is already acquired. The mathematical model of friction force of haptic feedback F_{haptic} can be defined as bellow

$$F_{haptic} = \mu_{contact} \cdot (F_{pressure} \times \cos \theta_{deviation}) \tag{1}$$

where $\mu_{contact}$ is the desired stable friction coefficient of the contact surface. $\theta_{deviation}$ is the deviation angle between the pressure $F_{pressure}$ and the vertical pressure $F_{vertical}$. Then, the Equation (1) can be re-edited as bellow

$$F_{haptic} = \mu_{contact} \cdot F_{vertical} \tag{2}$$

B. Collaborative operational mechanism

Collaborative operation is a major highlight in the developed vascular interventional robot. Two separate operating handles are presented to satisfy collaborative control with guidewire manipulator unit and catheter manipulator unit located in slave side. Note that the coaxial layout of a couple of handles maximum assurance the natural and professional surgical habits of interventionists in this robot. The mechanism of collaborative operation is depicted in Fig. 4.

From Fig.4, we can see that both of catheter handle and guidewire handle have two types of moving modes including delivery motion and rotary motion. Surgeons can select different operating ways to control two handles according to actual surgical environment and accumulated surgical experience. These operation approaches could be summarized into 3 categories, which are displayed as bellow

(a) Individual delivery: The individual linear delivery can be achieved by only permitting delivery motion for two handles that usually used in the situation when surgical instruments entering patient's thicker vessel.

(b) Individual rotary: This operating mode is adopted to choose a right angle to let guidewire/catheter access steep vascular branch by rotating only one of handles on master side.

(c) Collaborative operation: This kind of collaborative mode is able to control both of two separate handles by operator's hands. It is significant to conduct some complex procedures that require multiple adjustments for the suitable position of surgical instruments.

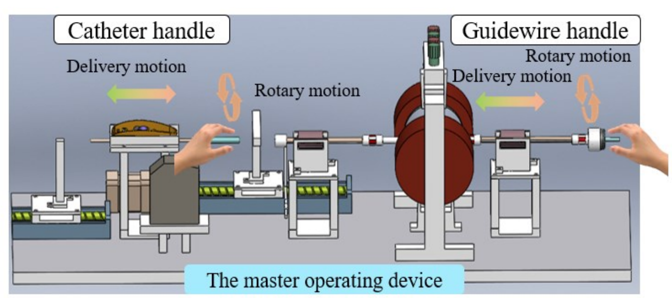


Fig. 4 The installation view and achieving mechanism of haptic feedback.

IV. Experiments and Results

In order to evaluate the performance of this developed vascular interventional robot, A set of contrasting experiments are conducted in this study. Results part shows the actual operational force data when slave manipulator control guidewire/catheter insert into patients. Moreover, the summative discussion of the VIS robot is presented at the end of this section.

A. Experimental setup

With the aim of verifying surgical performance of this novel robot, a glass blood vessel is applied in this experimental setup part. The detailed experimental setup of performance evaluation is shown in Fig. 5. The slave manipulator, a medical catheter sheath, and a transparent glass blood vessel are adopted to conduct comparative vitro experiments on slave side. From Fig. 5, glass blood vessel is mounted on 2 fixed frames and the medical catheter sheath is used to simulate a realistic surgical delivery environment by 3D printed component to clamp the three-way valve. The slave manipulator can flexibly clamp and control surgical instruments delivery motion and rotary motion. Moreover, the master side is located in opposite side at a same experimental room. In this study, the length of guidewire is 150 cm, and the diameter of guidewire is 0.89 mm. The length of catheter is 100 cm, and the outside diameter of catheter is 5 Fr (1 Fr = 0.33 mm).

B. Results

We conduct two types of experiments in glass blood vessel under different environments. The catheter and guidewire are advanced in two experiments simultaneously. The first one is inserting guidewire in dry situation of glass blood vessel. The second experimental environment is wet glass blood vessel within simulated pink blood. Please note that operating speed should be limited in a gentle value, 5 mm/s. It is vital to ensure safe, stable, and same manipulation habits for both of two contrasting experiments. We highlighted record several position information at different experimental moments, which is shown in Fig. 6. The recording time is approximately 11s. And also, by measuring the force between two types of experiments, the comparative results of the developed vascular interventional robot in glass blood vessel are depicted in Fig. 7.

