Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

Electromagnetism Force Feedback Control of Bionic Grippers for Robotic Endovascular Intervention System

Haijin Xu
Department of Instrument Engineering
Shanghai Jiao Tong University
Shanghai, 200240,China
xuhaijin@sjtu.edu.cn

Kundong Wang
Department of Instrument Engineering
Shanghai Jiao Tong University
Shanghai, 200240,China
kdwang@sjtu.edu.cn

Abstract - At present, the operation of most Robotic Endovascular Intervention (REI) can only through visual feedback, that is, the operator can only observe the situation on the scene through the X-ray equipment, and issue manipulation commands according to the observed scene conditions. Although the master-slave system with force feedback has made significant progress, some essential problems still need to be solved, especially the complicated structure and large external dimensions, which gives the operator a strong sense of weight and affects the sense of teleoperation. For a high safety of remote operation, this research proposed a kind of REI with bionic grippers and developed a prototype to verify its expectation of telepresence. The REI used the sliding table and steel wire to realize the forward and backward delivery of guidewire and catheter, and the bionic grippers were used to accomplish the twisting of guidewire and catheter imitating hands and fingers of human. A high-resolution force sensor is used to acquire the intervention resistance on bionic grippers, and a loading mechanism composed of electromagnetic coil, handle, and spring will reproduce the resistance on the doctor's fingers through the handle. Laser displacement sensors and Rotary encoders are used on a master manipulator to control the movement and rotation of slave grippers. The experiments show that force feedback precision can reach 0.03 N, and response delay is less than 100ms when the frequency of the loaded force is above 3Hz. This research has laid a necessary foundation for REI technology.

Index Terms - Robotic Endovascular Intervention, Bionic grippers, Force feedback, Telepresence, Electromagnetic coil

I. INTRODUCTION

Nowadays, cardiovascular diseases (CVD) have been the number 1 cause of death globally and more people die annually from CVDs than from any other cause. Percutaneous coronary intervention (PCI) is an effective procedure used to treat narrowing of the coronary arteries of the heart found in coronary artery disease. However, the doctor is usually exposed to radiation damage during X-ray visualization.

To avoid radiation damage and improve surgical quality, Robotic Endovascular Intervention (REI) has been developed for the past ten years [1][2]. Robotic-assisted PCI is a novel approach to PCI that utilizes remote-controlled technology to manipulate catheters, thereby significantly reducing radiation exposure to the operators [3]. David Filgueiras-Rama developed a new remote navigation system that improves current limitations of conventional manually guided catheter ablation in complex cardiac substrates such as left atrial flutter [4]. The first-generation CorPath 200 robotic-assisted system for PCI is effective but is limited by the lack of an active robotic guide-catheter control. The CorPath GRX device enables robotic guide-catheter manipulation, in addition to guidewire and balloon/stent delivery [5]. Masayuki Hara introduced an approach to realize the classic full-body illusion (FBI) paradigm using a robotic master-slave system, which allows us to examine interactions between action and the sense of body ownership in behavior [6]. Nan Xiao proposed a robotic catheter system with force sensors, monitors, and a master-slave remote control system. They use a force sensor to obtain the force information when the catheter contacted the blood vessel [7]. REI used control architecture of master-slave by manipulation similar to the da Vinci Surgical System.

REI has its features because of the remarkable difference between the vascular intervention devices and the traditional scalpel and surgical scissors. Additionally, the da Vinci robot does not care about the telepresence because the soft viscoelastic organs always have remarkable deformation. The surgeon can judge the risk according to the deformation. The vessel has a higher stiffness than the soft tissue. Especially to the calcification, plaque, and embolism, rashly will lead to deadly medical accidents. So, the operator's haptic sense to the intervention devices is essential to surgical safety. Several reports about the force feedback control of the robotic endovascular surgery were published. Park designed a haptic user interface device with force feedback using a force or torque signal either measured with a sensor and estimated from the current signal of a motor on the slave side [8]. Lu reported a kind of special catheter with a high-sensitivity force sensor installed on the tip of the catheter [9]. The contact between the catheter and blood vessels can be detected and recreate on the hands of the surgeon. Piers designed a micro force sensor for the minimally invasive robotic surgery based on the train gauge. The deformation is acquired by a reflective measurement of three optical fiber [10]. Guo proposed a pressure sensor array to detect the contact force between the vessel and the catheter. But it still faces some critical problems such as Miniaturizing and integration [11][12]. Yoneyama proposed a force-detecting gripper and force feedback system. A strain gauge is embedded in the gripper [14]. Another method realizing force feedback is to obtain the force on the distal of the intervention devices, which can complete manipulation to guidewire like a human hand. Payne proposed a kind of master-slave force feedback system for endovascular catheterization, which may be used in a natural situation with enhanced ergonomics [15]. Kesner reported an actuated catheter tool that compensates for the

