The Catheter and Guidewire Operating Systems of Vascular Interventional Surgical Robots: A Systematic Review

Pengfei Chen, Yutang Wang, *Member, IEEE*, Dapeng Tian, *Senior Member, IEEE*, Yunbao Guo, and Kan Xu

***Abstract*—Vascular interventional surgical robots (VISR) assisted doctors in surgery can not only protect doctors from X-ray radiation, but also improve the accuracy of surgery. The catheter and guidewire operating systems with master-slave operation mode play an important role in VISR. In recent years, the operating systems have gradually become a research hotspot. After nearly two decades of development, they have made great progress, but there are still some problems to be solved. This review first introduces the research necessity and development history of these operating systems. Then, we summarize the research direction of operating systems from the perspective of hardware devices and algorithms. In the hardware devices, we analyzed the catheter and guidewire operating mechanisms, contact force detection devices, master operating mechanisms and master force feedback devices. In the algorithm, we introduce the bilateral control methods, security strategies and skill evaluation methods. Next, we discuss the actual performance and shortcomings of the operating systems from the perspective of clinical application. Finally, we summarize the current problems of the operating systems and propose the future development direction. This review is helpful for researchers to understand the current situation, and provides a reference framework of catheter and guidewire operating system.**

***Index Terms*—Robot-assisted, vascular interventional surgery, catheter and guidewire operating system, master-slave.**

I. INTRODUCTION

MINIMALLY invasive vascular interventional surgery is a means for doctors to operate interventional instruments for treatment under the guidance of medical image. Interventional doctors are not only exposed to X-ray radiation during operation [1], but also prone to low efficiency due to physical fatigue. As early as the 1980s, robot technology was applied to surgery. With the development of robot technology, robot-assisted surgery is becoming more and more common [2], [3]. The appearance of vascular interventional surgical robots (VISR) have greatly reduced the X-ray radiation suffered by doctors. They also improved the surgical accuracy and stability [4], [5], [6].

In order to keep doctors away from radiation sources, the VISR mostly adopt master-slave control mode [7]. Doctors operate the master robot under the guidance of medical image [8]. Then, the slave robot receives the orders from the master robot, so as to perform surgery on patients. In recent years, many companies have devoted themselves to developing it. Especially the surgical robot used in percutaneous coronary intervention (PCI) and peripheral vascular intervention (PVI).

VISR include positioning mechanical arms [9], medical image systems [8] and catheter and guidewire operating systems [10]. Positioning mechanical arms are used to assist the installation of slave robots. Whether it is artificial interventional surgery or robot-assisted surgery, doctors need to operate under the guidance of medical image. The purpose of VISR is to replace doctors to operate catheter, guidewire and other instruments on site. Catheter and guidewire are basic interventional instruments with the function of guiding direction. Doctors control the interventional instruments to enter different blood vessels by pushing, pulling and rotating the catheters and guidewires. Therefore, the catheter and guidewire operating systems are the specific problems to be solved by the VISR, and the subsequent content will be referred to as the operating systems for short. These operating systems pay more attention to the structures of master-slave robot and the control algorithms. The control algorithms pays more attention to the mutual tracking of position [11] between master and slave robots and the tactile transmission [12].

After nearly 20 years of development, many companies have proposed a variety of operating systems. In 2006, Beyar et al. of Haifa hospital in Israel proposed a remote navigation system (RNS) [13]. It mainly used for PCI. This operating system used multiple groups of friction wheels to deliver the guidewire and catheter. Compared with the magnetic drive catheter, the RNS does not need to develop special instruments separately. So it is more applicable. Subsequently, several companies proposed similar solutions, such as the Magellan system [14] of Hansen Medical (USA), the Amigo system [15] of Catheter

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Pengfei Chen, Yutang Wang, and Dapeng Tian are with the Key Laboratory of Airborne Optical Imaging and Measurement, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China, and also with the University of Chinese Academy of Sciences, Beijing 100049, China (e-mail: Meetuser_cpf@outlook.com; ytwang@ciomp.ac.cn; d.tian@ciomp.ac.cn).

Yunbao Guo and Kan Xu are with the Department of Neurosurgery, The First Hospital of Jilin University, Changchun 130061, China (e-mail: yunbaoguo@jlu.edu.cn; xukan@jlu.edu.cn).

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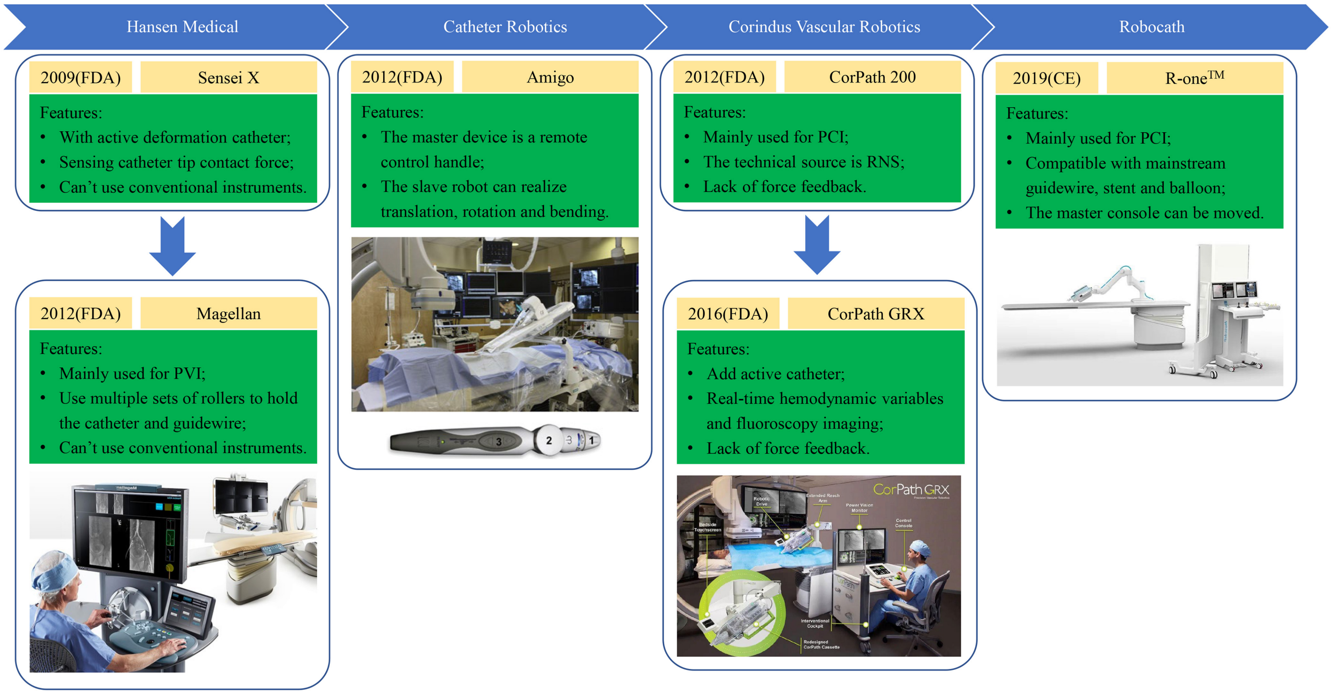

2009(FDA) Sensei X

Features:

- With active deformation catheter;
- Sensing catheter tip contact force;
- Can't use conventional instruments.

2012(FDA) Magellan

Features:

- Mainly used for PVI;
- Use multiple sets of rollers to hold the catheter and guidewire;
- Can't use conventional instruments.

2012(FDA) Amigo

Features:

- The master device is a remote control handle;
- The slave robot can realize translation, rotation and bending.

2012(FDA) CorPath 200

Features:

- Mainly used for PCI;
- The technical source is RNS;
- Lack of force feedback.

2016(FDA) CorPath GRX

Features:

- Add active catheter;
- Real-time hemodynamic variables and fluoroscopy imaging;
- Lack of force feedback.

2019(CE) R-one$^{\mathrm{TM}}$

Features:

- Mainly used for PCI;
- Compatible with mainstream guidewire, stent and balloon;
- The master console can be moved.

Fig. 1. An overview of several famous commercial operating system of VISR.

Robotics (USA), the CorPath system [16] of Corindus Vascular Robotics (USA) and the R-one system of Robocath (France). Fig. 1 shows an overview of the above robot systems, including the time of Food and Drug Administration (FDA) approval or CE certification, and the features of each robot system.

In the first section of this review, we introduced the necessity of developing the catheter and guidewire operating systems for VISR and the development history of the commercial operating systems. The rest of this review is organized as follows. In Section II, we will introduce the search method and literature analysis of this review. Then in Sections III and IV, we introduce the key technologies of the operating systems from the perspective of hardware devices and algorithms. In Section V, we will discuss the clinical application status and limitations of the current operating systems. We propose the challenges and prospects of the operating systems in Section VI. Finally, We will give the conclusion of this review.

