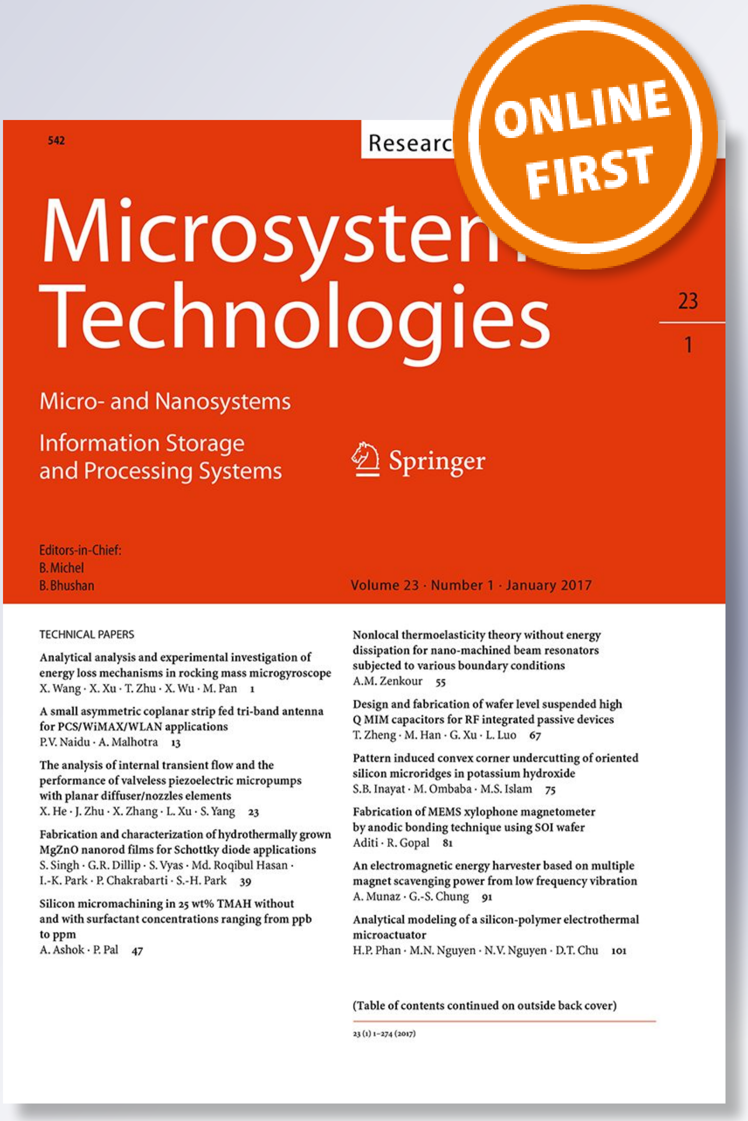
Online measuring and evaluation of guidewire inserting resistance for robotic interventional surgery systems

Yuan Wang, Shuxiang Guo, Nan Xiao, Youxiang Li & Yuhua Jiang

Microsystem Technologies
Micro- and Nanosystems Information Storage and Processing Systems

ISSN 0946-7076

Microsyst Technol
DOI 10.1007/s00542-018-3750-4



542

Researc

Microsystem
Technologies

23
1

Micro- and Nanosystems

Information Storage
and Processing Systems

Springer

Volume 23 · Number 1 · January 2017

TECHNICAL PAPERS

(Table of contents continued on outside back cover)

23 (1) 1–274 (2017)

Springer

Microsystem Technologies
https://doi.org/10.1007/s00542-018-3750-4

TECHNICAL PAPER

Online measuring and evaluation of guidewire inserting resistance for robotic interventional surgery systems

Yuan Wang[1] · Shuxiang Guo[1,2] · Nan Xiao[1] · Youxiang Li[3] · Yuhua Jiang[3]

Received: 12 December 2017 / Accepted: 19 January 2018

Abstract

Detecting catheter resistance during surgery is an important aspect of robotic interventional surgery. This haptic feedback can improve doctors' sense of realism, and therefore, the safety of the procedure. The resistance to the catheter or guidewire is the only basis for providing doctors with haptic feedback, and is also an important parameter in surgical safety strategy design. In master–slave interventional robots, catheter resistance is measured by the slave side, specifically, the catheter or guidewire manipulator. Any of four problems may occur during catheter and guidewire resistance measurements: friction and slipping, bending, damage to the catheter, or damage to the guidewire. In this study, we designed a novel torque that nondestructively clamps the catheter or guidewire to prevent slippage and damage. We also developed a new catheter/guidewire manipulator that allows the catheter/guidewire's movements and resistance measurements to occur coaxially, preventing the catheter/guidewire from bending during motion and measurement. All movable parts in the manipulator are connected by sliding rails to reduce errors caused by friction. The results of evaluation of haptic feedback using simulated surgery indicate that the operators provided with haptic feedback can significantly reduce the duration of an operation and the resulting impact force.

1 Introduction

Cardiocerebral vascular diseases are a leading cause of death worldwide. Increasingly, cardiovascular surgery has adopted micro-invasive treatments that produce small wounds, promote fast recovery, and minimize injury to the human body. With the development of robot technology, interventional surgery robots (Ikeda et al. 2005; Saliba et al. 2008; Jayender et al. 2009; Kesner and Howe 2011; Penning et al. 2011; Dankelman et al. 2011) have become an effective way to improve operation efficiency and protect doctors from radiation.

In recent years, a series of minimally invasive surgical systems has been developed, including active catheter systems such as Sensei and Amigo. The Hansen Medical Company developed the Sensei robot system, which has a specialized vascular intervention propulsion mechanism for a catheter or guidewire, and the Catheter Robotic Corporation developed the Amigo propulsion mechanism (Khan et al. 2013). Both mechanisms can achieve complex catheter motions, including pushing, pulling, rotating, and bending of the catheter tip. Stereotaxis Corporation developed the Niobe remote navigation system (Thakur et al. 2011) that can locate a guidewire via magnetic navigation. Other invasive surgical systems include passive catheter systems, such as Corpath 200 (Lock and Laing 2010), developed by Corindus for percutaneous coronary intervention. Such systems consist of two parts: a slave system that controls the guidewire and a master system

---

✉ Shuxiang Guo
guoshuxiang@bit.edu.cn

✉ Nan Xiao
xiaonan@bit.edu.cn

Yuan Wang
wangyuan1988@bit.edu.cn

Youxiang Li
liyouxiang@263.net

Yuhua Jiang
jxy_200321@163.com

[1] School of Life Science, Beijing Institute of Technology, No. 5, Zhongguancun South Street, Haidian District, Beijing 100081, China

[2] Faculty of Engineering, Kagawa University, 2217-20 Hayashi-cho, Takamatsu, Kagawa 760-8521, Japan

[3] Beijing Neurosurgical Institute, Beijing Tiantan Hospital, Capital Medical University, No. 6 Tiantan Xili, Chongwen District, Beijing 100050, China

operated by surgeons. Of the two, the slave system requires a mechanical arm to assist with its location, whereas the master system can be moved anywhere in the operation room.