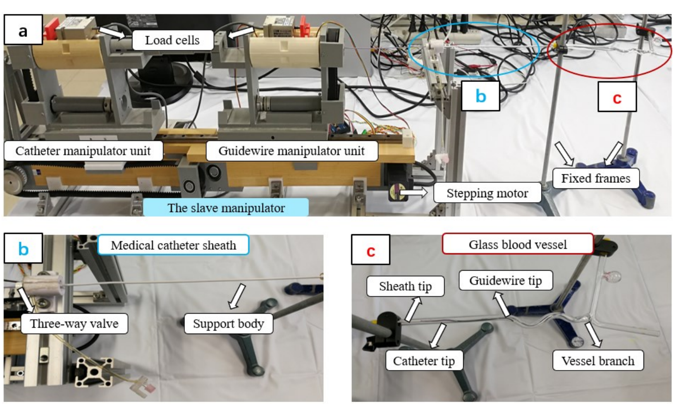
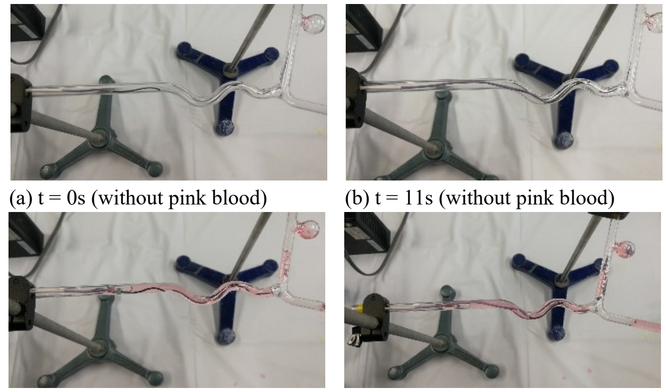


Fig. 5 The experimental setup for performance evaluation. (a) The slaver manipulator. (b) Medical catheter sheath. (c) Glass blood vessel.



(a) t = 0s (without pink blood) (b) t = 11s (without pink blood)

(c) t = 0s (with pink blood) (d) t = 11s (with pink blood)

Fig. 6 Position information at different experimental moments

The sampling time interval for proximal force of guidewire is 100 ms.

From the Fig. 7, we can see that two kinds of experiments have obvious divergence about the proximal force information when conducting surgeries. According to medical knowledge, the pink simulated blood has significant effect of lubrication to avoid strong contact between surgical instruments and vessel walls, which is a vital function for human's body. In addition, the value of proximal force in both of experiments is less 0.18N due to the unique smooth property of glass blood vessel. The maximum value of proximal force for guidewire without pink blood is 0.1498 N. Contrastingly, the maximum value of proximal force for guidewire with pink simulated blood is 0.0905 N. By changing experimental environments with pink blood and without pink blood in this part, the performance of this developed vascular interventional robot can be evaluated based on a glass blood vessel. The comparative results indicate that the vascular interventional robot can successfully delivery catheter and guidewire at different environments by collaborative operation. Moreover, the operating speed of surgeons can not be strictly controlled within a same value. Consequently, force information in two experiments generate various degrees of jitter signals.

C. Discussion

For robot-assisted vascular interventional surgery, the flexible master design, and collaborative operating handles are important to ensure safe delivery and natural surgical habits [24].

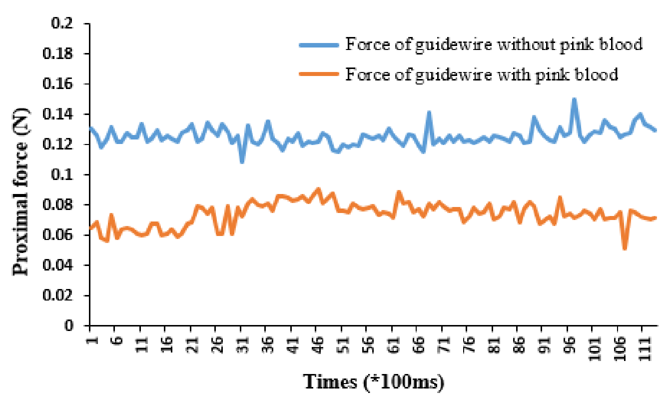


Fig. 7 Comparative results of proximal force for guidewire

Considering these problems, we developed a collaborative vascular interventional robot by using two handles and a magnetically controlled haptic feedback. In this paper, we analyze the implementation mechanism of force feedback based on MCH and introduce three modes of collaborative operation for this robot. Although the performance of haptic feedback does not further deep study so far, the collaborative performance has been tested by a glass blood vessel in different environments with simulated blood or not. Experimental results shows that this kind of robot can satisfy surgical tasks in various environments. It also has potential advantages to guide the design of master side and inspire the development of co-operating robots.