978-1-7281-6321-5/19//$31.00 ©2019 IEEE

motion of heart structures like the mitral valve apparatus by serving a catheter guidewire inside a flexible sheath [16][17].

At present, a great breakthrough has appeared in the field of force feedback technology. In the industrial field, force feedback technology has been used in mature products. Generally, Force feedback technology is divided into two categories, passive force feedback, and active force feedback. The former mainly adjusts the force by controlling the damping of the movement of the handle, and the advantage of this method is simple in structure and easy to control. Most of the passive feedback is realized using a magnetic damper. By changing the magnitude of the current, the value of the magnetic field on the handle is controlled, that is, the magnet particles adsorbed on the handle, and finally the value of system damping can be controlled. However, since this method is to load the resistance onto the handle, which has been moving, the accuracy of force feedback may be weak, and the high delay will be another serious problem. At the same time, how to generate feedback force under static is also a problem that passive feedback needs to solve. By contrast, inactive force feedback, the generation of force does not depend on the motion of the handle, so as long as the accuracy of the force loading device meets the requirements, the accuracy of the force feedback system can be guaranteed. The performance in terms of delay is various according to the force-generating device selected. For example, springs and motor structures are often used as force-generating devices because of its simplicity in the control system. However, the high latency caused by too many links is also a problem that cannot be ignored. The electromagnetic force is also a good choice because of its short response time and simple structure. Still, the nonlinear relationship between force and displacement is a major obstacle for researchers to use this method.

II. REI DESIGN

As shown in Fig. 1. The master-slave architecture is used to realize the remote manipulation. The whole system designed with the master-slave structure, including bionic slave grippers and master manipulators mainly. The slave side, which manipulates guidewire and catheter directly using bionic fingers, may be placed in the environment of ionizing radiation. But the master side can be placed away from the radiation. In theory, as long as the communication meets the requirements, it can even be placed in a different city from the slave completing remote surgery. In order to realize the actions performed by the four hands of the surgeon and his assistant during the operation, this paper designed four grippers to complete the corresponding action. Bionic grippers on the slide of a robotic arm can complete the forward and backward movements by the wire. And the rotary motion is driven by the motor on the slide. The master manipulator used to control the slave side contains handle, an electromagnetic coil, and some sensors. In terms of force feedback control, some critical issues need to be addressed, such as the real-time and accuracy of resistance reproduce and the sensitivity of the measurement. And this research will force on these problems.

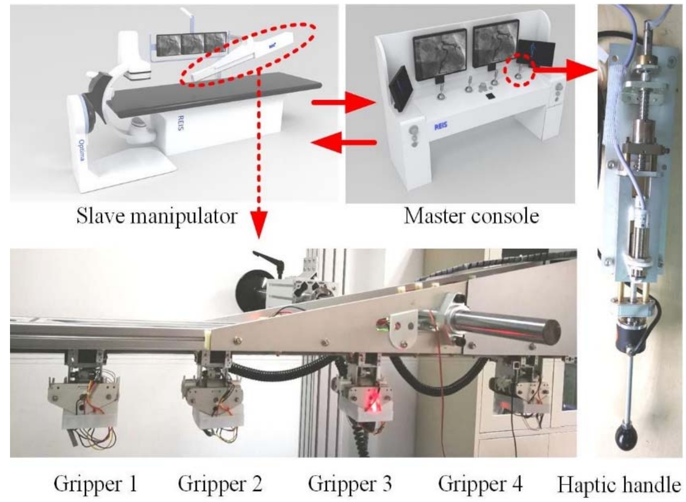

Fig. 1 Master-slave robotic endovascular intervention system.