In addition to the products available, scholars worldwide have also investigated minimal surgery. For example, Guo et al. presented a novel catheter robotic system (Guo et al. 2012, 2014; Ma et al. 2012; Xiao et al. 2012; Yin et al. 2014) that uses master–slave control to facilitate remote surgery (Guo et al. 2015, 2016; Guo and Guo 2016; Xiao et al. 2011; Yin et al. 2015; Wang et al. 2016; Song et al. 2017; Zhang et al. 2017). Further, researchers at the Shenyang Institute of Automation investigated algorithms for a closed-loop catheter robotic control system to transport the catheter to the desired position.

However, the studies cited above did not solve the problem of force feedback. Haptic rendering for operators has yet to be implemented in most remote-control surgical robotics systems. Systems implementing haptic feedback functions simply provide conventional visual instruction for surgeons, which is limited by the available images and lacks key rendering information that cannot satisfy surgical demands for accurate manipulation throughout a procedure (Back et al. 2015; Gelman et al. 2016).

In cardiovascular intervention surgery, the sense of touch is important for perceiving the procedure and surgical condition when surgeons manipulate the catheter and guidewire. In high-risk areas near blood vessels, excessive force between the guidewire and the blood vessel walls can result in complications such as inflammation, blood clots, perforation, and hemorrhage. An experienced doctor can estimate the position and state of the catheter. With this estimation, a next-step operation can be obtained and risk can be avoided during surgery. However, current research and products have shortcomings in realizing real-time haptic rendering.

Haptic rendering techniques can be categorized into two types. In the first type, a special catheter uses sensing instruments to measure resistance and transmits a force signal—which is transformed into haptic feedback—to the master device. However, the special catheter is too small to be applied to narrow, fragile blood vessels because of its built-in sensor. In the second type, haptic feedback is simplified into resistance alerts, in which the resistance is unrelated to the output of the feedback force; this kind of haptic feedback provides less information to the operator. For ideal haptic rendering in intervention surgical robots, the goal is to provide real resistance between the guidewire and blood vessel wall during surgery. Consequently, our research is focused on measuring and transmitting the resistance force.

In our team's preliminary studies, we designed instruments for measuring resistance and adopted them in our robotic surgical system. However, the resistance of a conventional guidewire could not be acquired. The first difficulty was slipping of the guidewire while being clamped, which results from the guidewire's small diameter, and affects the resistance detection efficiency. The second difficulty is that the accuracy of the resistance measured by sensors cannot be guaranteed because of the effects of friction in the clamping structure. Our research aims to solve these problems and to design a new surgical intervention robot that can offer real haptic feedback to surgeons. In this study, we first improved the torsion device to eliminate clamping issues. Then, we designed a new force testing structure that overcomes oversized friction forces. In addition, a pattern is applied to simulate surgeons' hand movements to ensure that the resistance on the slave side is consistent with the motion of the master device.

The remainder of this paper is structured as follows: in Sect. 2, we present the design principle and components of the proposed interventional surgery robotic system. In Sect. 3, we demonstrate the principle by which force is measured with the slave device and the result of experimental validation. In Sect. 4, we focus on verifying the haptic rendering function of intervention surgical robots, as realized by the vascular model EVE, and analyze the performance of remote-control surgery. Finally, we outline our conclusions and future work in Sect. 5.

2 Master–slave system hardware platform

2.1 Overview of the interventional surgical robot system

Interventional surgical robot systems consist of master and slave sides. The master side of the system controls the surgery, whereas the slave side manipulates the catheter. In minimally interventional surgical robot systems, the master side uses a phantom desktop, and the slave side uses a self-designed multi-axis structure. The motion of the slave side is similar to the process of traditional minimally interventional surgery performed by surgeons. The master–slave system maintains high consistency for finishing the surgery. The master side communicates with the computer by Ethernet. The slave side communicates with the computer via the PCI bus protocol. A schematic of the master–slave system is shown in Fig. 1.

2.2 Master-side system

The master side consists of a phantom, laser ranging finders, a force sensor, a slide rail, a handle, and a support structure made using a 3D printer (shown in Fig. 2). The catheter motion is controlled by this mechanism, which