V. Conclusion

In this study, we analyzed implementation mechanism of haptic feedback and different collaborative operational modes for a developed vascular interventional robot based on the design of separate handles in master side. Besides, we evaluated the delivery performance through two types of experimental environments in a glass blood vessel. The experimental results of this robot indicate that the performances of insertion and extraction are good to manipulate surgical instruments in both of two environments with pink blood or not. In addition, our study also shows that collaborative VIS robot has better application prospects to cope with a variety of surgical environments, which is an important step to let robot smoothly use in hospital. Moreover, a large number of potential benefits of collaborative operation and haptic feedback will likely be concerned including the fields of biomedical, haptic research, and co-operating robot. Unfortunately, we only preliminarily evaluated delivery performance of the robot by contrastive experiments in glass blood vessel. In the future, we will do further study on performance evaluation and improvement of magnetically controlled haptic feedback.

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References

[1] C. Yang, S. Guo, Y. Guo, and X. Bao, "Cloud Communication-based Sensing Performance Evaluation of a Vascular Interventional Robot System," *IEEE Sensors Journal*, DOI. 10.1109/JSEN.2022.3160760, 2022.

[2] X. Li, S. Guo, P. Shi, X. Jin, and M. Kawanishi, "An Endovascular Catheterization Robotic System Using Collaborative Operation with Magnetically Controlled Haptic Force Feedback," *Micromachines*, vol. 13, no. 4, 505, 2022.

[3] X. Yin, S. Guo, N. Xiao, T. Tamiya and H. Hirata, "Safety Operation Consciousness Realization of a MR Fluids-Based Novel Haptic Interface for Teleoperated Catheter Minimally Invasive Neurosurgery," *IEEE/ASME Transactions on Mechatronics*, vol. 21, no. 2, pp. 1043-1054, 2016.

[4] X. Jin, S. Guo, J. Guo, P. Shi, T. Tamiya and H. Hirata, "Development of a Tactile Sensing Robot-assisted System for Vascular Interventional Surgery," *IEEE Sensors Journal*, vol. 21, no. 10, pp. 12284-12294, 2021.

[5] P. Shi, S. Guo, L. Zhang, X. Jin, H. Hirata, T. Tamiya, and M. Kawanishi, "Design and evaluation of a haptic robot-assisted catheter operating system with collision protection function," *IEEE Sensors Journal*, vol. 21, no. 18, pp. 20807-20816, 2021.

[6] X. Jin, S. Guo, J. Guo, P. Shi, T. Tamiya and H. Hirata, "Total Force Analysis and Safety Enhancing for Operating Both Guidewire and Catheter in Endovascular Surgery," *IEEE Sensors Journal*, vol. 21, no. 20, pp. 22499-22509, 2021.

[7] Y. Yan, H. Wang, H. Yu, F. Wang, J. Fang, J. Niu, and S. Guo, "Machine Learning-based Surgical State Perception and Collaborative Control for a Vascular Interventional Robot," *IEEE Sensors Journal*, DOI. 10.1109/JSEN.2022.3154921, 2022.

[8] X. Li, S. Guo, P. Shi, X. Jin, and M. Kawanishi, "A Novel Tremor Suppression Method for Endovascular Interventional Robotic Systems," *In Proceedings of 2021 IEEE International Conference on Mechatronics and Automation (ICMA)*, August 8-10, Takamatsu, Japan, pp. 1050-1054, 2021.

[9] W. Zhou, S. Guo, J. Guo, F. Meng, and Z. Chen. "ADRC-Based Control Method for the Vascular Intervention Master–Slave Surgical Robotic System," *Micromachines*, vol. 12, no. 12, 1439, 2021.

[10] Y. Song, S. Guo, X. Yin, L. Zhang, T. Tamiya, H. Hirata, and H. Ishihara, "Performance evaluation of a robot-assisted catheter operating system with haptic feedback," *Biomedical Microdevices*, vol. 20, no. 2, pp. 50, 2018.

