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Toward Cooperation of Catheter and Guidewire for Remote-controlled Vascular Interventional Robot

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Abstract— **Remote-controlled vascular interventional surgery robots (RVIR) are being developed to reduce the occupational risk of the intervening physician, such as radiation, chronic neck and back pain, and increase accuracy and stability of surgery operation. Moreover, some successful RVIR are used to operate catheter or guidewire accurately. However, catheter and guidewire are operated respectively by intervening physician during surgery, because the support of catheter and the navigation of guidewire are necessary when guidewire passes through the vessel, especially the narrow vessel branch. Therefore, lacking of cooperation of catheter and guidewire is a great challenge for complete or complex surgery. In this paper, a cooperation of catheter and guidewire concept is firstly introduced in RVIR. The prototype operates catheter and guidewire respectively and accurately. The experimental results show that: the average error of the axial motion is 0.33mm, and the maximum error of the axial motion is 1.42mm. The RVIR, effectively realize the cooperation of catheter and guidewire, is feasible for minimally invasive surgery.**

Index Terms— **Minimally invasive surgery; Remote-controlled vascular interventional surgery robot (RVIR); Cooperation of catheter and guidewire**

I. INTRODUCTION

Minimally invasive surgery is widely used in surgery because it can reduce pain of patients and allow for quick recovery. However, the minimally invasive surgery causes several difficult problems for surgeons: the partial protection for the radiation [1], heavy radiation protection garments, chronic neck, and back pain [2], due to the specific surgical procedure and small work space. Therefore, development of the surgical support devices with the application of robot technology is in demand [3]. Robotically controlled steerable catheter navigation systems, allowing the surgeons to be released from radiation and heavy radiation protection garments, have seen a growing interest in the field of endovascular surgery. Also, the catheter navigation system can reduce radiation exposure, increase precision and stability of motion, and add operator comfort [4].

At present, the main commercial interventional robots mainly include: Sensei (Hansen Medical) [5], Niobe (Stereotaxis Inc.) [6], Corpath (Corindus Vascular Robotics) [7], and Amigo (Catheter Robotics Inc.) [8]. The Sensei system has been successfully used in different clinical applications, such as endovascular aneurysm repair and cardiac ablation, because of the validation of its efficacy in reducing radiation exposure and fluoroscopy time. Meanwhile, the shortage of the Sensei system is obvious, including large size, high cost, and longer setup times. The Sensei system can provide 2-DOF in catheter manipulation, as well as the Niobe system and the Amigo system. Meanwhile, the Corpath system allows for only 2-DOF to control catheters in vascular applications.

Also, a remote-controlled interventional robot was developed in [9], which has 2-DOF and force feedback. In [10], an endovascular tele-operated system including haptic feedback was presented, which can manipulate both catheter and guidewire. The endovascular tele-operated system can provide 2-DOF in catheter manipulation. In [11]-[12], another master–slave robot system allowing for 3-DOF was designed, which allows the surgeons to operate with a joystick or a graphical user interface. In [13]-[18], a tele-operated system, proving 2-DOF in the slave side, can measure the force precisely and realize the force feedback in the master side.

Generally speaking, according to the operating characteristics, the catheter used in surgery can be divided into two types: active catheter rotating its head by using its own mechanism, and passive catheter rotating its head by using the mechanism operating like the surgeon's hand and located at the end of itself. Owing to the guiding ability, the active catheter can pass through the vessel branch easily, and it can be used in abdominal surgery and cardiac surgery successfully. However, the size and safety problems of the active catheter limits its application in cerebrovascular surgery, because the drive mechanism in the head of active catheter make the size and safety problems obvious.

Meanwhile, passive catheter has a wider application field, such as abdominal surgery, cardiac surgery, and cerebrovascular surgery, and a guidewire is needed to cooperate with the passive catheter. Catheter and guidewire are operated respectively by intervening physician during surgery, because the support of catheter and the navigation of guidewire are necessary when guidewire passes through the vessel, especially the narrow vessel branch. Therefore, lacking of cooperation of catheter and guidewire is a great challenge for complete or complex surgery. However, to our knowledge,

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there is no reported specification on a cooperation of catheter and guidewire concept in RVIR.