II. METHODS

A. Search Methodology

In order to make a systematic review, we need to take appropriate methods to retrieve relevant literatures. We conduct a preliminary search in two knowledge bases: Web of Science and IEEE Xplore. The search keywords include (“interventional surgical robot” OR “endovascular”) AND (“operating system” OR “catheter and guidewire”). By reading the article titles and abstracts, we excluded some literatures with low relevance and finally restricted our results to the remaining papers published in journals and conferences up to December 2022.

B. Paper Analysis

After searching the literatures, we will introduce the key technologies of the operating system from two perspectives, hardware devices and algorithms. The hardware devices mainly introduce the composition and structure of the master-slave robot, including catheter and guidewire operating mechanisms, contact force detection devices, master operating mechanisms and force feedback devices. The algorithms are applied to hardware devices. We introduce it from three perspectives, bilateral control methods, security strategies and skill evaluation methods.

Fig. 2 shows a classification diagram of hardware devices and algorithms. Among them, the yellow background is hardware devices, and the green background is algorithms. Further, we divide the bilateral control methods into research on position tracking and force transmission and research on time delay. After that, we will analyze the usage and limitations of the current operating systems from the perspective of clinical application.

III. HARDWARE DEVICES

A. Catheter and Guidewire Operating Mechanisms

Catheter and guidewire are the core of interventional instruments and have the function of guidance. The catheter and guidewire operating mechanism should include at least the delivery and rotation freedom of catheter and guidewire, as shown in Fig. 3. At present, the design method can be roughly divided into the form of friction wheel and the form of linear platform [17].

1) Form of Friction Wheel: The operating mechanisms in the form of friction wheel usually uses one set of friction wheels to operate the catheter, and another set of friction

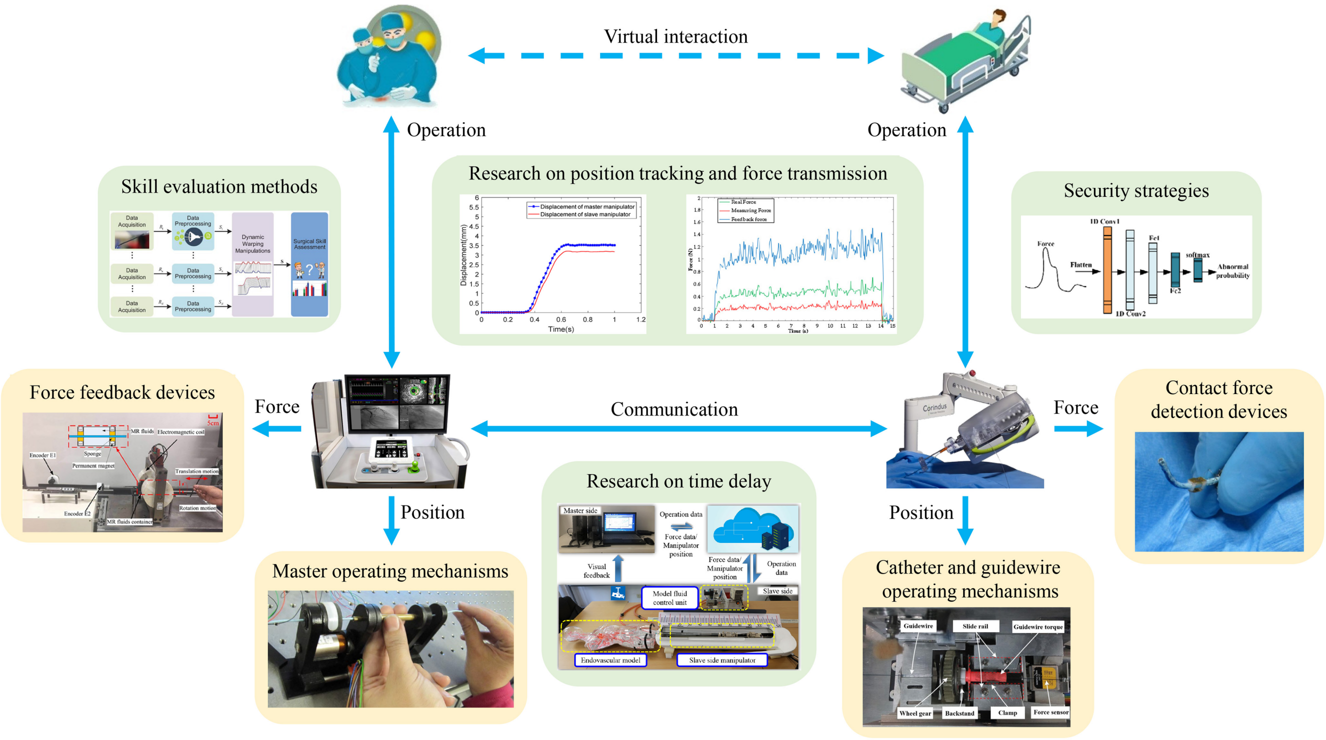

Fig. 2. Classification diagram of hardware devices and algorithms.

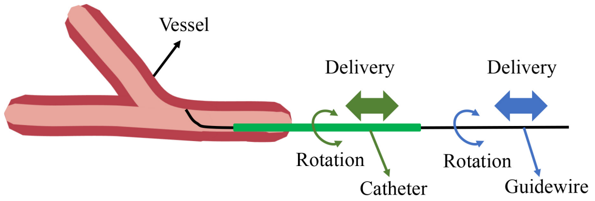

Fig. 3. Schematic diagram of catheter and guidewire movement.

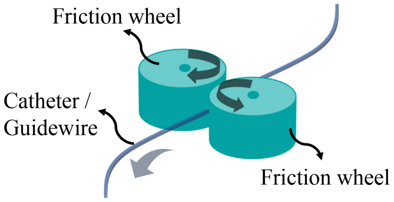

Fig. 4. Form of friction wheel.

wheels to operate the guidewire. When a group of friction wheels approaches gradually until the catheter or guidewire is clamped, the catheter or guidewire can be controlled to move forward by rotating the friction wheel in the direction shown in Fig. 4, and vice versa. When a group of friction wheels are away from each other, the catheter or guidewire will be released.

The Remote Navigation System (RNS) designed by Beyar et al. is one of the most representative catheter/guidewire operating systems. They used multiple sets of friction wheels to deliver the guidewire and balloon stent catheter respectively. Fig. 5(a) shows the schematic diagram of this

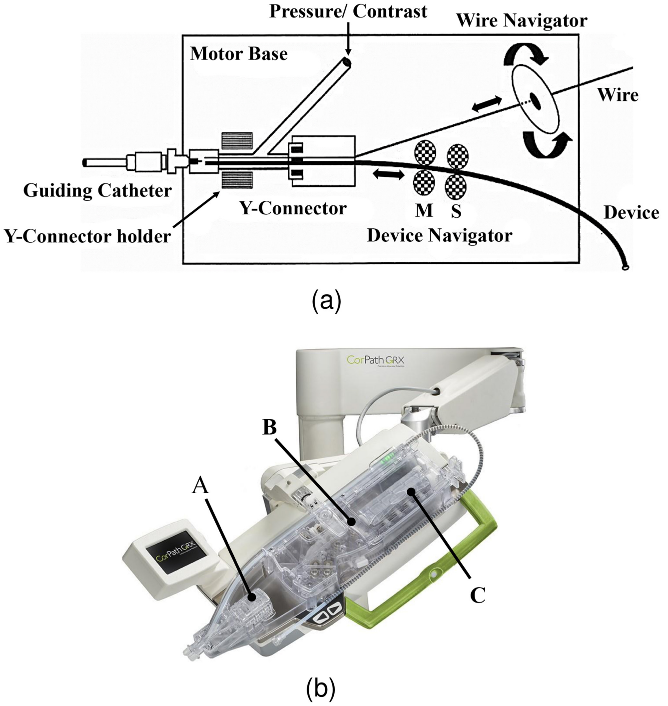

Fig. 5. Several mechanisms in the form of friction wheel: (a) Catheter/ guidewire delivery mechanism designed by Beyar et al. [13]; (b) Slave robot of CorPath GRX system: A, Catheter rotation module; B, Guidewire linear module; C, Guidewire rotation module.

mechanism, where M represents motored roller and S represents sensing roller. They used motored roller to achieve axial delivery of the catheter, and if the device detects resistance or motored roller slippage, the sensing roller will report a fault and the system will stop [13]. The CorPath GRX system developed by Corindus Vascular Robotics using RNS technology also uses multiple sets of friction wheels to deliver catheter and guidewire, as shown in Fig. 5(b). In addition, the Magellan system also uses a similar principle to operate the catheter and guidewire.