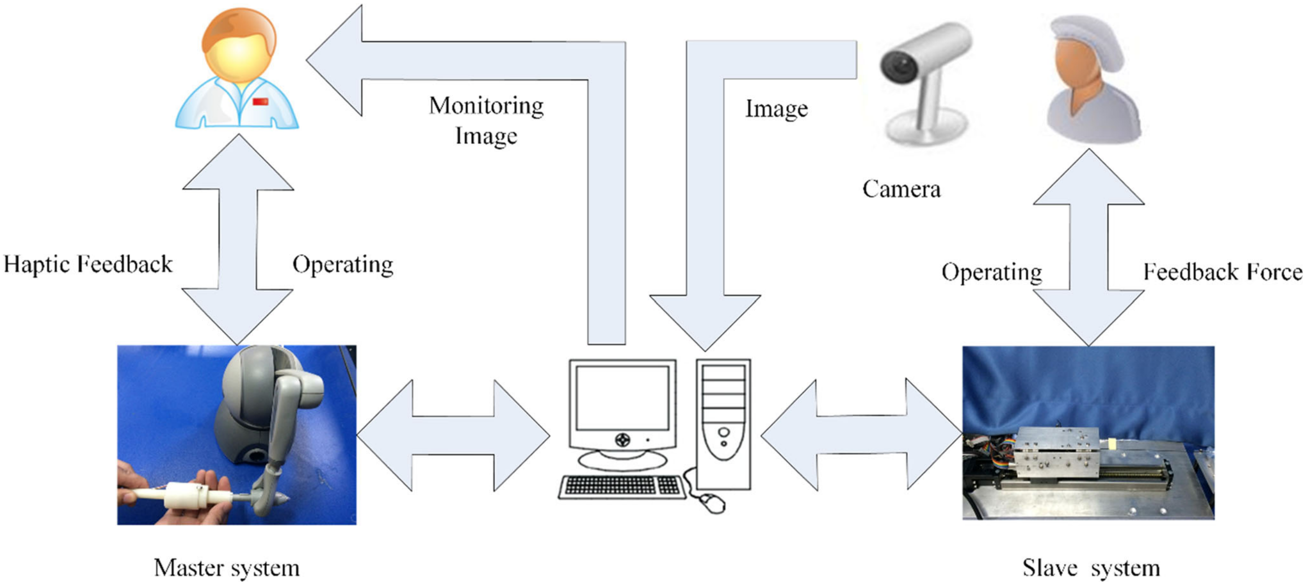
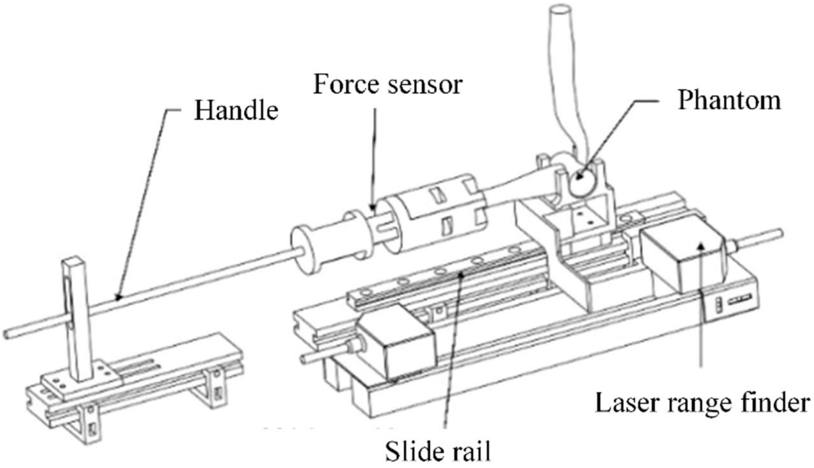
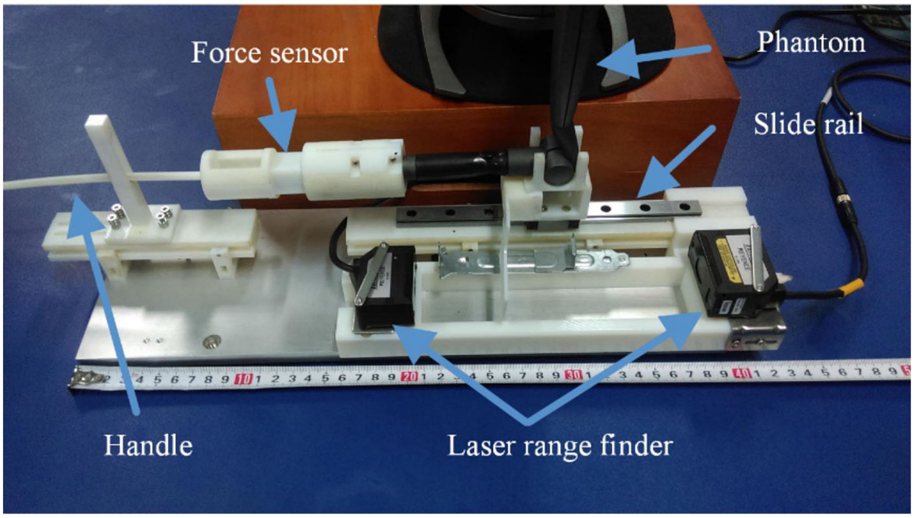


Fig. 1 Interventional surgical robot system

Fig. 2 Master-side system



(a) 3D model of the master-side system



(b) Prototype of the master-side system contains two degrees of freedom: axial movement along the frame and rotational movement. Axial movement can be measured using the laser range finders and rotational motion can be measured with an optical-electricity encoder. The laser range finders are used to measure linear motion, which can make control more precise and stable than a phantom. The phantom device is only used to generate force feedback based on the resistance on the catheter. The laser range finders and optical-electricity encoder are connected to the AD converter of a PMAC motion-control card. Synchronization between the master and slave sides are guaranteed through the PLC function of PMAC. The measurement of both axial and rotational movements can proceed simultaneously. However, the phantom generates the same force transferred from the FUTEK mechanical sensor on the slave side.

2.3 Slave-side system

The slave system carries out three functions. First, the linear displacement model consists of a servo motor with a single-axis actuator. The axis actuator moves forward and backwards to control the guidewire moving forward and backwards. The second function is the guidewire control and rotation model; when the device is clamped to the guidewire, it can rotate through the gear on the motor. The third function is the force feedback measurement model, which employs a small force sensor to measure feedback from the guidewire.

The structure of the slave side is shown in Fig. 3. Part A is a platform to which the catheter sheath is fixed; this part is in contact with the patient. Part B is a guidewire manipulator that controls the guidewire's rotation. It is fixed to Part C, the slide motor, whose function is to drive Part B for translation.

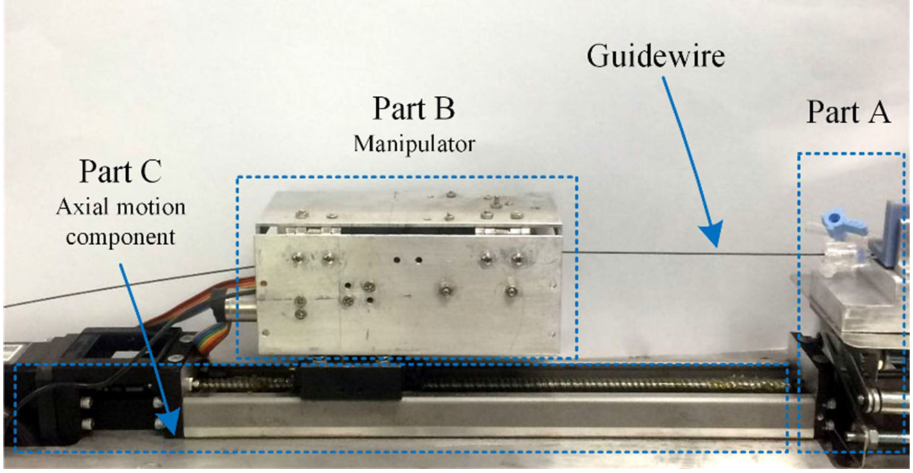
Part C is the axial motion component, which consists of a servo motor and a linear slide. The SMC motion-control card, from which accurate position feedback data is obtained, controls linear motion. Inside Part B is a guidewire rotation component and a control axis component (that control guidewire clamping and relaxing). These two parts ensure that the entire interventional operation can be completed by remote control, eliminating the need for doctors to enter the operating room during the procedure. In addition, inside Part B is a FUTEK force sensor from which force feedback can be measured and sent to the master side.