In this paper, a cooperation of catheter and guidewire concept is firstly introduced in RVIR, and a prototype is developed to realize the motion of catheter and guidewire. Firstly, the operational approach was introduced, as well as the cooperation principle of catheter and guidewire. Secondly, the mechanical realization was presented, including a rotational motion mechanism and a linear motion platform. Thirdly, to evaluate the feasibility of RVIR, an experiment was developed, and the device was tested.

II. SYSTEM DESCRIPTION

A. Operational approach

In order to realize the cooperation of catheter and guidewire, a catheter control unit and a guidewire control unit are needed to control the movement (pull, push and rotation) of catheter and guidewire respectively. The catheter control unit should be designed to pull, push, and rotate the catheter solely, as well as measure force/torque of catheter. The guidewire control unit should have the same function with the catheter control unit. Also, these two units should be operated respectively, because of the independent movement of catheter and guidewire. In other words, movement interference between catheter unit and guidewire unit do not exist, and every unit can realize the movement respectively and freely without restriction of the other unit.

The cooperation principle of catheter and guidewire is shown in Fig.1. We introduce a cooperation principle to realize the movement of catheter and that of guidewire respectively. The catheter unit achieves the linear and rotational motion using block 1 and block 3 respectively, and the guidewire unit achieves the linear and rotational motion using the block 2 and block 4 respectively. The block 1 and block 2 are coaxial, and the block 3 has the same height with block 4, because guidewire is located in catheter's interior in the surgery, and they are almost coaxial. Fig.2 shows the cooperation of catheter and guidewire.

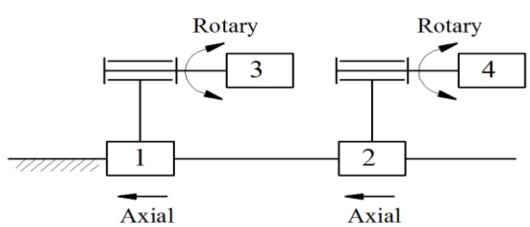

Fig. 1 Cooperation principle of catheter and guidewire.

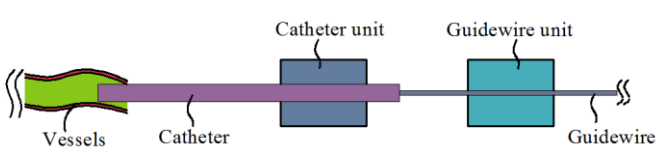

Fig. 2 Cooperation of catheter and guidewire: the catheter and guidewire are operated respectively to realize both rotary and axial motion of catheter and guidewire.

B. Mechanical realization

Based on the analysis above, the catheter unit and the guidewire unit all have linear motion and rotational motion, so we designed a linear motion platform to achieve the linear motion of the catheter unit and the guidewire unit, and designed a rotational motion mechanism to realize the rotational motion of the catheter unit and the guidewire unit. Thus the RVIR is composed of two parts: a linear motion platform and a rotational motion mechanism.

(1) Rotational motion mechanism

In [19], we introduced a novel guidewire navigation robot, which can reach high precision and accuracy of guidewire motion, measure the force/torque of guidewire, and realize the force/torque feedback to the surgeon. The experimental results show that: axial error was no more than 0.5mm, the rotational error was no more than 1 degree, force error was no more than 0.031N, and the novel guidewire navigation robot is feasible for minimally invasive surgery. The novel guidewire navigation robot is composed of a mobile platform, a shell, a gripping unit, and a driving unit. The mobile platform was designed to realize the linear motion of guidewire, and it provides the support to the shell, accommodating the gripping unit and the driving unit. The shell, the gripping unit and the driving unit can realize rotational motion of guidewire, as well as force/torque measurement. In this paper, we designed a fixing mechanism of shell, connecting the shell and linear motion platform, and used the shell, the mechanisms in it (gripping unit and driving unit) as the rotational motion mechanism of guidewire.