As shown in Fig. 2, the communication between the master manipulator and slave manipulator can be divided into two parts. The control signals, including command of movement and value of force, may be delivered from the master side to the slave side through a dedicated channel. This channel needs to safe and reliable to ensure the safety of REI operation, and TCP/IP protocol is used to realize conversion and transmission of information.

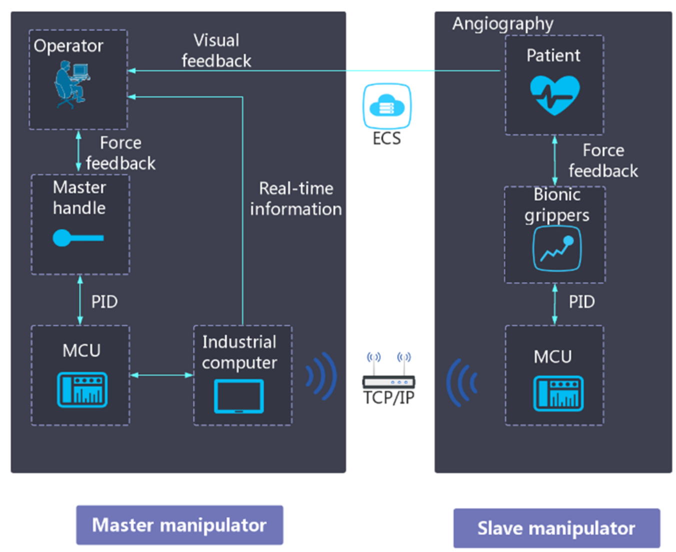

Fig. 2 Overview of control system

The other part of the information refers to the real-time medical image, and it needs to process by Elastic Compute Service (ECS) with computer vision. Because the image information takes up a lot of space and it not more important than control signals, it is necessary to use the Internet to complete the transmission of information to the ECS. And ECS will complete the work of image processing and send the processed image to the master side.

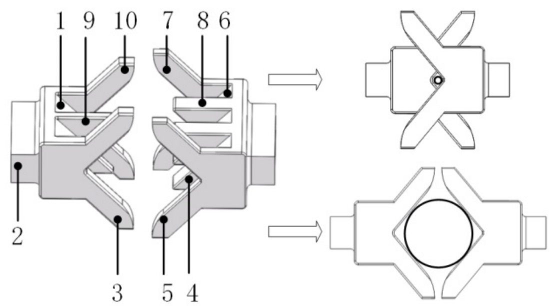

Fig. 3 Bionic self-adaptive finger

In Fig. 3, the bionic finger consists of two parts imitating the human index finger and thumb to pinch the catheter and guidewire. 1 and 6 are the cavities between the fingers, 2 is the elastic pad, 3 and 10 are the fingers of hand inside, 5 and 7 are the fingers of hand outside, and 8 and 9 are the internal fingers. The portion of the finger that can be used to grip the appliance is a "V" type structure and is divided into an inner gripping finger and an outer gripping finger. This structure ensures that the concentricity can be automatically realized during the process of holding the catheter, and the rotary and the linear motion can be limited. The hand inside also has an internal finger, so the surface of the gripping hand will be large enough to prevent stress concentration during the movement.