Since then, many researchers have designed a variety of delivery mechanisms in the form of friction wheels. In order to increase the friction of the friction wheel, Sankaran et al. added knurling on the roller [18]. The mechanism designed by Fu et al. [19] and Bian et al. [20] can realize the movement of rotation, pull and push. Srimathveeravalli et al. used friction wheels to achieve axial delivery of catheter and guidewire, and created an automatic adjustment system to adapt to interventional instruments with different diameters [21]. Wang et al. [22] and Cha et al. [23] also proposed a similar mechanism with adjustment function. Cha et al. have set a spring handle on the side of the passive roller, which can easily adjust the friction between the active and passive rollers, and can also be applied to guide wires of different sizes. Using springs to adjust friction is a common method. Zhao et al. used active and passive wheels to clamp the catheter forward, and detected the actual moving distance through the photoelectric encoder installed on the passive wheel [24]. Yuan et al. proposed a balloon catheter conveying device, which uses friction wheels to drive the balloon catheter, and designed a pressure regulating device for regulating the contact force between the balloon catheter and the conveyor belt [25].

2) Form of Linear Platform: The mechanism in the form of linear platform uses linear motor to drive other components to deliver axially. Interventional instruments, grippers, rotating motors and various sensors are installed above the linear motor. People can use many methods to design a new mechanism for clamping the catheter or guidewire. After nearly 20 years of development, many researchers have proposed different solutions. Fig. 6 shows several mechanisms in the form of linear platform.

According to the operation of artificial interventional surgery, many researchers analyzed the motion freedom of interventional instruments, and designed this mechanism. Yang et al. designed a catheter intervention device, which completes the axial movement and rotation of the catheter by the cooperation of fixed finger, pushing finger and rotating finger [26], but did not design the guidewire movement mechanism. The mechanism designed by Wang et al. has higher degrees of freedom, and all four manipulators designed can perform push, pull, and rotational motions with strong synergistic capabilities [27], as shown in Fig. 6(a). Bao et al. designed catheter motion equipment and guidewire motion equipment respectively. After analyzing the actual movement of catheter and guidewire, they divided the slave operating mechanism into five units for design. This mechanism can operate both catheter and guidewire to perform complex surgical operations [28]. The guidewire operating mechanism designed by Guo et al. can complete push, pull and rotation, but the mechanism is heavy [29]. Shen et al. also adopted modular design and designed guidewire translation module, guidewire rotation module, force feedback module and support module. This mechanism allows translation and rotation movement at the same time [30].

As shown in Fig. 6(b) and Fig. 6(c). It is a common method to realize the rotation of conduit or guidewire through gear transmission. Gear transmission has the advantages of smooth transmission, high precision and high efficiency. Jia et al. realized the guidewire rotation through spur gear transmission [31]. In order to better ensure sterile conditions, Wang et al. designed a catheter rotation structure based on bevel gear transmission [32]. Apamon et al. adopted another idea to install the catheter between two planes and rotate the catheter through the shear movement of the two planes [33].

The function of the grasper is to fix and release the interventional instruments, which are often designed by imitating the operation of doctors' manual intervention. Its main role is to clamp the intervening instruments and to control the amount of clamping force. Excessive clamping force will damage the interventional instrument, and too small clamping force will lead to operation failure. Jia et al. designed a grasper for clamping the torque controller to realize the conversion of different operations through the clamping and release of the clamp [31]. The adaptive clamping mechanism designed by Zhang et al. can adjust the magnitude of electromagnetic force by adjusting the current, so as to realize the clamping and release of the catheter or guidewire. This mechanism also facilitates the replacement of different types of interventional devices. In addition, they pasted silica gel on the clamping surface to increase the friction coefficient [34]. Guo et al. used multiple wedge blocks to clamp the guidewire. When the wedge blocks were close to each other, the guidewire was clamped. A spring is also arranged between the wedge blocks to realize the function of resetting. In addition, they also coated the clamping surface with flexible materials to avoid damaging the guidewire [35].

3) Discussion: The operating mechanism based on friction wheel has the advantages of small volume, unlimited movement stroke and convenient replacement of different interventional instruments. Many commercial interventional robot systems adopt this method. But its disadvantage is the risk of slipping. Obviously, if we want to avoid this problem, we must increase the friction force. We can choose the friction wheel with larger friction coefficient, or we have to increase the pressure of a group of friction wheels on the catheter or guidewire. At the same time, we should realize that too much pressure will bring the risk of damaging the interventional device. Therefore, although the operating mechanism in the form of friction wheel is simple and easy to use, it often brings uncontrollable risk of slipping. If this type of operating mechanism is used in the future, we should conduct detailed friction analysis and fatigue analysis after selecting the appropriate friction wheel material. And we should carry out a lot of experimental verification.

The operating mechanism based on linear platform has the advantage of strong expansibility. It can integrate a variety of sensors and mechanical structures inside, so as to simulate the movement of doctors' daily operation. This delivery method can increase the contact area between the clamping mechanism

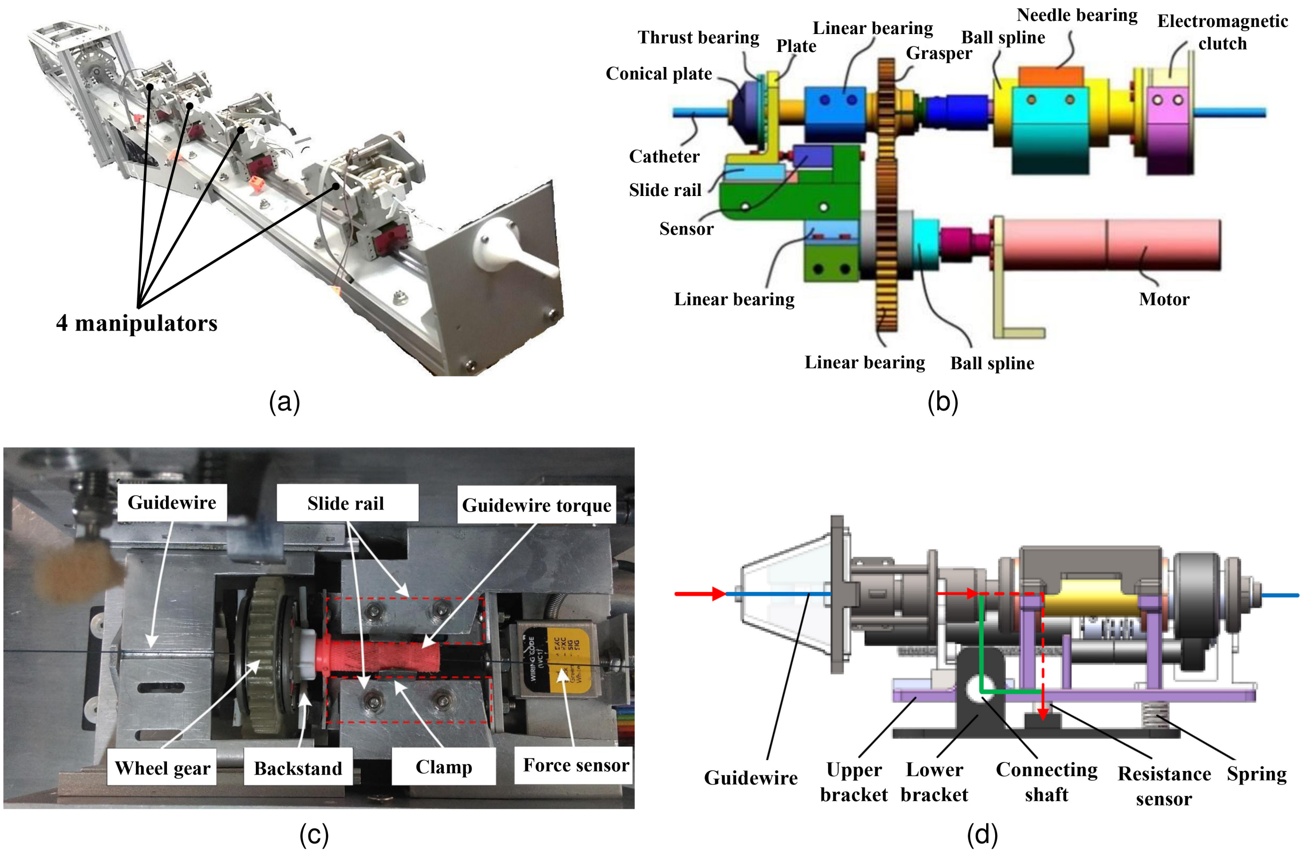

Fig. 6. Several mechanisms in the form of linear platform: (a) Catheter /guidewire cooperative operating mechanism designed by Wang et al. [27]; (b) Catheter operating mechanism designed by Bao et al. [28]; (c) Guidewire operating mechanism designed by Guo et al. [29]; (d) Guidewire operating mechanism designed by Yu et al. [43].

and the interventional device as required. This will help to increase friction and effectively avoid damage to interventional instruments. We can install force sensors, optical sensors, etc. in this form of operating mechanism. In the future, we can use multiple sensor information fusion to control the slave robot more intelligently. However, it is usually very heavy. We will have to consider the lightweight analysis of mechanical structure and the compensation of load inertia.