We used a guidewire gripper for gripping the guidewire in [19] and similarly, we designed a catheter gripper for gripping the catheter. So we can use the rotational motion mechanism of guidewire as a rotational motion mechanism of catheter by replacing the guidewire gripper with a catheter gripper, without redesigning the other mechanism.

(2) Linear motion platform

The linear motion platform realizing linear motion of guidewire unit and catheter unit, is composed of four parts: supporting platform, mobile mechanism, tightening mechanism and driving mechanism (Fig. 3). From analysis above (Fig. 1), the guidewire unit and the catheter unit are located coaxially. In [18], we proposed a novel robot-assisted catheter surgery system, and in this system we used two graspers to control the catheter (Fig. 4): the surgeon can drive the catheter to move along axial direction when the catheter is clamped by grasper 1; the catheter keeps its position and the catheter-driven part can move freely when the catheter is clamped by grasper 2. In other words, when grasper 1 needs to change gripped position of catheter (just like the surgeon changes his/her hand gripped position), catheter could move randomly without restriction in axial direction because grasper 1 do not clamp the catheter. So grasper 2 was designed to clamp the catheter in order to avoid surgical risk caused by loss of control of catheter.

Based on this concept, in order to realize the control of guidewire and catheter, it is necessary to design two additional graspers. Meanwhile we developed a novel catheter manipulator clamping the end of catheter to control the catheter, so the catheter unit can absolutely control the catheter safely and accurately without the additional grasper. However, we developed the guidewire unit based on this concept above and there will be an additional grasper to control the guidewire. So, three axial motion control units including three mobile platforms realizing three axial motions were developed in the linear motion platform.

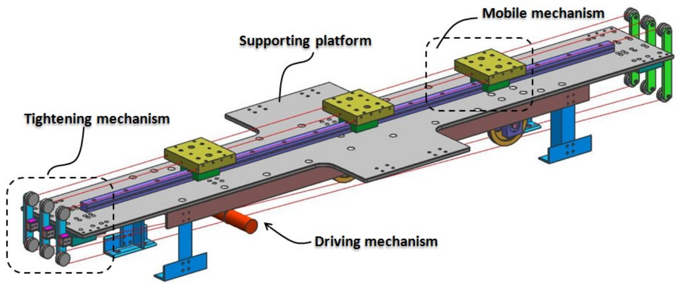

Fig. 3 Linear motion platform, including supporting platform, mobile mechanism, tightening mechanism and driving mechanism.

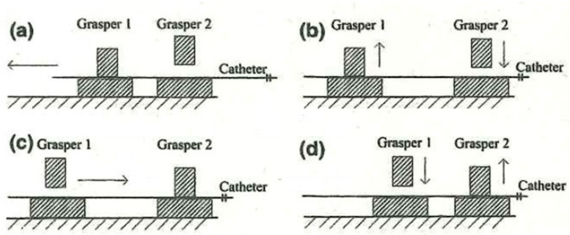

Fig. 4 Insertion process of catheter [18].

Supporting platform

The supporting platform was designed to support and regulate most of devices in the surgery. On the one hand, it is mounted on the manipulator regulating relative pose of the RVIR and patient. On the other hand, it supports and mounts mobile mechanism, tightening mechanism, and driving mechanism and impel them work together to realize the axial motions of the RVIR. In this paper, we firstly introduced a cooperation of catheter and guidewire concept in RVIR, and in order to realize and evaluate feasibility of the prototype, we paid great attention to its function realization instead of its appearance and dimension.

Mobile mechanism

In order to realize the three axial motions analyzed before, we used a slide rail mounted on the supporting platform and three sliders mounted on the slide rail. The slide is driven by the cable-driven mechanism because of low inertia, simple structure and small volume of the cable-driven mechanism. Each slide is linked with a wire rope and the wire rope passes through a hole in slide. As the Fig. 5 shows, wire rope 1 linking with slider 1 can move freely in the hole of the other two sliders (slider 2 and slider 3). Meanwhile, slider 2 and slider 3 have the same fixation principle with slider 1. This structure can guarantee the three sliders to realize three axial motions in same axial direction without interference. Also, a limit switch is mounted on each slider, in order to avoid a collision between two sliders when the two sliders move into a limit distance.