3 Force measurement in the slave-side system

3.1 Slave-side system force measurement principles

This study focused on measuring the resistance of the guidewire in robot-assisted surgery to provide efficient real-time haptic feedback information. To ensure safety, resistance measurement has to be very accurate. Consequently, to improve measurement efficiency, we analyzed previous surgical robot system designs and identified three main problems that are crucial to system design: (1) Deformation and slipping of the guidewire. If the guidewire is not clamped tightly enough, it will slip, and the resistance force cannot be transformed to the clamping unit, which results in inaccurate resistance measurements. In contrast, if the guidewire is damaged by clamping unit, another guidewire is needed to continue the procedure, and the measured resistance is inaccurate. (2) The resistance is passed in the direction of movement of the guidewire; hence, the measured force is inaccurate if the movement direction of the guidewire and the measuring direction are not in the same axis. (3) During surgical robotic system operation, friction inevitably occurs, which influences

Fig. 3 Slave-side system



measurement accuracy. This study undertook to solve these three problems by designing a novel intervention surgical slave system. The top-view figure of the designed structure is shown in Fig. 4.

First, the slipping and clamping deformation of the guidewire should be resolved, because this problem is directly related to the stability and efficiency of force measurement. In this study, a specified guidewire torque, illustrated in Fig. 5, was applied to clamp the guidewire. The guidewire has a head and a stern. The head of the guidewire torque comprises a gear and a cylinder with a conical hole. The stem clamps the guidewire with four thin metal arms that apply an even force in four directions. The head and stem are connected by threads. The guidewire passes through the hole shaped by the four metal arms of the stem. When these two parts are tightened, the hole becomes smaller and clamps the guidewire tightly. This structure has been verified in conventional surgery with normal instruments as preventing deformation and slipping of the guidewire. However, we have enhanced it with a gear wheel to ensure that it meets the demands of mechanical operation. Furthermore, we have designed different types of guidewire torques to meet the requirements of different types of guidewires and catheters (Fig. 6).

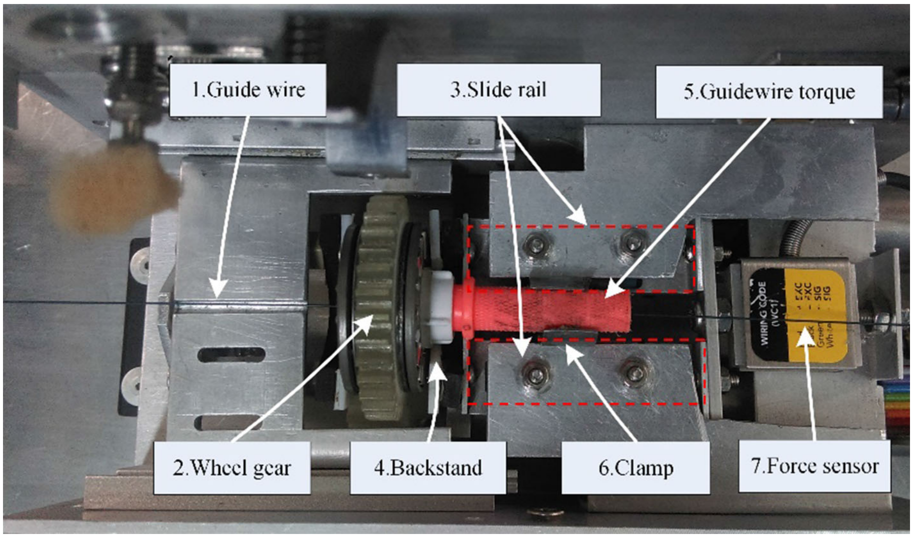
The second problem to solve is whether the movement and measurement directions are in the same axis. When these directions differ, the resistance measured by the sensor does not represent the real force on the guidewire. Hence, in this study, we designed a fixed-front unit, a back unit, and a clamping unit. These three units maintain the stability of the guidewire torque such that the torque can only move in a single direction. Further, the design ensures that the three units, torque, and fixed sensor hole are in the same axis (Fig. 7).

The last issue to solve is the influence of friction, which affects the accuracy of resistance measurements. The force sensed by sensors is the resultant force in the direction of motion of the guidewire, so relative motion in the direction of different components affects the precision of force measurements. In our research, unfixed parts are connected by sliding rails to reduce the interference of the friction force. On the slave side, the front and back units, which cause friction with the guidewire, are designed to restrict twisting motion in a single direction. In addition, these fixed parts are connected to the outer shell of the system to ensure that their motion is consistent with that of the torque, which eliminates the relative motion. This design not only restricts the movement direction to a line, but also reduces the frictional force. A detailed design is depicted in Fig. 8. Before the operation, the front and back parts are connected to the gear wheel. In the clamping procedure, the torque is tightened and manipulates the guidewire to move in the opposite direction of the resistance force, in which the gear pushes the back unit. Then, the back component transmits the sensed force to sensors through the sliding rail and transmits the resistance force.

3.2 Force measurement detection module

Depending on the complexity of the endovascular environment and the use of different guidewires, in this study, we designed a variety of experiments to prove the reliability of the force feedback device. The experimental platform is shown in Fig. 9. In the platform, the rod is held by the guidewire torque and performs the role of the guidewire. Because the rod is rigid, it avoids force measurement error from deformation. The manipulator controls the axial movement of the hard rod. A mechanical sensor fixed on a slide rail is placed on the path of the hard rod. The direction of the slide rail coincides with the direction of movement of the manipulator. This design prevents too