B. Contact Force Detection Devices

The catheter and guidewire operating mechanism is one of the most important components of the slave robot. Next, we will introduce the parts that are closely related to them, namely, the contact force detection devices. If the doctor can only receive medical image information when the robot assists the doctor in endovascular surgery, the operation will be distorted. This is different from the tactile perception of doctors in artificial intervention surgery. The premise for doctors to perceive the real tactile is that the slave robot can detect the accurate contact force. Next, the method of obtaining the slave contact force will be introduced in detail. The slave end contact force can be divided into two types: one is the internal force collected by interventional instruments such as catheter/guidewire, and the other is the external force collected from the operating mechanism.

1) Internal Force: The internal force can also be called the distal force. It is a complex resultant force, including the contact force, friction and viscous force between interventional instruments and vessels [36]. The precise detection of internal force helps to control the slave robot more intelligently and safely. Measuring the internal force usually requires placing the sensor outside the catheter. Fig. 7 shows part of the internal force detection method.

Wang et al. used a micro piezoelectric sensor fixed to the catheter tip to detect the tactile force between the catheter tip and the vessel. The feedback force exceeding the threshold caused the robot system to stop [22]. They used glue to paste polyvinylidene fluoride (PVDF) onto the catheter, and the rubber membrane isolated the PVDF from the blood. When the external force is applied to the PVDF, the voltage with opposite polarity on both sides is amplified and output. After that, they also calibrated the contact force and output signal. Guo et al. used the load cell to measure the friction between the catheter and the blood vessel, used the optical fiber force sensor to measure the contact force between the catheter tip and the vessel [37], and then increased the ability to detect the contact force between the catheter sidewall and the vessel [38]. Payne et al. installed two strain gauges on both sides of the catheter near the top and connected with a half bridge structure to measure the force when the catheter tip contacts the blood vessel [39]. Jin et al. used the self-developed force

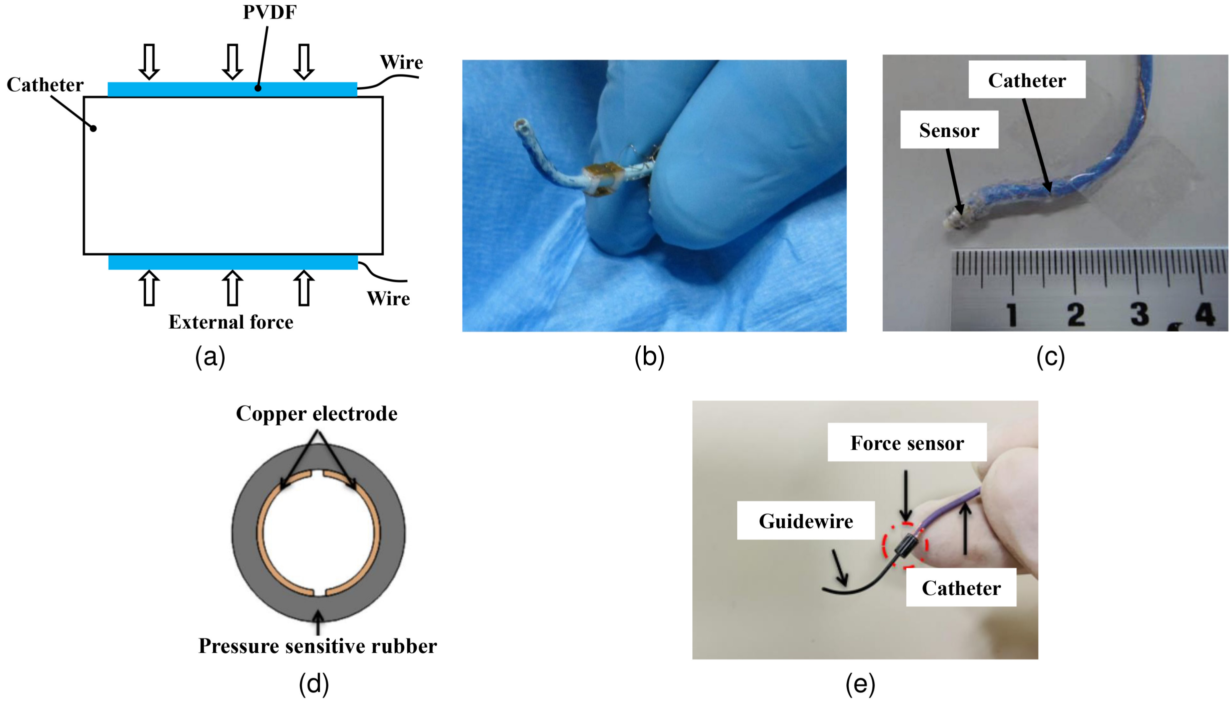

Fig. 7. Several internal force detection methods: (a) The force sensor developed by Wang et al. [22]; (b) The force sensor developed by Payne et al. [39]; (c) The force sensor developed by Guo et al. [38]; (d) Front view of force sensor made by Jin et al. [36]; (e) The physical picture of force sensor made by Jin et al. [36].

sensor to confirm the collision force between the catheter tip and the blood vessel wall, and combined with the tactile force feedback of the system to improve the accuracy of force feedback [36]. This sensor relies on the piezoresistive effect of pressure-sensitive rubber to measure the force between the end of the catheter and the blood vessel. The relationship between voltage and contact force is calibrated.

Akinyemi et al. developed a one-dimensional miniature optical fiber force sensor based on Fiber Bragg Grating (FBG). The force sensor is designed with bending structure, which can achieve millinewton resolution, and has higher stability and accuracy than the intensity modulation proximity force sensor [40]. In 2022, they further proposed a prototype of an FBG-based 2-D distal force sensor [41].

2) External Force: External force can also be called proximal force. The external force usually consists of an internal contact force in the catheter and guidewire operating mechanism and a contact force between the interventional instrument and the vessel. The external force completely covers the internal force, and the size of the external force is closer to the force perceived by doctors in artificial intervention surgery. Therefore, we can only measure the external force by placing force sensors inside the robot. We can easily find the position of the force sensor in Fig. 6. Among them, the sensor shown in Fig. 6(b) is placed in the front, the sensor shown in Fig. 6(c) is placed at the back, the sensor shown in Fig. 6(d) is placed below. Although the installation positions of force sensors are different, they have the same purpose. They are used to obtain the contact force generated during the operation of the catheter or guidewire.

The contact force detection device designed by Bao et al. adopts the static connection method. There is no sliding between the catheter and the sensor, and the actual contact force can be directly transmitted to the sensor [28], as shown in Fig. 6(b). Zhao et al. designed a new torque measuring device. The working torque will be transmitted to the elastic beam fixed with the strain gauge through the clamping device, and the strain gauge will have voltage output. Finally, the calibration experiment of the torque measuring device is carried out [42]. Yu et al. installed the pressure sensor under the slave operating mechanism and amplified the contact force between the catheter/guidewire and the vessel by using the lever principle to facilitate detection [43], as shown in Fig. 6(d). Chen et al. paid attention to the circumferential force feedback of guidewire and catheter during operation, and designed and calibrated a clamping mechanism for the circumferential force feedback device [44].