Tightening mechanism

A tightening mechanism was developed to realize tension of the wire rope in the cable-driven mechanism during installation and debugging (Fig. 6). Two pulleys mounted on a rod are used for a guidance of the wire rope in each tightening mechanism. The rod liking with a telescopic handle located in sleeve can move in axial direction and make the wire rope relaxing or tight by adjusting the screw in the end of sleeve. The axial accuracy and precision of the linear motion platform depend on the tension of the wire rope, so it is quite important to adjust the tension during installation and debugging.

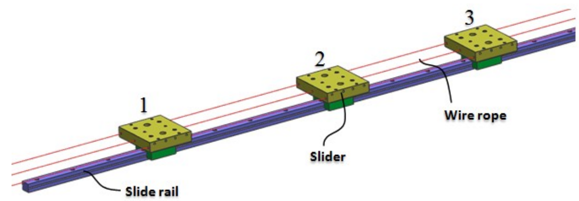

Fig. 5 Mobile mechanism of the linear motion platform.

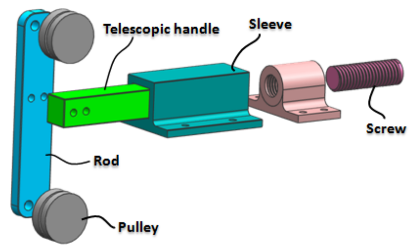

Fig. 6 Tightening mechanism of the linear motion platform.

Driving mechanism

As the Fig. 7 shows, a servo motor is used to drive the cable-driven mechanism. The wire rope is mounted on rope sheave, driven by the servo motor. The rotary motion of servo motor is transformed into axial motion of the slider by the wire rope and the cable-driven mechanism. In order to realize the axial motion of the slider more accurately, we use a motor encoder mounting on the motor and use the position signal got form the motor encoder as a feedback to the control system of RVIR. Meanwhile, the servo motor will stop rotate when the servo motor receive a stop signal from the control system of RVIR, because the limit switch transmit a stop signal to the control system as two sliders move into a limit distance.

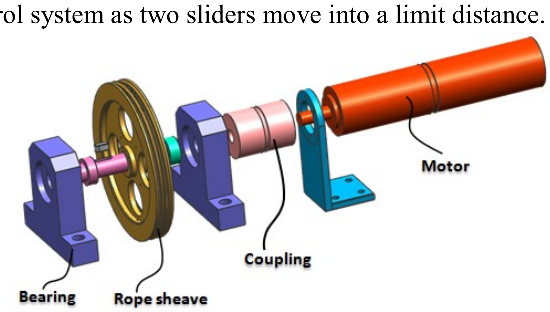

Fig. 7 Driving mechanism of the linear motion platform.

III. SYSTEM EVALUATION

To evaluate feasibility of the RVIR (prototype of the RVIR is shown in Fig. 8), a system evaluation is developed, including the verification of axial motion, rotational motion and force measurement. The prototype proposed in this paper, is composed of two parts: rotational motion mechanism realizing the rotational motion and force measurement of catheter and guidewire, and linear motion platform realizing the axial motion of catheter and guidewire. The rotational motion mechanism was proposed previously in [19], and in this paper, we designed a fixing mechanism to link it with the linear motion platform without redesigning it. So its verification of rotational motion and force measurement is feasible for minimally invasive surgery, because it has been already evaluated in [19].