Fig. 4 Structure of the manipulator



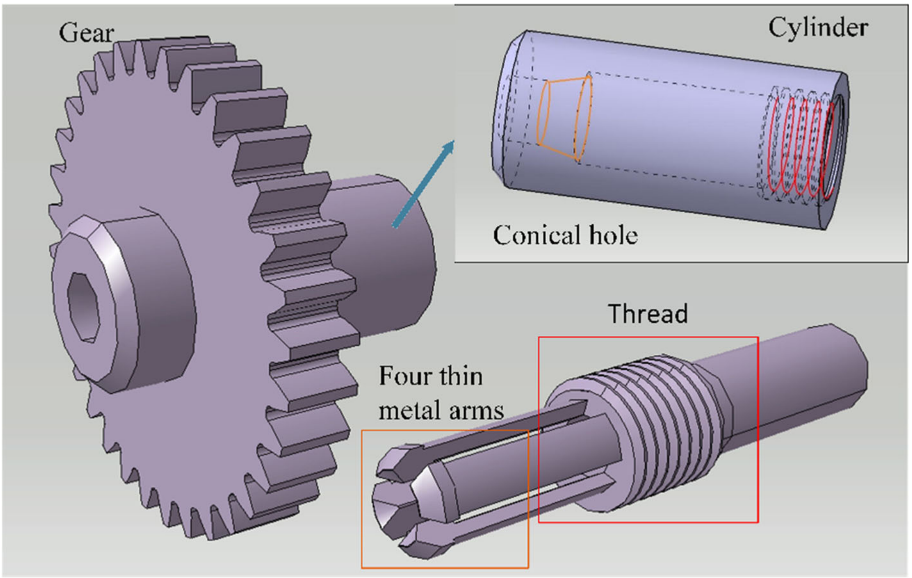


Fig. 5 Structure of the guidewire torque

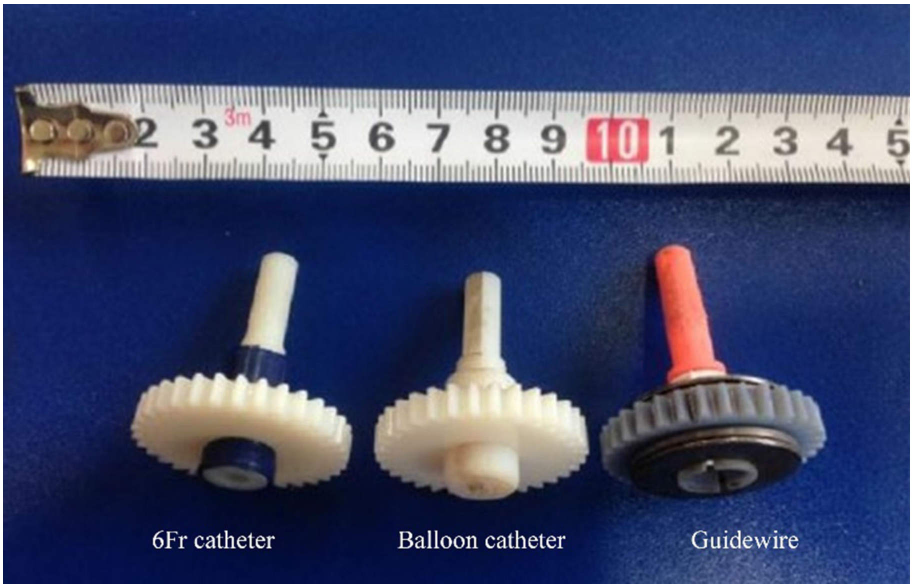


Fig. 6 The different types of guidewire torques designed

much resistance arising, thereby ensuring the accuracy of force measurement, as too much resistance can cause rod deformation and sensor damage. Before the start of the test, the manipulator controlled the rod to make slight contact with the sensor. Further, the internal sensor on the slave side and the external sensor were adjusted to zero at the same time. As shown in Fig. 9, the rod touches the sensor through a plastic tube simulating the blood vessels. The tube limits the angle of the hard rod to ensure that the hard rod is in contact with the sensor during movement.

Firstly, the movement between the master side and the slave side was cut off. The manipulator and the rod were controlled for reciprocating movement. The rigid rod made contact with the sensor periodically, at which point the two sensors recorded their respective impact force. Data from the external sensor represented the resistance applied to the guidewire. The closer the data of the two sensors, the better the effect of force measurement. Following this set of experiments, the slave was disconnected from the master and volunteers operated the surgical robots. Force measurement under irregular motion was thereby validated.

4 Experimental results and analysis

4.1 Force measurement experimental results

In this experiment, we obtained two resistances: the force on the guidewire and the force on the slave side. By comparing the difference between these two resistances,

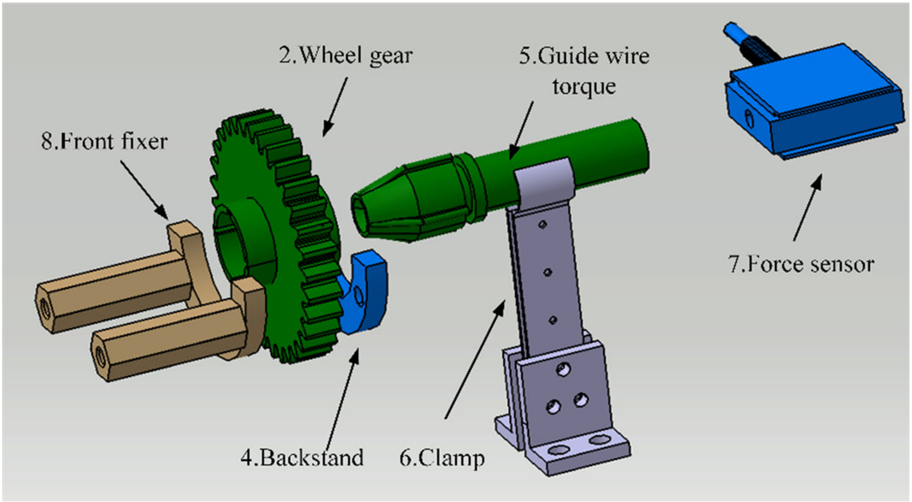


Fig. 7 Direction restriction component

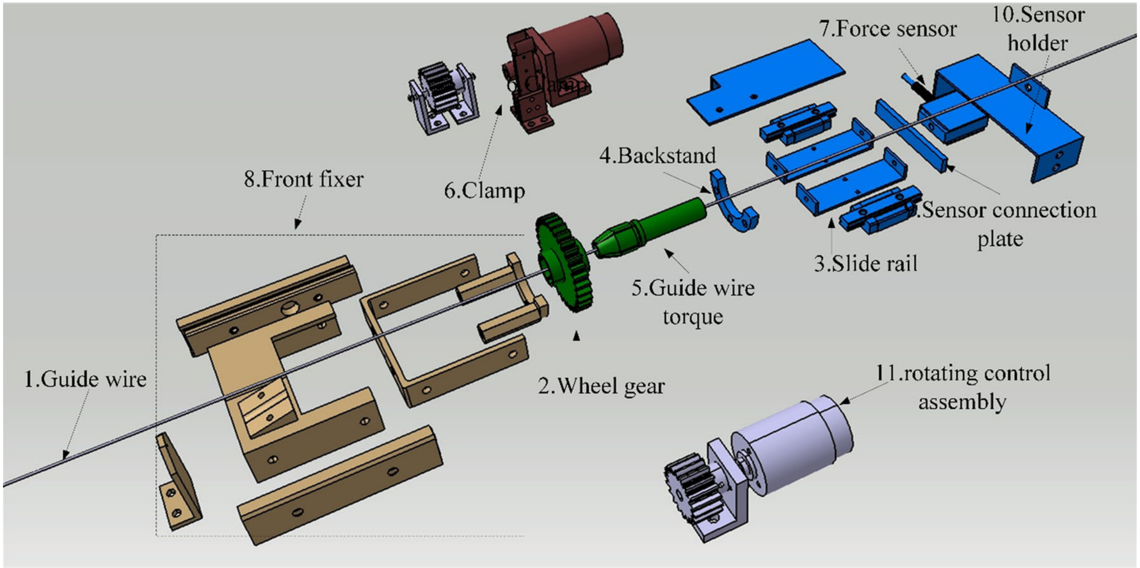
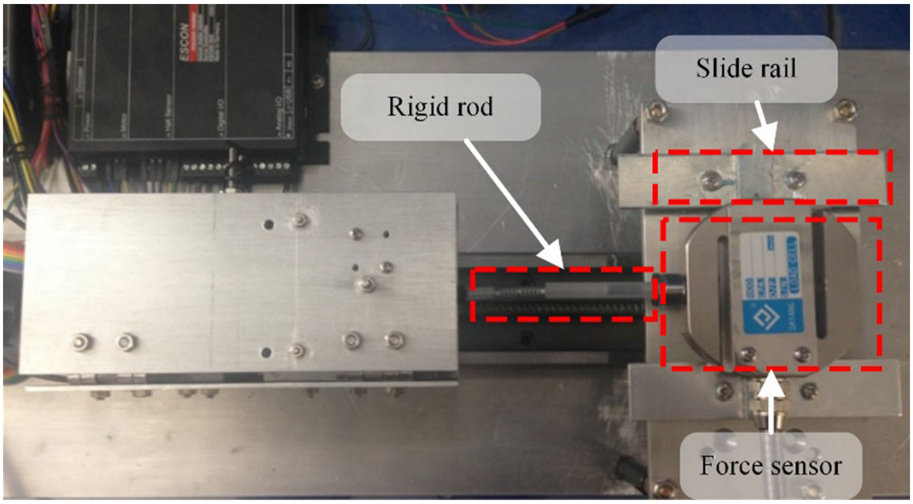