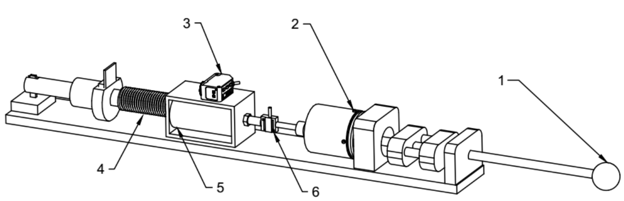

Fig. 4 Master manipulator
1-Handle, 2-Rotation Encoder, 3-Laser displacement sensor
4-Spring, 5-Electromagnet, 6-Force sensor

As shown in Fig. 4, the master manipulator consists of six parts. The handle may be used to manipulate the bionic gripper and feel resistance to bionic fingers by doctors and assistants. If the end of the guidewire or catheter deviates, the doctor needs to twist it and make it entre the expected vessel. Rotation encoder and laser displacement sensor can catch the movement and rotation of the doctor's hand and deliver it to bionic grippers. Spring may be used to modify the nonlinearity of the electromagnet force. An electromagnet is used as the force-generating device, and a force sensor is used to ensure the accuracy of the feedback force.

III. Mathematic Models

A. Electromagnet model

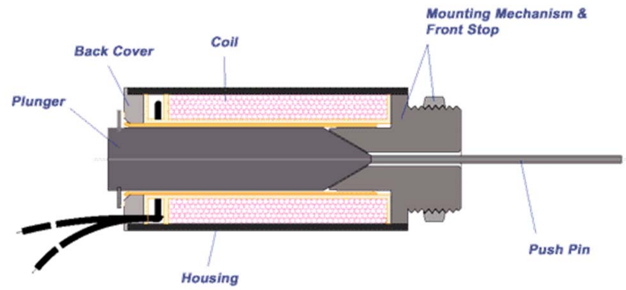

Fig. 5 Push-pull electromagnet model

The force of the electromagnet is mainly related to the magnitude of the current and the position of the core [18]. In order to get the relationship between the position of the core and the electromagnetic force, we must first find an expression of the variation of inductance with the position, $L(x)$. When $x = 0$, the core is completely in the coil. When $x = l$, the core is at the entry edge of the coil. According to these two positions the inductance is easy to define by the standard approximation for the inductance of a coil.

$$L_0 = \frac{\mu_r \mu_0 N^2 A}{l} \tag{1}$$

$$L_l = \frac{\mu_0 N^2 A}{l} \tag{2}$$

$$A = \pi r_0^2 \tag{3}$$

$$L(x) = L_0 e^{-\frac{\alpha}{l}x} \tag{4}$$

$L(0)$ is larger than $L(x)$ because μ_r, the relative permeability of the iron core, is much larger than μ_0, the permeability of free space. N, A, and l are the number of turns of the coil, the cross-sectional area of the coil and length of the coil, respectively. r_0 is the inside radius of the coil, while r_a is the outside radius of the coil. The difference between r_0 and r_a is whether it contains the coil. The parameter α can be calculated by (1) and (4). $L(x)$ will vary monotonically between these two extremes, and this variation of force with position depends on the shape of the solenoid.

$$F = \frac{dE_L}{dx} \tag{5}$$

$$E_L = \frac{V^2}{2R^2} L(x) \tag{6}$$

$$R = 2\pi r_a N \gamma \tag{7}$$

According to the law of conservation of energy, the relationship between force and displacement can be easily obtained, as shown in equation (1). Furthermore, several substitutions must be made, in order to obtain the force in terms of coil design parameters. First, R may be obtained from the resistance per unit length of the wire, γ, and the length of the coil and the parameter γ can be found in the table of wire gauge.

$$F = \frac{-V \mu_r \mu_0}{8\pi\gamma^2 l^2} \left(\frac{r_0}{r_a}\right)^2 \alpha e^{-\frac{\alpha}{l}x} \tag{8}$$

TABLE I shows the related parameters of the Equation (8).

TABLE I
PARAMETERS OF THE MATHEMATIC MODELS

Parameters	Meaning	Value	Unit
l	Length of coil	100	*mm*
r_0	Inside radius of the coil	50	*mm*
ra	Outside radius of the coil	30	*mm*
N	Turns of the coil	600	/
μ_0	Permeability of free space	$4\pi \times 10^{-7}$	*H/m*
μ_r	the relative permeability of the iron armature	700	/
γ	resistance per unit length	0.12	*Ω/m*

B. *Model discussion*

As shown, the force and displacement have a nonlinear relationship. In order to avoid the influence caused by displacement, voltage, and position must maintain a dynamic relationship, and voltage cannot be used to change the value of force directly. The magnitude of the feedback force should be determined by both voltage and displacement.