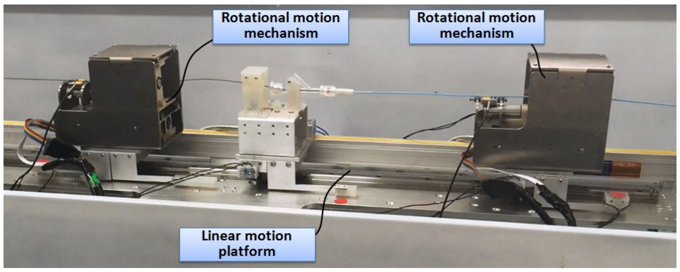

Fig. 8 Prototype of the RVIR.

In order to evaluate feasibility of linear motion platform, a grating scale was used to measure its axial motion. The grating scale was mounted on the supporting platform and the reading head of the grating scale was mounted on the slider. The reading head of the grating scale has the same motion with the slider, and the axial motion of the slider can be measured by using the grating scale.

In this experiment, a grating scale (JCXE-DK, GUIYANG XINTIAN OETECH Co., Ltd, CN) mounted on the linear motion platform is shown in Fig. 9. The control system of RVIR sends a control signal to the servo motor, and the slider driven by the servo motor and cable-driven mechanism moves. Then we compared the axial motion of the slider got from the grating scale and the control signal sent by the control system of RVIR.

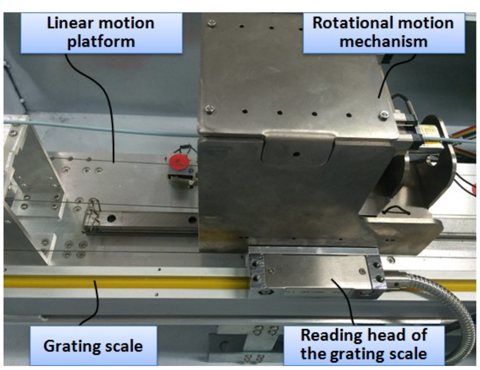

Fig. 9 Experimental devices for axial motion evaluation.

IV. RESULTS AND DISCUSSIONS

The results are shows in Fig. 10. The figure shows a good agreement between axial motion of the slider and the control signal except for the place that the slider accelerates suddenly. The maximum axial error between axial motion of the slider and the control signal is 1.42 mm and average error of it is 0.33 mm. The error between axial motion of the slider and the control signal exists inevitably because of two kinds of errors: random error existing randomly and eliminated impossibly, and systematic error caused by the prototype system, such as mechanism and control system. In this experiment, the systematic error mainly includes delay error and mechanical error. As our control system is a master-slave system, the delay error exists inevitably, even if some measures were taken to eliminate it and all what we can do is to decrease it. Meanwhile, the mechanical error has great influence on the systematic error because of mechanical characteristic and machining error of different kinds of mechanisms.

In Fig. 10, the axial error increases maximally at t=0.6s, because of sudden acceleration the slider and deficient stiffness of the driving mechanism and the mobile mechanism. The sudden acceleration exists generally in the surgery when the surgeon operates the catheter and guidewire. Meanwhile, the deficient stiffness caused by the coupling in the driving mechanism and wire rope in the mobile mechanism cannot be eliminated. The wire rope will be elongated due to its elastic characteristics when it transfers force during the process of driving the slider. Similarly, the coupling has a torsional deformation when it transfers torque during the process of driving the rope sheave. Also, in this experiment, we chose a membrane coupling, so the torsional deformation is more obvious because it is a flexible coupling. These two factors make the error more obvious when the slider accelerates or decelerate suddenly.