3) Discussion: In the internal force detection method, the sensor is placed outside the catheter or guidewire, which will make it difficult for the catheter to enter the narrow blood vessel. On the other hand, the output data of the force sensor requires the connection of electrical wires and follows the catheter in the blood vessel, which will increase some potential risks. The external force detection method is vulnerable to external interference, such as friction, inertia and so on. This may be difficult to reflect the real force of the interventional device in the blood vessel. In the future, the contact force detection method should comprehensively consider the internal force and external force, and the development of new force sensors is also needed. We can use the external

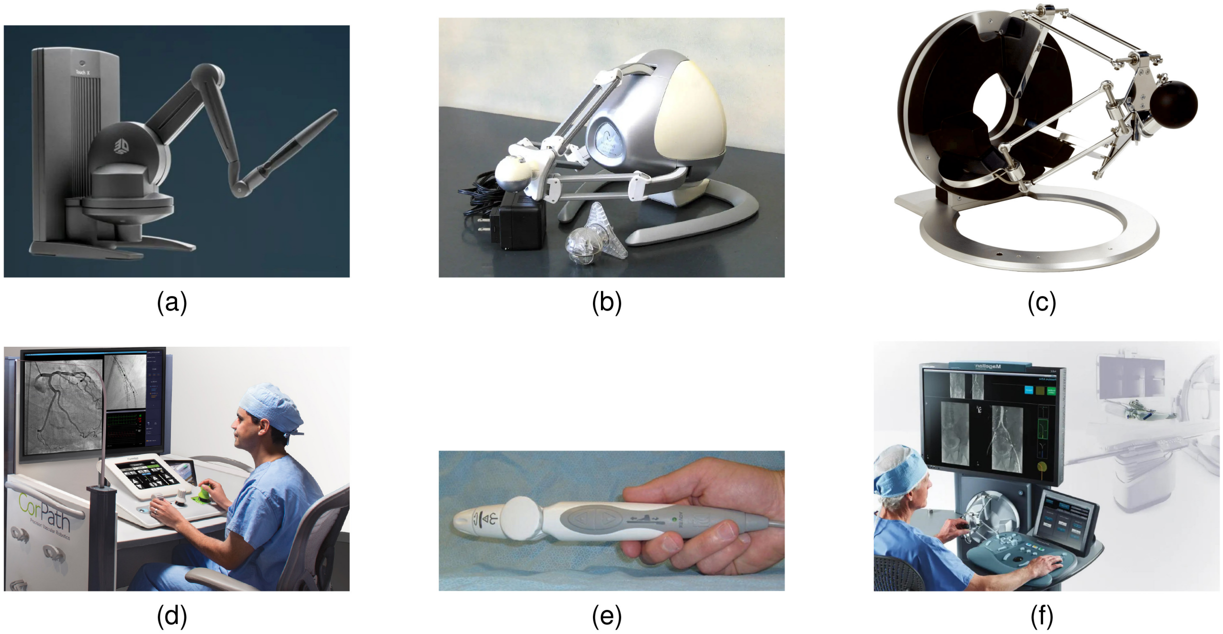

Fig. 8. Several common master operating mechanism based on the operating handle: (a) Geomagic Touch X; (b) Novint Falcon; (c) Omega 3; (d) The master operating mechanism of the CorPath GRX robotic system; (e) The master operating mechanism of the Amigo system; (f) The master operating mechanism of the Magellan system.

force as the master force feedback. The internal force can be used as safety early warning information to avoid catheter or guidewire damaging blood vessels. In addition, the research on the replacement of catheter and guidewire by continuous robot may be another solution. The end of the continuum robot can more easily integrate multiple sensors without being limited by traditional interventional devices.

C. Master Operating Mechanisms

The master operating mechanism is contact with the doctor, and its quality directly affects the authenticity of the doctor's operation. At present, the master operating mechanism can be divided into two categories: one is operating handle, and the other is the mechanism developed based on doctors' skills.

1) Operating Handle: Fig. 8 shows the common master operating mechanism based on the operating handle. Some researchers use commercial operating handle as the master operating mechanism, such as Geomagic Touch X [45], [46], [47], Omega 3 [48] and Novint Falcon [19]. As shown in Fig. 8(a), Fig. 8(b) and Fig. 8(c). These master operating mechanisms not only need to solve the kinematic model and dynamic model, but also need to establish the mapping relationship with the slave operating mechanism.

In addition, many commercial interventional surgery robot systems also use the master operating mechanism in the form of operating handle. As shown in Fig. 8(d), Fig. 8(e) and Fig. 8(f). The master operating mechanism of the CorPath GRX robotic system is three operating handles. One is used to operate the bracket, the second is used to operate the guidewire, and the third is used to operate the catheter. Amigo system uses the remote control handle as the master operating mechanism. It enables catheter delivery, withdrawal, and rotation. Magellan system provides doctors with two operation modes: console key operation mode and three-dimensional joystick operation mode.

2) The Mechanism Based on Doctors' Skills: This kind of mechanism is designed based on the operation method of doctors' manual intervention. The doctor performs operations such as clamping, rotation and delivery at the master end, and similar operations are reproduced at the slave robot.

Payne et al. designed a compact mechanism, which the operator operates in a manner similar to manual cannulation [39]. The mechanism designed by Wang et al. has an operating sleeve and an operating shaft, where the operating sleeve moves axially along the operating shaft to enter and exit the corresponding catheter/guidewire, and the rotating operating shaft can correspond to the rotation of the catheter/guidewire [49]. Fig. 9 shows part of the master operating mechanism.

3) Discussion: At present, the master operating mechanism in the form of operating handle has been widely used. But the operation method is different from that of manual intervention. The master operating mechanism based on doctors' skills can solve this problem to in part. This kind of mechanism has stronger expansibility. Theoretically, doctors can complete more complex surgical operations at the master end. Doctors' operating habits are preserved. The future master operating mechanism should be designed based on this method.

D. Force Feedback Devices

The master operating mechanism is closely related to the force feedback device. The sensors required for force feedback devices are generally installed near the master operating mechanism. Master-slave tactile transmission is an important part of

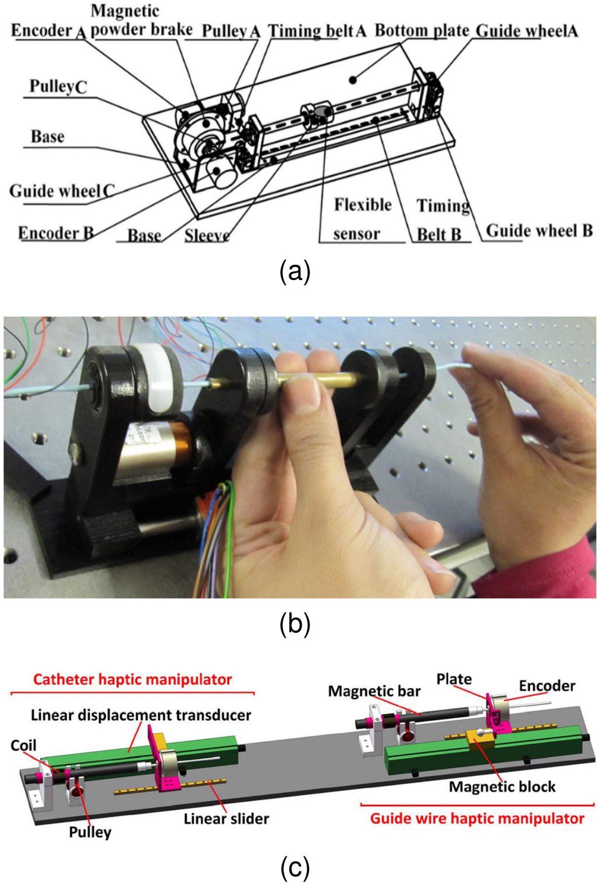

Fig. 9. Part of the master operating mechanism based on doctors' skills: (a) The master operating mechanism designed by Wang et al. [49]; (b) The master operating mechanism designed by Payne et al. [39]; (c) The master operating mechanism designed by Guo et al. [35].

human-computer interaction. Doctors can sense the slave end contact force in real time through the master force feedback device, which can effectively avoid vascular damage caused by excessive slave end contact force, and the doctor's operation will be more realistic.

At present, most of the master force feedback devices are designed based on the principle of electromagnetism. For example, Yu et al. used the magnetic particle clutch as the master tactile feedback device [50]. When the operator delivers the catheter or guidewire, the magnetic particle clutch designed by them can provide a static resistance to the operator. This static resistance is amplified by the contact force detected from the slave end. Zhou et al. used the friction generated by the mutual attraction of opposite magnets as the master axial force feedback [51].

Guo et al. continuously developed several main end tactile feedback devices based on the principle of magnetorheological fluid [52], [53], [54]. They first coaxially inserted the catheter into the magnetorheological fluid. When the contact force is detected from the slave robot, an external magnetic field will be applied to the magnetorheological fluid. By controlling the magnitude of the magnetic field intensity, the resistance of the catheter in the magnetorheological fluid can be changed, and the master force feedback can be realized.

Wang et al. proposed a master force feedback device based on SEA (series elastic actuator), which can provide feedback force with high force/torque fidelity, low impedance and inertia [55]. Their idea to solve the master force feedback is to connect the operating handle with the spring, and adjust the resistance of the handle movement by adjusting the spring compression.

In fact, if the master operating mechanism uses a commercial operating handle, their own force feedback function can be used. However, because the operation logic of the commercial handle does not conform to the operation habits of doctors, the form of force feedback is also different from the force felt by doctors in artificial surgery. Future research on force feedback devices will certainly be closer to the tactile sensation in artificial intervention surgery. The tactile feedback function of the commercial handle is obviously not enough. The master feedback force should make full use of the internal and external forces detected by the robot. When the external force is too large, the master force feedback device should make the operator get tactile feedback in time. The more accurate and more real master force feedback function is an important part of constructing telepresence of telerobot.