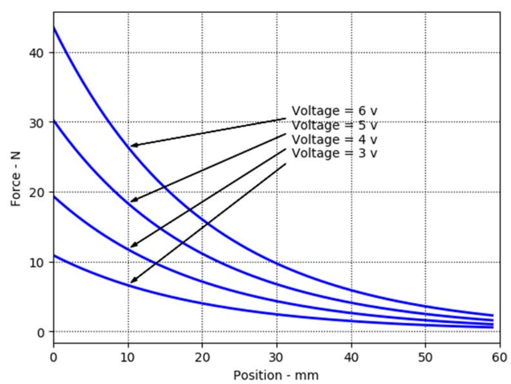

Fig. 6 Relationship between force and position

C. *Control execution analysis*

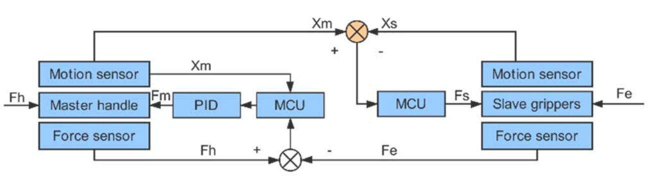

Fig. 7 Control flow chart of force feedback module.

The flow graph of the force feedback control is shown in Fig. 7. Fm is the driving force of the master handle, Fh is the force applied by the operator to the main end, Fe is the contact force between the guidewire and the vessel and Xm and Xs represent the displacements of the main hand and the slave hand respectively. Proportional-Integral-Derivative (PID) Controller using a control loop feedback mechanism to control Fm was designed for MCU to improve the control performance of the system and parameters of the PID controller have been tuned after serval experiments. Finally, the entire control will maintain a dynamic equilibrium between Fe and Fh.

IV. EXPERIMENTS AND EVALUATIONS

An experimental device has been built to evaluate the performance of the master-slave control system. A laser sensor is used in the system to acquire the displacement and transmit it to the MCU through the ADC. Then the MCU determines the value of PWM, in other words, the value of voltage by the acquired position and the force needed. The laser displacement sensor was fixed on the electromagnet, and the output voltage of the laser displacement sensor, which has a linear relationship with the position of the master handle, was loaded into the MCU to determine the voltage needed by the electromagnet. And the current force on the master handle, which may be caught by a force sensor combined with the stiffness coefficient of the spring that served as the feedback link of the PID control loop. A digital force gauge was used to acquire the value of the contact force to detect the accuracy of feedback. Considering that the aim of the experiment is to investigate the performance of both the master and slave side, the information acquired by the slave end is delivered to the master controller continuously. The performance of the system in terms of accuracy and real-time tracking was evaluated by using force data from the slave side and the value acquired by the digital force gauge.

Feedback force evaluation experiments were performed to evaluate the telepresence and precision of the loaded force on the handle. Feedback force was detected by the digital force gauge installed onto the front end of the master manipulator. Slave grippers were used to drive the catheter to perform the same movement as the master manipulator. Then, a series of force in the range of 0-3 N was loaded onto the slave side to estimate the precision of the master-slave system. The experimental is shown in Fig. 8.

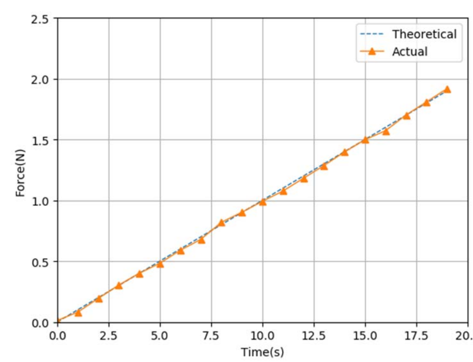

Fig. 8 a Theoretical force and measured force.