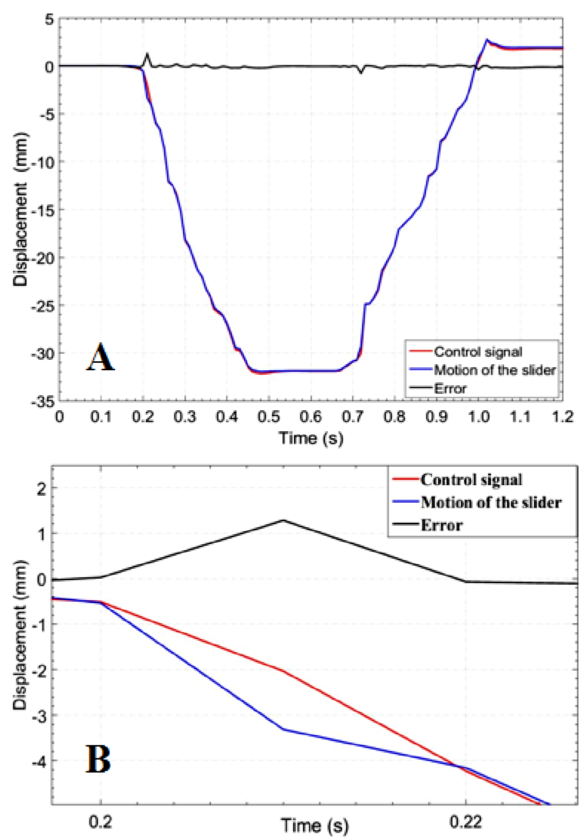

Fig. 10 Experiment results: axial motion of the slider and the control signal of RVIR are shown in (A), (B) shows the magnified versions of the 0.2-0.22 second of the profiles in (A).

Except for these mechanical characteristics causing the mechanical error, machining error of the rope sheave is another factor. The rope sheave is used to transform rotary motion into linear motion, so its cylindricity is the key element affecting the axial accuracy. However, the cylindricity of the rope sheave is finite because of the machining error, so the slider's axial motion is variable even if the rotary motion of the rope sheave is the same with a same control signal. In other words, the relationship between the rotary motion of the rope sheave and the axial motion of the slider is nonlinear.

V. CONCLUSIONS

A cooperation of catheter and guidewire concept is firstly introduced in RVIR and the prototype can operate catheter and guidewire respectively. We designed a linear motion platform to achieve the linear motion of the catheter unit and the guidewire unit, and designed a rotational motion mechanism to realize the rotary motion of the catheter unit and the guidewire unit. The feasibility of the rotational motion mechanism was evaluated previously. In this paper we designed an experiment to evaluate the feasibility of the linear motion platform. The results show that the linear motion platform can realize the axial motion accurately and the error can be reduced by some measures in the subsequent research.

In the subsequent research, two measures will be taken to reduce the axial error. Firstly, the stiffness of the linear motion platform can be improved. The wire rope and the membrane coupling decrease the stiffness of the linear motion platform drastically, so improving their high stiffness is a good choice by choosing a larger diameter wire rope and a high stiffness coupling. Secondly, we can use a compensation algorithm to reduce the mechanical error of the rope sheave. The slider's axial motion is variable even if the rotary motion of the rope sheave is the same with a same control signal because of the machining error, so two measures will be help. On the one hand, we can build a model reflecting the relationship between the rotary motion of the rope sheave and the axial motion of the slider, and use a compensation algorithm to make the relationship between the rotary motion of the rope sheave and the axial motion of the slider approximately linear. On the other hand, in this paper, we use a motor encoder mounting on the motor and use the position signal got form the motor encoder as a feedback to the control system of RVIR, and the control mode is semi-closed loop. In the subsequent research, a grating scale can be used to measure the axial motion of the slider and the position signal of the slider is sent to the control system. The control system uses the position signal got form the grating scale as a feedback, and it can improve the accuracy of axial motion greatly.

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REFERENCES

[1] M. Whitby, and C. J. Martin, "A study of the distribution of dose across the hands of interventional radiologists and cardiologists," *The British journal of radiology*, vol. 78, no. 927, pp. 219-29, 2014.

[2] L.W. Klein, et al., "Occupational health hazards in the interventional laboratory: time for a safer environment," *Catheterization and Cardiovascular Interventions*, vol. 73, no. 3, pp. 432-438, 2009.

[3] R. H. Taylor, and D. Stoiariovici, "Medical robotics in computer-integrated surgery," *IEEE Transactions on Robotics & Automation*, vol. 19, no. 5, pp. 922-926, 2003.