IV. ALGORITHMS

A. *Bilateral Control Methods*

Bilateral control methods is the core of control system. We pay more attention to the mutual tracking of master-slave positions and the transmission of forces. Its control target is shown in Formula 1.

$$\begin{cases} x_m - x_s \to 0 \\ f_m + f_s \to 0 \end{cases} \tag{1}$$

where, x represents position, f represents force, m represents master, s represents slave. In addition, some researches on remote surgery focus on the impact of time delay on system performance.

1) Research on Position Tracking and Force Transmission: PID control algorithm is the most commonly used control algorithm, which has the advantages of simple principle, convenient parameter adjustment and strong adaptability. Wang et al. used PID algorithm for motion control according to the established master control model, and optimized the parameters for fast response time and stability [55].

Based on the traditional PID algorithm, some researchers use fuzzy PID algorithm to track the master-slave position and transfer the force. Guo et al. designed the fuzzy PID controller to change different control laws according to the different feedback force of the guidewire [56]. They also use fuzzy PID controller to adjust PID parameters to improve master-slave tracking performance [57] and force feedback performance [58]. Precup et al. proposed a fuzzy control scheme based on linear inner loop and outer loop cascade control system structure based on Takagi Sugeno PID fuzzy controller, which significantly improved the overshoot and adjustment time [59]. Chen et al. used fuzzy PID to achieve more accurate position tracking. In addition, they also used the data of near-end force to fit the far-end force through neural network. Most force estimation errors are below 50 mN, which is within the acceptable range [60].

In addition, Ma et al. combined BP neural network with traditional PID controller to improve regulation time and response speed [11]. To increase the system resistance to external disturbances, robust controllers [61] and ADRC [62] are among the commonly used methods.

Due to the flexibility of the catheter body, the axial motion applied to the proximal part of the catheter often cannot be correctly reflected at its distal end, resulting in the lag phenomenon of motion. To solve this problem, Omisore et al. proposed a three-state control strategy for adaptively compensating the gap in the process of cardiovascular pathway. The system uses an adaptive neuro fuzzy inference system to predict the possible gap based on bounded input and output signals [63].

2) Research on Time Delay: If the master-slave robots are far away from each other, then the time delay will significantly affect the system performance. This will also reduce the safety of robot assisted surgery.

Guo et al. established a remote control system based on Internet. The slave robot is placed in Takamatsu, Japan, and the master robot is placed in Beijing, China. The server client structure is adopted to realize communication. In order to ensure the security of data and improve the accuracy of data, control data and image data are transmitted separately [64]. In 2020, they also proposed an algorithm combining fuzzy PID and improved Smith estimation compensation to reduce the error and time delay caused by time delay of vascular interventional surgery robot [65].

Yuan et al. used a 4G-Data Transfer unit (DTU) communication device as the communication terminal. The two DTUs are respectively connected to the master station and slave station of the robot. They deploy all motion control calculations on the slave side. In the process of operation, the upper computer only needs to send motion control information to the lower computer [66]. Aiming at the problem of cumulative increase of communication delay of transmission control protocol (TCP) in robot teleoperation, Li et al. proposed a network delay control method with multiple TCP connections. The multi TCP connection control method can reduce the delay accumulation problem and reduce the overall delay [67].

After analyzing the influence of time delay on remote operation, Yang et al. proposed a control strategy of predicting time delay. They carried out research from the two aspects of "remote cloud communication" and "perception performance evaluation", proposed a prediction method of operation delay, and conducted many remote surgery experiments [68].

B. Security Strategies

When interventional instruments are operated from slave robot, blood vessels are in danger of rupture. The method to solve this problem can be divided into two steps: detection mechanism and corresponding mechanism. We have described in detail the specific method of slave contact force detection. The corresponding mechanism means that the master robot feeds back the excessive force to the operator, so that the operator can control the robot to move forward slowly or back a short distance [69].

In order to increase the safety of the system and prevent the excessive contact force between the catheter/guidewire and the inner wall of the blood vessel, resulting in the rupture of the blood vessel, Zhang et al. designed a collision protection mechanism. Once the contact force between the catheter and the blood vessel is greater than the protection threshold, the catheter will be released to avoid the puncture of the blood vessel [70]. Wang et al. proposed a variable coefficient follow-up control method based on force and torque identification. By inputting the force and torque samples received by the catheter in a period of time into the convolution neural network, the risk probability of operating force and torque is obtained to ensure the safety of surgery [71].

Bao et al. proposed a multimodal force feedback method. If the contact force from the end is less than the safety threshold of the blood vessel, the doctor is applied with the same force feedback. If the contact force from the end is greater than the safety threshold of the blood vessel, the doctor is applied with force feedback amplified several times [72]. As shown in Formula 2.

$$F_M = \begin{cases} F_R & F_R < F_S \\ F_S + n(F_R - F_S) & F_R \geq F_S \end{cases} \tag{2}$$

where F_M is the force generated by master robot, F_R is the slave contact force, F_S is the safety threshold of vessel, and n is the magnification times of force feedback ($n > 1$). Subsequently, they divided the operation process into safe area, potential unsafe area and unsafe area, and proposed a multi-level force feedback method to improve the safety of the operation [73].

Shi et al. used the collision detection method based on z-score [12]. As shown in Formula 3.

$$z_c = \frac{f_c - \mu_t^*}{\sigma_t^*}. \tag{3}$$

where μ_t^* is the mean of the force, σ_t^* is the standard deviation of the force, f_c is the current force, z_c is the z-score of f_c. It is used to describe the distance between the current force value and the average force value of the previous period. Set z_t as the threshold for triggering collision. When z_c is larger than z_t, it is considered that collision has occurred at the slave end. The response mechanism triggered accordingly is shown in Formula 4.

$$F_h = \begin{cases} \alpha f_c & (z_c > z_t) \\ f_c & (z_c \leq z_t) \end{cases} \tag{4}$$

where α is force scaling parameter. When collision is detected at the slave end, the operator will be applied with α times of feedback force at the master end.

Aiming at the vibration suppression of isometric tremor caused by muscle tension after long-term operation, Guo et al. proposed a recognition algorithm based on support vector machine and moving mean filtering to recognize and suppress isometric tremor signals. The control signal is transmitted to the slave robot after passing through the filter to realize the accurate movement of the slave without being affected by surgeon tremor [74]. In addition, they also proposed other methods to solve the problem of physiological tremor. For example, they also used moving-window-least-square-support-vector-machine based recognition algorithm [75] and multi-step LSTM reactor prediction method based on a moving window [76]. This method is helpful to improve the safety of robot-assisted surgery. For regular tremor and sudden tremor, Li et al. proposed a tremor suppression method based on active constraint and passive correction. In addition, this method has some advantages in the timeliness of signal processing [77].

C. Skill Evaluation Methods

The operation skills of interventional doctors directly affect the operation effect. The traditional skill evaluation methods are easy to be affected by subjective factors, resulting in the deviation of the results. Therefore, it is very important to find an objective skill evaluation method.

By collecting kinematics data and image data generated during robot-assisted surgery, machine learning method can be used to objectively evaluate the operation skills of different doctors [78]. We can also analyze the differences in the operation of different doctors by means of skill evaluation, so as to provide interpretable feedback with clinical application value. In the field of surgical robots, the application of existing skill evaluation methods can be divided into two categories. One is to divide the operator into experts and novices, and the other is to classify different surgical operations according to the doctor's hand movements in the operation.

The purpose of these two research directions is to dredge up the same fate. They all explore the similarities and differences of operators with different experience in surgical operations through machine learning. This can provide an objective evaluation framework.

1) Operation Level Evaluation: Rafii-Tari et al. proposed an automated and objective performance evaluation framework to perform different intubation tasks by learning the force and movement patterns of operators with different skill levels. The Discrete Hidden Markov model framework is used to model the behavior of operators with different skill levels. The results show that the cross validation classification accuracy using force based skill model is 94% (expert) and 98% (novice), and the cross validation classification accuracy using motion based model is 83% (expert) and 94% (novice) [79]. Guo et al. included the vascular difficulty level into the evaluation index, and proposed an evaluation method of operational skills including the difficulty level index of intravascular catheter insertion into the aortic arch, with an accuracy of 96.67% [80]. O'Malley et al. recorded knife tip movement in intravascular surgical navigation tasks performed using Magellan robotic system and inanimate vascular model and evaluated using standardized structured scoring tools. Logistic regression analysis using a single motion measure can accurately classify subjects as novices and experts in robotic surgery [81].

In 2019, Zhou et al. conducted an intervention experiment on live pigs. They use a guide wire to deliver to two left circumflex arteries.They evaluated the operation quantitatively and qualitatively. Qualitative evaluation can obtain 92% classification accuracy, while the results of quantitative evaluation are very similar to the global rating scale (GRS) scores obtained by traditional methods [82]. In 2022, Zhou et al. improved the traditional dynamic time warping algorithm to make it not limited to matching with two sequences. They chose two different vascular branches of PCI for intervention experiments. They found that in simple intervention operations, it is not easy to distinguish novices from experts, but in complex tasks, the operating experience of experts can be brought into play [83]. In the same year, Zhou et al. used wavelet packet decomposition (WPD) to extract the characteristics of operational data. They also designed a learning framework consisting of local learning and ensemble learning, and the accuracy of this dual-frame structure is also significantly higher than that of the single-frame structure [84].