Fig. 8 3D model of the guidewire/catheter manipulator

Fig. 9 Experimental platform



we ascertained the accuracy and timeliness of the force feedback structure.

In the first test, the slave side was disconnected from the master side. We made the slave side reciprocate movement in multiple sets of different constant speeds, showing that force information can be measured when the guidewire, which is clamped by the slave side, moves straight forward. The measurement results showed good accuracy and real-time performance. The result of a random test is show in Fig. 10.

In the second experiment, the operator used the master side to control the slave side, and we contrasted the detected precision of resistance in the manual operation (Fig. 11).

When the experimenters pushed the guidewire from the master side, force information from the slave side was measured in real time with good accuracy. The maximum tracking error was 0.19 N.

4.2 Force feedback experiment

An insertion experiment was also conducted to evaluate the effect of haptic feedback. In this study, we conducted experiments with an EVE vessel model of human blood vessels, shown in Fig. 12. The vascular model can be highly realistic in simulating the blood vessel environment in the body, including blood pressure and heart rhythm.

In this experiment, we invited ten volunteers with no operation experience. The operation was carried out in a simulation environment with and without haptic feedback. Each volunteer performed simulated treatment for five different lesions. Operations were carried out at each lesion ten times with and without haptic feedback. The volunteers directed the guidewire through the aortic arch, in a relatively simple set of treatments, shown in Fig. 13, and the resistance and completion time of each volunteer's operations were recorded.

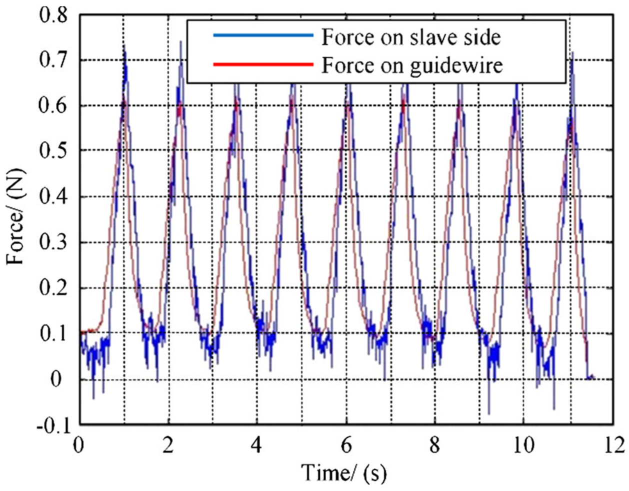


Fig. 10 Constant speeds movement results

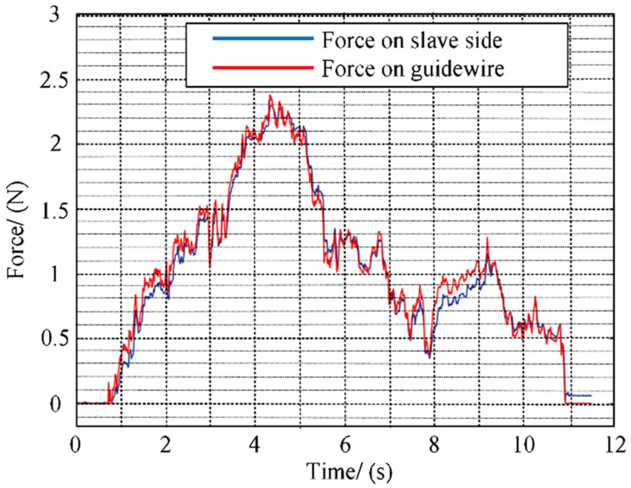


Fig. 11 Manual manipulation result

4.3 Force feedback results

To verify whether the operator can correctly sense feedback, a mechanical sensor was installed on the master side. To improve the accuracy of the haptic feedback, this study also adopted a fuzzy PID control and a Kalman filter to reduce force feedback errors in implementation and transmission. The results are shown in Fig. 14.

A random set of experiments showed that when the volunteer pushed the guidewire on the master side, haptic feedback was realized with good accuracy and real-time performance. The maximum tracking error was 0.056 N.

4.4 Evaluating the effect of surgery

The operation completion times of five random volunteers are shown in Fig. 15. The three datasets represent the average operation time of volunteers under three different operating conditions. The manual operation consumed the least time, whereas the robotic operation without haptic feedback consumed the most time. Hence, compared to an operation without haptic feedback, force feedback makes completion of the operation more efficient. Manual operation is faster than machine operation because operators are overly careful to subconsciously reduce their operating speed. On the other hand, in order to ensure the safety of experiments, the maximum speed of machine operation is limited. Under the same circumstances, haptic feedback can provide doctors with more surgical information and improve operational efficiency. By recording resistance during operation, feedback can provide operators with warning messages, resulting in operators being more