[4] C.V. Riga, et al., "Evaluation of robotic endovascular catheters for arch vessel cannulation," *Journal of vascular surgery*, vol. 54, no. 3, pp. 799-809, 2011.

[5] W. Saliba, et al., "Atrial fibrillation ablation using a robotic catheter remote control system: initial human experience and long-term follow-up results," *Journal of the American College of Cardiology*, vol. 51, no. 25, no. 2407-2411, 2008.

[6] M. N. Faddis, et al., "Magnetic guidance system for cardiac electrophysiology: a prospective trial of safety and efficacy in humans," *Journal of the American College of Cardiology*, vol. 42, no. 11, pp. 1952-1958, 2003.

[7] Beyar, Rafael, et al., "Concept, design and pre-clinical studies for remote control percutaneous coronary interventions," *EuroIntervention: journal of EuroPCR in collaboration with the Working Group on Interventional Cardiology of the European Society of Cardiology*, vol. 1, no. 3, pp. 340-345, 2005.

[8] E. M. Khan, et al., "First experience with a novel robotic remote catheter system: Amigo™ mapping trial," *Journal of Interventional Cardiac Electrophysiology*, vol. 37, no. 2, pp. 121-129, 2013.

[9] C. Meng, et al., "A remote‐controlled vascular interventional robot: system structure and image guidance," *The International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 9, no. 2, pp. 230-239, 2013.

[10] G. Srimathveeravalli, T. Kesavadas, and X. Li, "Design and fabrication of a robotic mechanism for remote steering and positioning of interventional devices," *The International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 6, no. 2, pp. 160-170, 2010.

[11] E. Marcelli, L. Cercenelli, and G. Plicchi, "A novel telerobotic system to remotely navigate standard electrophysiology catheters," in *Proceedings of 2008 IEEE International Conference on Computers in Cardiology*, pp. 137-140, 2008.

[12] J. W. Park, et al., "Development of a Force‐Reflecting Robotic Platform for Cardiac Catheter Navigation," *Artificial organs*, vol. 34, no. 11, pp. 1034-1039, 2010.

[13] J. Guo, S. Guo, L. Shao, P. Wang and Q. Gao, "Design and performance evaluation of a novel robotic catheter system for vascular interventional surgery," *Microsystem Technology*, pp. 1-10, 2015.

[14] J. Guo, S. Guo, T. Tamiya, H. Hirata and H. Ishihara, "Design and Performance Evaluation of a Master Controller for Endovascular Catheterization," *International Journal of Computer Assisted Radiology and Surgery*, vol.11, no.1, pp.1-13, 2015.

[15] Y. Wang, S. Guo, and B. Gao, "Vascular Elastcity Determined Mass-spring Model for Virtual Reality Simulators," *International Journal of Mechatronics and Automation*, vol.5, no.1, pp. 1-10, 2015.

[16] J. Guo, S. Guo, T. Tamiya, H. Hirata, and H. Ishihara, "Design and Performance Evaluation of a Master Controller for Endovascular Catheterization," *International Journal of Computer Assisted Radiology and Surgery*, vol.11,no.1,pp:1-13, 2016.

[17] X. Yin, S. Guo, and N. Xiao, T. Tamiya, H.i Hirata and H. Ishihara, "Safety operation Consciousness Realization of MR Fluids-base Novel Haptic Interface for teleoperated Catheter Minimally Invasive neuro Surgery," *IEEE-ASME Transactions on Mechatronics*, vol. 21, no. 2, pp.1043-1054, 2016.

[18] S. Guo, N. Xiao, and B. Gao, "A Novel Robot-Assisted Catheter Surgery System with Force Feedback," in *Selected Topics in Micro/Nano-robotics for Biomedical Applications*. New York. U.S.: Springer, 2013, pp. 175-190.

[19] X. Bao, S. Guo, N. Xiao, et al., "Design and Evaluation of a Novel Guidewire Navigation Robot," in *Proceedings of 2016 IEEE International Conference on Mechatronics and Automation*, pp. 431-436, 2016.