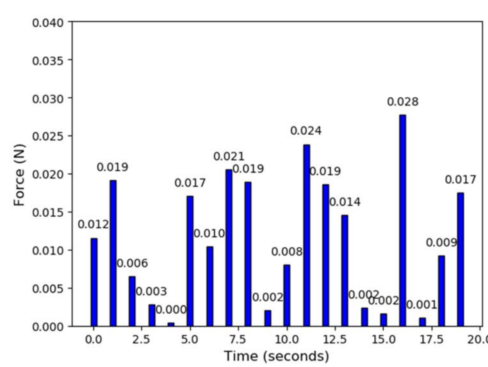

Fig. 8 b The error between theoretical force and measured force.

As shown in Fig. 8, a digital force gauge was used to detect the axial force of the master handle. The force loaded on bionic grippers is ranging from 0 N to 2 N. The results indicate that the maximal error is 0.028 N below 0.03 N, which meets the requirement of surgery, because the precision of the force on the catheter operated by an experienced surgeon is more than 0.05 N in the axial direction in conventional interventional vascular surgery.

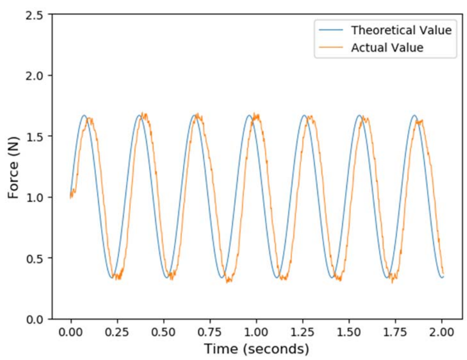

Fig. 9 Frequency response of force feedback control.

The tracking performance of the REI system can be achieved from the force detected from the master side and bionic grippers. The force tracking the performance of the system is shown in Fig. 9. According to medical research, real-time force feedback needs a refresh rate of more than 3 Hz to meet the real requirements. As shown in Fig. 9, there is a delay in the results of the frequency response experiment. The source of the delay mainly includes two parts. First, because the control system contains inertia links or energy storage elements such as electromagnetic coils, all of them will generate delays. Second, the process of message transmission will also cause a delay. In terms of the REI system, the response lag cannot exceed 100ms when the frequency of the loaded force is above 3Hz. Under the control of MCU with a PID algorithm, the results of the frequency response experiments indicate that the response lag is approximately 36ms when the frequency is 3.5Hz. And it is rapid enough to chase the movement of the human hand.

V. Conclusion

Based on the mechanism of human fingers, bionic grippers were designed, which can realize the forward and backward delivery and twisting of the guidewire and catheter imitating the hands of the doctor. A master manipulator with force feedback was designed to control the movement and rotation of bionic grippers to enhance the telepresence of the doctor. Three experiments were conducted to evaluate the performance of the REI system about the accuracy, latency, and traceability. The precision experiment indicates that the error between the master handle and bionic fingers is small enough and acceptable. Experiments about the latency of the bionic grippers were also conducted and the results show that the response time of the system is below 100ms. Finally chasing experiment proves that the master manipulator can recurrent the force waveform loaded on the bionic fingers precisely when the frequency of force is higher than 3Hz. The experimental results show that the developed REI system can complete the vascular interventional surgery and the ensure that the safety of REI is not lower than manual operation.

Acknowledgment

The authors appreciate the help of the Shanghai Engineering Research Center for leading the intelligent diagnosis and treatment instrument (15DZ2252000). This work was partially supported by the International Academic Cooperation and Exchange Projects of Shanghai (16550720100) and the Natural Science Foundation of Shanghai (18ZR1421300).

References

[1] George A. Antoniou, Celia V. Riga, Erik K. Mayer, et al. Clinical applications of robotic technology in vascular and endovascular surgery. Journal of vascular surgery. 2011, Vol.53(2): 493-499

[2] Hedyeh Rafii-Tari, Christopher J. Payne, and G. Yang. Current and Emerging Robot-Assisted Endovascular Catheterization Technologies: A Review. Annals of Biomedical Engineering, 2013, Vol.42(4):697-715

[3] Mangels DR, Giri J, Hirshfeld J, Wilensky RL. Robotic-assisted percutaneous coronary intervention. Catheter Cardiovasc Interv. 2017 Nov;90(6) 948-955. doi:10.1002/ccd.27205. PMID: 28722293.