[11] X. Bao, S. Guo, Y. Guo, C. Yang, L. Shi.; Y. Li, Y. Jiang. "Multilevel Operation Strategy of a Vascular Interventional Robot System for Surgical Safety in Teleoperation.," *IEEE Transactions on Robotics*, DOI. 10.1109/TRO.2022.3140887, 2022.

[12] C. Yang, S. Guo, Y. Guo, and X. Bao, "An Isomorphic Interactive Device for the Interventional Surgical Robot after In Vivo Study," *Micromachines*, vol. 13, no. 1, 111, 2022.

[13] D. Kundrat, G. Dagnino, T. Kwok, M. Abdelaziz, W. Chi, A. Nguyen, C. Riga, G. Yang, "An MR-Safe endovascular robotic platform: Design, control, and ex-vivo evaluation," *IEEE Transactions on Biomedical Engineering*. vol. 68, no. 10, pp. 31974–31982, 2021.

[14] K. H. Lee, K.C.D. Fu, Z. Guo, Z. Dong, et al. "MR Safe Robotic Manipulator for MRI-Guided Intracardiac Catheterization," *IEEE/ASME Transactions on Mechatronics*, vol. 23, no. 2, pp. 586–595, 2018

[15] H. Yu, H. Wang, J. Chang, J. Niu, F. Wang, Y. Yan, Y, et al. "Novel Vascular Intervention Surgical Robot Based on Force Feedback and Flexible Clamping," *Applied sciences*, vol. 11, no. 2, 611, 2021.

[16] Y. Zhao, S. Guo, N. Xiao, Y. Wang and Y. Li, "Operating force information on-line acquisition of a novel slave manipulator for vascular interventional surgery," *Biomedical Microdevices*, vol. 20, no. 2, pp. 33, 2018.

[17] J. Choi, S. Park, Y. Kim, Y. Moon, J. Choi, "Vascular Intervention Assist Device Using Bi-Motional Roller Cartridge Structure and Clinical Evaluation," *Biosensors*, vol. 11, no. 9, 329, 2021.

[18] L. Pancaldi, P. Dirix, A. Fanelli, A.M. Lima, N. Stergiopulos, P.J. Mosimann, D. Ghezzi, M.S. Sakar, "Flow driven robotic navigation of microengineered endovascular probes," *Nature communications*, vol. 11, 6536, 2020.

[19] J. Sikorski, A. Denasi, G. Bucchi, S. Scheggi, S. Misra, "Vision-Based 3-D Control of Magnetically Actuated Catheter Using BigMag-An Array of Mobile Electromagnetic Coils. *IEEE/ASME Transactions on Mechatronics*, vol. 24, no. 2, pp. 505–516, 2019.

[20] A. Nguyen, D. Kundrat, G. Dagnino, W. Chi, et al. "End-to End Real-time Catheter Segmentation with Optical Flow-Guided Warping during Endovascular Intervention," *In Proceedings of 2020 IEEE International Conference on Robotics and Automation (ICRA)*, May 31–August 31, Paris, France, pp. 9967-9973, 2020.

[21] M. Li, R. Obregon, J.J Heit, A. Norbash, E.W. Hawkes, T.K. Morimoto, "VINE Catheter for Endovascular Surgery," *IEEE Transactions on Medical Robotics and Bionics*, vol. 3, no. 2, pp. 384–391, 2021.

[22] S. Kang, D.Y. Lee, "Hydraulically Steerable Micro Guidewire Capable of Distal Sharp Steering," *IEEE Transactions on Biomedical Engineering*. vol. 68, no. 2, pp. 728–735, 2021.

[23] Y. Zhou, X. Xie, X. Zhou, S. Liu, G. Bian, Z. Hou, Z, "A Real-Time Multifunctional Framework for Guidewire Morphological and Positional Analysis in Interventional X-Ray Fluoroscopy," *IEEE Transactions on Cognitive and Developmental Systems*, vol. 13, no. 3, pp. 657–667, 2021.

[24] J. Guo, X. Jin, S. Guo, and Q. Fu, "A Vascular Interventional Surgical Robotic System Based on Force-Visual Feedback," *IEEE Sensors Journal*, vol. 19, no. 23, pp. 11081-11089, 2019.