2) Classification of Operation: Since the objective evaluation did not take into account the vascular characteristics of specific patients, Cui et al. used the machine learning K-means model to describe the operation difficulty of different vessels in aortic arch surgery, and then verified the clustering results with external and internal indicators [85].

Zhou et al. proposed a framework based on Hidden-Markov-Model (HMM) to identify six typical intervention operations. The experimental results show that the recognition accuracy of experts in the six operations is higher than that of novices [86]. In 2019, they also proposed a framework based on HMM to identify different intervention operations. This study collected more operator data, and the new hierarchical classification framework also significantly improved the recognition accuracy [87]. In 2020, They proposed a multi-layer architecture with pattern-decoupling layer, local-decision layer and decision-fusion layer. This architecture can achieve an overall accuracy of 96.41%, which is higher than the single-layer recognition architecture (92.85%) [88].

Omisore et al. proposed a deep integration model for identifying intervention operations. They use neural networks to extract the characteristics of EMG signals, and use soft weighting technology to guide the contribution of each base learner. Compared with four other recognition methods, this model has higher recognition accuracy [89]. They also proposed a multi-layer recognition model to identify different surgical operations. The model has initial decision level, motion decision level and mixed decision level. The initial decision level is used to classify whether the experiment is successful, the motion decision level is used to classify 7 different motion operations, and the mixed decision level will recognize 14 motion operation results on this basis. This model can effectively explore the corresponding relationship between the operator's natural behavior and the intervention experiment [90].

V. CLINICAL APPLICATION

VISR are directly applied to human body, so their reliability and safety are very important. Therefore, their development process often needs multiple tests and improvements. In this process, clinical trials are essential. This section will introduce the clinical status of VISR in actually operating aspect.

A. Animal Experiments

Animal experiments are important means to verify the integrity of interventional surgery robots. If researchers have completed most of the above technical points, they can prepare animal experiments. Researchers and doctors can improve robots by completing animal experiments together.

The anatomical structure and blood physiology of pigs are similar to those of human beings, especially miniature pigs, which have become one of the most commonly used animals in animal experiments. After passing the review of the local ethics committee, researchers should abide by the ethical principles, treat animals well and take the least painful method to deal with animals in the experiment.

In animal experiments, robots must ensure sterility, which will directly affect the surgical results. In addition, because different instruments need to be replaced in interventional surgery, the interventional robot must be easy to replace different modules in surgery. Before conducting animal experiments, the researcher and the doctor should jointly confirm the type of surgery, and the researcher must inform the doctor of the robot's operation in detail.

The results of robot-assisted animal experiments should be evaluated in detail and compared with artificial intervention experiments. In terms of X-ray radiation, the radiation received by doctors under the condition of robot-assisted experiment should be significantly less than that of artificial intervention surgery. In terms of vascular injury, the vascular injury should not be greater than that of artificial interventional surgery when using robot-assisted interventional experiment. In terms of postoperative investigation, long-term follow-up should be conducted for animals in robot group and animals in artificial group. The robot group should not have more complications.

Now we will select several typical robot systems to introduce. Lu et al. performed cerebral angiography on a dog by using VIR-2. The operation was completed between Kagawa University in Japan and Beijing Naval General Hospital. The experimental results show that the remote positioning accuracy is 1 mm, the radiation exposure time of the staff is 0 minutes and the time delay is 1 s. Except for the operation of inserting the vascular sheath into the femoral artery, other operations are completed by the robot controlled by the doctor [91].

Guo et al. conducted a clinical animal experiment for a pig in Beijing Tiantan Hospital. After the experiment, the error of linear tracking performance is between 2.5 mm and −2mm, with an average error of 0.22 mm, and the rotation motion error is between 2.6° and −1.9°, with an average error of 0.17° [92]. Wang et al. used the robot to assist doctors in stent implantation of superior mesenteric artery and common iliac artery in an adult sow. The results showed that the stent implantation was accurate, there was no obvious displacement and the blood flow was unobstructed. The whole release process is stable. No X-ray is detected in the master console during operation. The whole process takes 35 minutes [93].

Legeza et al. conducted in vivo experiments on pigs to evaluate the impact of network delay on the performance of CorPath GRX robotic system. The experimental results show that remote robot assisted femoral artery, carotid artery or coronary artery intervention should be performed when the network delay is less than 400 ms [94].

B. Human Experiments

Human experiments need to be considered more carefully than animal experiments. Through a large number of human experiments, it can promote the robot system to be produced more quickly.

In 2006, Beyar et al. conducted a clinical trial on 18 patients using the RNS system. The results show that the use of balloon and stent during PCI is feasible for patients with coronary stenosis. The system provides the operator with radiation safety and can improve the accuracy of stent placement and balloon expansion strategy. The fluoroscopy time of assisted surgery with RNS system is slightly higher than that of standard technology [13].

Corindus Vascular Robotics has successively developed the CorPath 200 robotic system and the CorPath GRX robotic system, both of which have been approved by FDA. In 2019, Siemens announced the acquisition of Corindus Vascular Robotics for $1.1 billion, which is enough to see the future development potential of vascular interventional surgery robot system.

Weisz et al. conducted 164 human experiments using the CorPath 200 robotic system, and obtained the results that the success rate of clinical surgery reached 97.6%, and the radiation received by the main operator was 95.2% lower than that of traditional interventional surgery [95]. Mahmud et al. demonstrated the feasibility of unprotected percutaneous coronary intervention of high-risk left main artery with or without percutaneous hemodynamic support using the CorPath 200 robotic system [96].

CorPath GRX robotic system is the only vascular interventional surgery robot system approved by FDA and certified by CE. At present, there have been many clinical examples. In 2019, Pereira et al. performed aneurysm surgery on a 64 year old patient using the CorPath GRX robotic system. The operation time was 2 hours and 9 minutes. The patient had no complications and was discharged the day after the operation [97]. Cancelliere et al. used the CorPath GRX robotic system to perform intracranial aneurysm embolization on 6 patients. The technical success rate was 100%. There was no incidence rate or mortality related to the operation. Microcatheters, wires and stents could be accurately controlled. In addition, the safety of the operation process was high enough [98].

Amigo remote catheter system is developed by Catheter Robotics of the United States, which mainly includes two parts: the slave delivery device placed on the side of the operating table and the master remote control handle located outside the operating room [99].

In 2013, Khan et al. used Amigo remote catheter system assisted to conduct experimental evaluation on nearly 200 patients. The results proved the effectiveness and safety of the doctor's operating system for surgery, and it is easy for doctors to operate [100]. Datino et al. used Amigo remote catheter system assisted and manual methods to complete arrhythmia

TABLE I
OVERVIEW OF CLINICAL APPLICATION OF VISR

Robot system	References	Year	Object	Operation	Success rate	Evaluation
RNS	[13]	2006	18 patients	PCI	83.3%	Improve the precision of stent deployment.
Magellan	[104]	2013	1 patient	Fenestrated endovascular aneurysm repair	100%	High accuracy and stability;
	[101]	2017	23 patients	Cerebral angiography Intracranial intervention	100%	Reduce X-ray radiation;
	[14]	2021	13 patients	Carotid artery stent	100%	Robot system setup time is short.
Amigo	[100]	2013	181 patients	EP	94%	Easy to use;
	[15]	2014	50 patients	EP	96%	Reduce X-ray radiation;
	[99]	2017	43 patients	EP	100%	Unique manual override feature.
RobEnt	[105]	2018	1 patient	Carotid and vertebral angiographies	100%	Initially available for clinical use.
CorPath 200	[95]	2013	164 patients	PCI	98.8%	Reduce X-ray radiation;
	[96]	2016	102 patients	PCI	100%	Increased operating comfort.
CorPath GRX	[106]	2018	2 patients	PCI	100%	The first use of a robotic system for diagnostic coronary angiography; Reduce X-ray radiation; Bedside support team required; Lack tactile feedback; Safe and effective.
	[97]	2020	1 patient	Neuroendovascular intervention	100%	
	[107]	2020	6 patients	Transradial carotid artery stenting	100%	
	[98]	2021	6 patients	Embolization of intracranial aneurysms.	100%	
	[16]	2022	1 patient	PCI	100%	
	[108]	2022	14 patients	Carotid stent procedure	100%	

ablation surgery respectively, collected and compared the factors such as operation time, radiation dose, radiation time and RF catheter delivery time during the operation. The research shows that amigo surgical robot can significantly reduce the radiation received by doctors without specific operation strategies, but it does not have significant advantages in operation time [15].