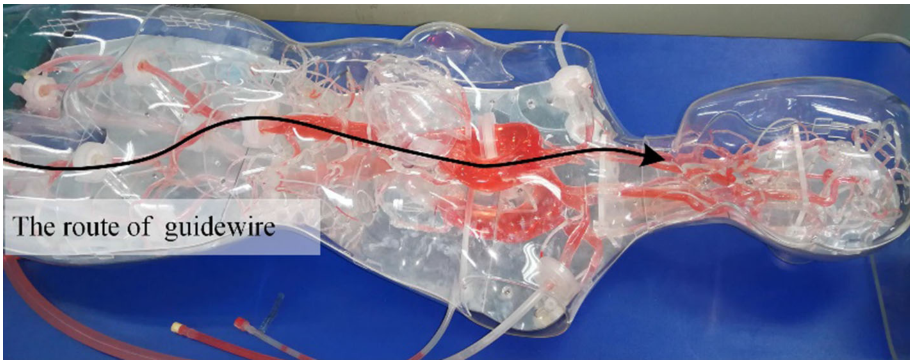


Fig. 12 Medical training vessel model

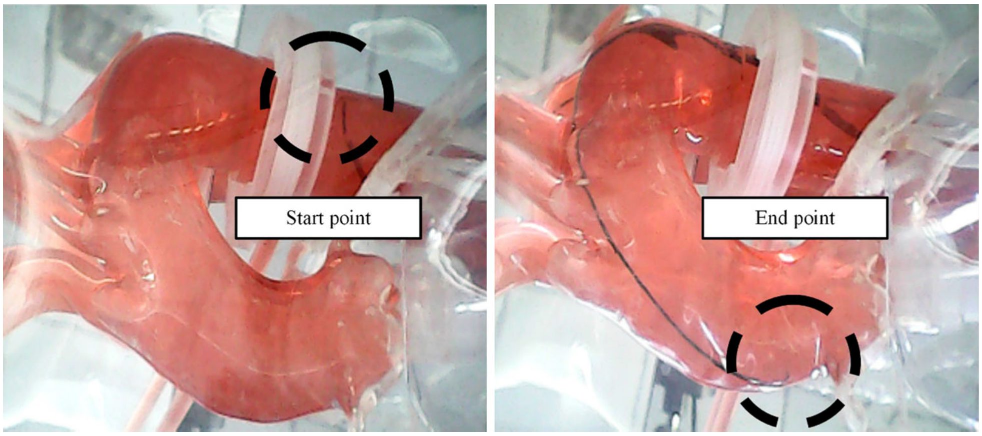


Fig. 13 Operation start and end points

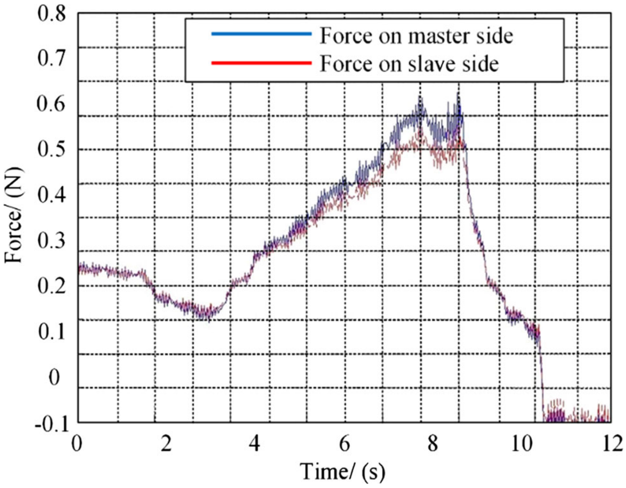


Fig. 14 Force feedback result of surgery

careful during operations. Conversely, too much feedback will hinder the operation of the doctor.

The resistance over time from a random experiment is shown in Fig. 16. Resistance was measured by slave-side sensors. This resistance is similar to the collision force between the guidewire and blood vessel. Less resistance ensures a safer operation. Figure 16a expresses the resistance of a situation without haptic feedback, with an average of 0.126 N and maximum of 0.412 N. Figure 16b expresses the resistance of a situation with haptic feedback, with an average of 0.072 N and maximum of 0.233 N. Two resistance measurements were made when the guidewire was inserted in the same lesions, showing that haptic feedback improves operation safety. Although the data for each test are not the same, all the data points for tactile feedback can improve the safety of surgery. In the group of tests shown in the Fig. 16, the mean vessel force decreased by 0.054 (42.8%) and the maximum impact force decreased by 0.179 N (43.4%).

5 Conclusion

This paper presented a novel robotic vascular interventional surgery system consisting of a coaxial force sensor structure that can measure the resistance of a guidewire using push force during operations. The system also comprises a guidewire torque that can hold the guidewire during operation. This design minimizes the force measurement error caused by skidding, and the guidewire clamp is nondestructive. Experimental results show that the

Fig. 15 Operation completion time

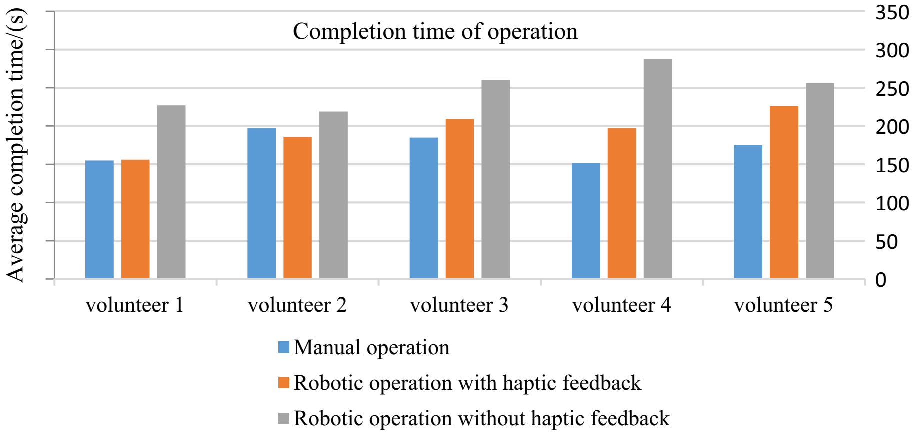
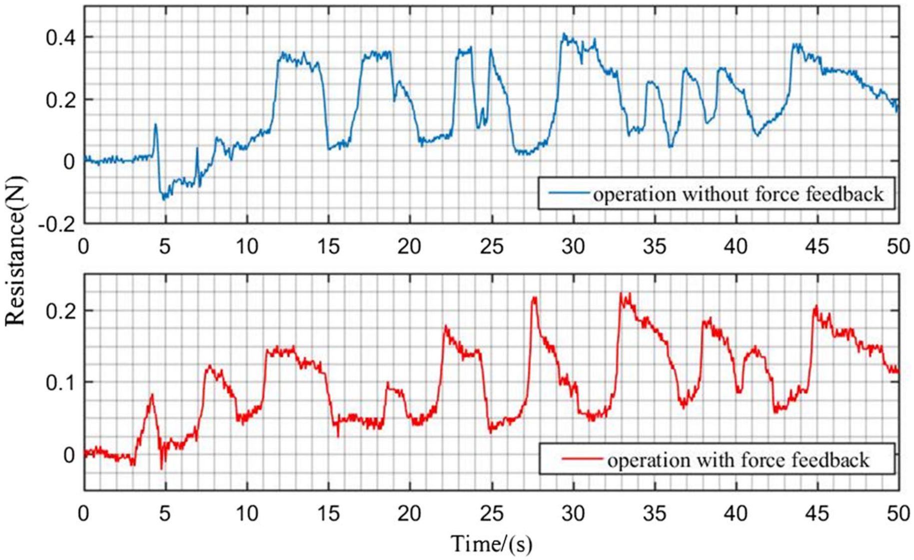


Fig. 16 Resistance during operation



device can effectively detect the push resistance of a guidewire during operation and can provide accurate force feedback for doctors in teleoperations. The results also show that a haptic feedback function that can effectively help improve remote operation efficiency and safety. In summary, the developed interventional surgery robot system has a reasonable structure, can be effective in providing haptic feedback to doctors, and can assist doctors in completing remote operation intervention.