[4] David Filgueiras-Rama, Alejandro Estrada, Josh Shachar, Sergio Castrejón, David Doiny, Marta Ortega, Eli Gang, José L. Merino. Remote Magnetic Navigation for Accurate, Real-time Catheter Positioning and Ablation in Cardiac Electrophysiology Procedures. Journal of Visualized Experiments. 2013, Vol.74: e3658

[5] Smitson CC, Ang L, Pourdjabbar A, Reeves R, Patel M, Mahmud E. Safety and Feasibility of a Novel, Second-Generation Robotic-Assisted System for Percutaneous Coronary Intervention: First-in-Human Report. J Invasive Cardiol. 2018 Apr;30(4) 152-156. PMID: 29335386.

[6] Masayuki Hara, Roy Salomon, Wietske van der Zwaag, Tobias Kober, GiulioRognini, Hiroyuki Nabae, Akio Yamamoto, Olaf Blanke, Toshiro Higuchi. A novel manipulation method of human body ownership using an fMRI-compatible master–slave system. Journal of Neuroscience Methods. Volume 235, 30 September 2014, Pages 25-34

[7] Xiao, N., Guo, J., Guo, S. et al. A robotic catheter system with real-time force feedback and monitor. Australas Phys Eng Sci Med (2012) 35: 283. https://doi.org/10.1007/s13246-012-0146-0

[8] Park JW, Choi J, Pak HN, et al. Developmentof a force-reflecting robotic platform for cardiac catheter navigation. Artif Organs 2010; 34(11): 1034–1039.

[9] Wang-sheng Lu, Wu-yi Xu, Feng Pan, Da Liu, Zeng-min Tian, Yanjun Zeng. Clinical application of a vascular interventional robot in cerebral angiography. Int J Med Robotics Comput Assist Surg 2016; 12: 132-136.

[10]Jan Peirs, Joeri Clijnena, Dominiek Reynaertsa, et al. A micro optical force sensor for force feedback during minimally invasive robotic surgery. Sensors and Actuators A 115 (2004) 447–455

[11]Guo, Shuxiang Guo, Yang Yu, Design and characteristics evaluation of a novel teleoperated robotic catheterization system with force feedback for vascular interventional surgery, Biomed Microdevices, (2016) 18: 76-92.

[12]J.Guo, S.Guo, P.Wang, W.Wei and Y.Wang, A Novel Type of Catheter Sidewall Tactile Sensor Array for Vascular Interventional Surgery, Proceedings of the 2013 ICME International Conference on Complex Medical Engineering, pp. 264–267 (2013)

[13]Takeshi Yoneyama, Tetsuyou Watanabe, Hiroyuki Kagawa et al. Force-detecting gripper and force feedback system for neurosurgery applications. Int J CARS (2013) 8:819–829

[14]Govindarajan Srimathveeravalli, Thenkurussi Kesavadas, Xinyan Li. Design and fabrication of a robotic mechanism for remote steering and positioning of interventional devices. Int J Med Robotics Comput Assist Surg 2010; 6: 160–170.

[15]Payne C J, Ra Tari H, Yang G Z. A force feedback system for endovascular catheterisation. In: Proceedings of the 2012 IEEE/RSJ International Conference on Intelligent Robotics and Systems. Vilamoura: IEEE, 2012. 1298-1304

[16]Kesner S B, Howe R D. Position control of motion compensation cardiac catheters. IEEE Transactions on Robotics, 2011, 27(6): 1045-1055
[17]Kesner S B, Howe R D. Force control of flexible catheter robots for beating heart surgery. In: Proceedings of the 2011 IEEE International Conference on Robotics and Automation. Shanghai, China: IEEE, 2011. 1589-1594
[18] Paul H. Schimpf Eastern Washington University, Cheney, WA, USA. A Detailed Explanation of Solenoid Force. Int. J. on Recent Trends in Engineering and Technology, Vol. 8, No. 2, Jan 2013