Hansen Medical has successively launched Sensei system and Magellan system, both of which have been approved by FDA. Their disadvantage is that they can not use conventional endovascular instruments, and they must use specially developed interventional instruments. In 2016, Hansen Medical was merged by Auris Health, a medical robotics company, for $80 million. In 2019, Johnson & Johnson Medical acquired Auris Health for $3.4 billion.

Magellan system is shown in Fig. 8(f). Vuong et al. demonstrated that the use of Magellan system can be technically used for cerebral angiography and cerebrovascular intervention without significantly increasing the risk of patients [101]. In the case of stent implantation failure in artificial intervention surgery, Lumsden et al. used Sensei system to assist doctors to successfully complete angioplasty surgery, in which the mechanical arm significantly enhanced the stability [102]. Rolls et al. successfully performed bilateral uterine artery embolization on 5 women with the assistance of Magellan system. All patients were discharged on the first day after operation without serious complications. The symptoms of all patients were significantly improved 6 months after operation [103].

In Table I, we summarize the clinical application of different VISR by time. We found that VISR assisted surgery has a high success rate. At present, there are many clinical applications. The vast majority of the robotic systems used therein were developed by robotics companies. We believe that more and more scientific research achievements will be transformed into products over time.

C. Discussion

The robot system that can carry out animal experiments needs better hardware devices and algorithms. If we prepare for human experiments, we need to consider more. There is no doubt that the vascular interventional surgery robot has advantages in radiation protection, doctor-patient isolation, operation accuracy and other aspects. But after the above introduction and analysis, we can find that there are still some limitations in the clinical application of vascular interventional surgery robot.

First of all, most of the existing interventional surgical robot products that can conduct human experiments lack force feedback. It is not enough for doctors to rely only on the visual information of digital subtraction angiography (DSA) equipment for surgery. Doctors also need accurate force feedback to ensure the quality of surgery. Next, there are few studies on the safety of robot-assisted surgery in the existing papers. We need to take protective measures in mechanical, electronic and algorithmic aspects. In addition, we should consider the learning curve of doctors operating robots. This is closely related to the complexity of the robot. When designing and replacing different interventional instruments in interventional surgery, we must ensure that robots are easy to replace. Finally, we note that the types of operations that the existing vascular interventional surgery robots can perform are still limited. Most surgical robots are developed for PCI and PVI. There are various types of vascular intervention surgery, and there is still a long way to go for vascular intervention surgery robot to replace artificial intervention surgery.

It is an important means to measure the integrity of robots in clinical application. In order to develop a better robot system, researchers, doctors and patients should contact more. Future robot systems need to make more efforts in mechanical structure, algorithm and security.

VI. CHALLENGES AND PROSPECTS

A. Challenges

1) Operating Mechanism With Stronger Compatibility: When doctors perform interventional surgery on different parts of patients, they will choose the corresponding interventional instruments. The size and structure of different interventional instruments are different. The existing research on the catheter and guidewire operating systems pay little attention to the replacement of different interventional instruments, which will limit doctors to carry out more complex surgical operations. In addition, most of the existing studies only focus on the delivery and rotation of catheter/guidewire, and there are few studies on the delivery of interventional instruments such as balloon and stent.

2) More Realistic Force Feedback: Doctors only rely on medical images for surgery, which will cause the distortion of doctors' operation. If there is no force feedback during the operation, the risk of vascular injury will be higher. How to make doctors perceive real and reliable force feedback is the research hotspot of interventional surgery robot. Many experts and scholars focus on developing new pressure sensors to construct real tactile feedback for doctors.

3) Remote Surgery: Due to the uneven distribution of medical resources, experienced expert doctors often work in hospitals in large cities. If patients in small cities are in urgent need of complex surgery due to sudden vascular diseases, and local doctors cannot complete it, remote experts can operate on patients with surgical robots that can perform remote surgery at the first time. As early as 2012, Guo Shuxiang's team used the developed vascular interventional surgery robot system to complete cross-border clinical animal experiments between China and Japan. With the development of 5G technology, the information transmission speed between master and slave controllers is faster and the network delay is lower. Doctors use interventional surgery robot to complete remote surgery, which gradually turns from dream to reality [109].

4) Skill Training: When doctors first use VISR to assist in surgery, they often need to be familiar with its use method in advance. This will not only increase the doctor's X-ray radiation level, but also increase the patient's surgical risk. Robot assisted surgery for vascular intervention on human vascular models or animals is far from the real human structure. Therefore, it is very important to develop a preoperative training system based on virtual reality. Doctors can train the operation for many times to avoid the harm to health caused by X-ray radiation, and also reduce the use cost of long-term training.

5) More Autonomy: At present, the VISR have a low level of autonomy. Even the CorPath GRX robotic system, which is widely used, must be assisted by the bedside team. Robots with a higher degree of autonomy will help doctors do more. But at the same time, we should also pay attention to the risks.

B. Prospects

With the increasingly close relationship between robot technology and vascular interventional surgery, the operating systems have gradually become a research hotspot in the field of VISR. There are still some aspects to be optimized. The first is to improve the human-computer interaction ability to increase the realism of doctors' operation. Secondly, the operating mechanism should be convenient to replace the interventional instruments, and the disinfection and sterilization function should also be designed. Finally, the operating systems should design safety protection strategies from the hardware level and software level to avoid surgical failure caused by sudden failure.

VII. CONCLUSION

This paper reviews the catheter and guidewire operating systems of vascular interventional surgical robots. The development of VISR not only transfers the surgery to the operating room, but also improves the accuracy and controllability of the operation. Catheter and guidewire operating systems are the core problems to be solved by VISR. We analyzed the related literatures and presented the research directions of the operating systems in terms of hardware devices and algorithms. Specifically, we introduced different kinds of mechanisms and tactile feedback devices in the hardware devices, and introduced the bilateral control methods, security strategies and skill evaluation methods in the algorithms. They basically cover the research direction of current operating systems. We believe that the development of surgical robotics cannot be separated from clinical trials. After doctors actually use the robot system, engineers will gradually iterate and optimize according to the feedback. Finally, we propose the current challenges and prospects of the operating systems. We hope that our review can provide a clear reference framework for researchers. With the increasing enthusiasm of academia and industry, a more perfect vascular interventional surgical robot will appear in the near future.

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Pengfei Chen received the B.E. degree in mechanical engineering from Changchun University of Technology in 2015. He is currently a doctoral student, affiliated with the Key Laboratory of Airborne Optical Imaging and Measurement, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, and also with the University of Chinese Academy of Sciences. His research interests are interventional surgery robots.

Yutang Wang (Member, IEEE) received the B.E. degree in automation and the M.S. degree in control science and engineering in 2009 and 2012, respectively, from the Beijing Institute of Technology. She received the Ph.D. degree in optical engineering from the University of Chinese Academy of Sciences, China, in 2019. Since 2012, she has been with the Key Laboratory of Airborne Optical Imaging and Measurement, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, and also with the University of Chinese Academy of Sciences. Her current research interests include optical imaging and motion control.

Dapeng Tian (Senior Member, IEEE) received the B.E. degree in aircraft design from the Beijing Institute of Technology, Beijing, China, in 2007. He received the Ph.D. degree from Beihang University, Beijing, China, in 2012. He was then directly recommended to study at Beihang University, Beijing, China. From 2009 to 2011, he was a Co-Researcher with the Advanced Research Center, Keio University, Yokohama, Japan. Since 2012, he has been with the Key Laboratory of Airborne Optical Imaging and Measurement, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, and also with the University of Chinese Academy of Sciences, where he is currently a Full Professor. His current research interests include motion control theory and engineering, optical imaging, and bilateral control.

Yunbao Guo received the bachelor's, master's, and Ph.D. degrees from Jilin University, Changchun, China, in 2000, 2003, and 2008, respectively. He is currently an Associate Chief Physician and an Associate Professor with The First Hospital of Jilin University. He is good at interventional and craniotomy treatment of aneurysms, extracranial and intracranial vascular bypass of moyamoya disease, and high and low flow vascular bypass treatment of complex aneurysms. He completed the first high flow extracranial and intracranial vascular bypass surgery in Jilin Province.

Kan Xu received the bachelor's and master's degrees in clinical medicine from Norman Bethune Medical University, Changchun, China, in 1990 and 1993, respectively, and the Ph.D. degree in neurosurgery from Jilin University, Changchun, in 2004. In 2013, he served as the Director of Neurovascular Surgery of The First Hospital of Jilin University. He has been engaged in neurosurgical treatment for more than 20 years, and is good at the surgical diagnosis and treatment of cerebrovascular diseases, various cerebral hemorrhage diseases and cerebral ischemia diseases, especially the surgical operation and interventional treatment of cerebrovascular diseases.