In future work, we plan to solve the problem involved in operating a catheter or guidewire collaboratively in actual operations, and to implement fully remote robotic operation intervention.

Acknowledgements This research is partly supported by the National Natural Science Foundation of China (61375094), National High Tech. Research and Development Program of China (no. 2015AA043202).

References

Back J, Karim R, Noh Y et al (2015) Tension sensing for a linear actuated catheter robot. In: Intelligent robotics and applications. Springer, pp 472–482. https://doi.org/10.1007/978-3-319-22876-1_40

Dankelman J, Dobbelsteen JJVD, Breedveld P (2011) Current technology on minimally invasive surgery and interventional techniques. In: Proceedings of 2011 international conference on instrumentation control and automation, pp 12–15

Gelman D, Skanes AC, Tavallaei MA et al (2016) Design and evaluation of a catheter contact-force controller for cardiac ablation therapy. IEEE Trans Biomed Eng 63(11):2301–2307

Guo J, Guo S (2016) Design and characteristics evaluation of a novel VR-based robot-assisted catheterization training system with force feedback for vascular interventional surgery. Microsyst Technol. https://doi.org/10.1007/s00542-016-3086-x

Guo J, Guo S, Xiao N, Ma X, Yoshida S, Tamiya T, Kawanishi M (2012) A novel robotic catheter system with force and visual feedback for vascular interventional surgery. Int J Mechatron Autom 2(1):15–24

Guo J, Guo S, Tamiya T, Hirata H, Ishihara H (2014) A virtual reality-based method of decreasing transmission time of visual feedback for a tele-operative robotic catheter operating system. Int J Med Robot Comput Assist Surg. https://doi.org/10.1002/rcs.1642

Guo J, Guo S, Shao L, Wang P, Gao Q (2015) Design and performance evaluation of a novel robotic catheter system for vascular interventional surgery. Int J Microsyst Technol. https://doi.org/10.1007/s00542-015-2659-4

Guo J, Guo S, Shao L, Yu Y (2016) Design and characteristics evaluation of a novel teleoperated robotic catheterization system with force feedback for vascular interventional surgery. Biomed Microdevices 18(5):76. https://doi.org/10.1007/s10544-016-0100-0

Ikeda S, Arai F, Fukuda T, Negoro M, Irie K, Takahashi I et al (2005) In vitro patient-tailored anatomical model of cerebral artery for evaluating medical robots and systems for intravascular neurosurgery. In: Proceedings of 2005 IEEE international conference on intelligent robots and systems, pp 1558–1563

Jayender J, Patel RV, Nikumb S (2009) Robot-assisted active catheter insertion: algorithms and experiments. Int J Robot Res (IJRR) 28(9):1101–1117

Kesner SB, Howe RD (2011) Position control of motion compensation cardiac catheters. IEEE Trans Robot 27(6):1045–1055

Khan EM et al (2013) First experience with a novel robotic remote catheter system: Amigo^{TM} mapping trial. J Interv Card Electrophysiol 37(2):121–129

Lock J, Laing G (2010) Quasistasic modeling of concentric tube robots with external loads. In: The proceedings of 2010 IEEE/RSJ international conference on intelligent robots and systems, pp 2325–2332

Ma X, Guo S, Xiao N, Guo J, Yoshida S, Tamiya T, Kawanishi M (2012) Development of a novel robotic catheter manipulating system with fuzzy PID control. Int J Intell Mechatron Robot (IJIMR) 2(2):58–77

Penning RS, Jung J, Borgstadt JA, Ferrier NJ, Zinn MR (2011) Towards closed loop control of a continuum robotic manipulator for medical applications. In: IEEE international conference on robotics and automation (ICRA), pp 4822–4827

Saliba W, Reddy VY, Wazni O, Cummings JE et al (2008) Atrial fibrillation ablation using a robotic catheter remote control system: initial human experience and long-term follow-up results. J Am Coll Cardiol 51:2407–2411

Song Y, Guo S, Yin X et al (2017) Design and performance evaluation of a haptic interface based on MR fluids for endovascular tele-surgery. Microsyst Technol. https://doi.org/10.1007/s00542-017-3404-y

Thakur Y, Bax JS, Holdsworth DW, Drangova M (2011) Design and performance evaluation of a remote catheter navigation system. IEEE Trans Biomed Eng 56(7):1901–1908

Wang Y, Guo S, Tamiya T, Hirata H, Ishihara H, Yin X (2016) A virtual-reality simulator and force sensation combined catheter operation training system and its preliminary evaluation. Int J Med Robot Comput Assist Surg 13:e1769. https://doi.org/10.1002/rcs.1769

Xiao N, Guo S, Guo J, Xiao X, Tamiya T (2011) Development of a kind of robotic catheter manipulation system. In: Proceedings of 2011 IEEE international conference on robotics and biomimetics, pp 32–37

Xiao N, Guo J, Guo S, Tamiya T (2012) A robotic catheter system with real-time force feedback and monitor. J Australas Phys Eng Sci Med 35(3):283–289

Yin X, Guo S, Hirata H, Ishihara H (2014) Design and experimental evaluation of a Teleoperated haptic robot–assisted catheter operating system. J Intell Mater Syst Struct. https://doi.org/10.1177/1045389x14556167

Yin X, Guo S, Xiao N, Tamiya T, Hirata H, Ishihara H (2015) Safety operation consciousness realization of MR fluids-base novel haptic interface for teleoperated catheter minimally invasive neuro surgery. IEEE/ASME Trans Mechatron. https://doi.org/10.1109/tmech.2015.2489219

Zhang L, Guo S, Yu H et al (2017) Performance evaluation of a strain-gauge force sensor for a haptic robot-assisted catheter operating system. Microsyst Technol. https://doi.org/10.1007/s00542-017-3380-2