Proceedings of 2022 IEEE
International Conference on Mechatronics and Automation
August 7 - 10, Guilin, China

Study on Admittance Control for the Vascular Interventional Surgical Robot

Xianguo Liao[1], Jian Guo[1,2*]
Shuxiang Guo[1,2,3*]
and Yu Song[1]

[1]*Tianjin Key Laboratory for Control Theory & Applications In Complicated systems and Intelligent Robot Laboratory*
Tianjin University of Technology
Binshui Xidao Extension 391,Tianjin,300384,China
jasonsongrain@hotmail.com; 2209044124@qq.com

[2]*Shenzhen Institute of Advanced Biomedical Robot Co., Ltd.*
No.12, Ganli Sixth Road, Jihua Street, Longgang District, Shenzhen,518100,China
**corresponding author : jianguo@tjut.edu.cn;*

[3] *Key Laboratory of Convergence Medical Engineering System and Healthcare Technology,The Ministry of Industry and Information Technology,School of Life Science*
Beijing Institute of Technology
No.5, Zhongguancun South Street, Beijing,100081, China
**corresponding author : guoshuxiang@hotmail.com*

Abstract –**When a doctor operates a vascular interventional surgery robot for surgery, the surgical instrument contacts the vascular environment to generate a force. If this force exceeds the safe force threshold, it is easy to pierce the blood vessel wall and cause danger. In order to solve this problem, this paper proposes a method of using admittance control to realize active compliance control. The force information is combined with the motion control closed-loop. When the contact force is too large, the admittance control is performed. The force is used as the input and the displacement is the output. The position of the slave side is adjusted in real time, and the contact force is reduced through the position control. The simulation experiment of the admittance control were carried out in this paper, and the results indicated that the admittance control can limit the excessive contact force and the penetration depth of the slave at the same time, and it significantly improved the safety and compliance of the slave.**

Index Terms – Vascular intervention robot, Safe force threshold, Admittance control.

I. Introduction

At present, cardiovascular and cerebrovascular diseases have become an important problem that cannot be ignored in the world[1]. However, there are various problems in traditional vascular interventional surgery[2]. More and more researchers have begun to study the vascular interventional surgery robots to protect doctors and improve surgical safety[3].

During the surgical operation of the vascular interventional surgical robot, it is not only necessary to ensure the control accuracy of the master-slave displacement[4], but also to consider the force of the catheter and the guide wire in contact with the vascular environment[5]. Because under the simple position control, the robot slave side will strictly follow the desired displacement of the master side. If the vascular interventional surgery robot generates excessive external force due to its own reasons or external changes during the movement process, at this time, under the simple position control, the robot will only continue to track the desired displacement. If the position is not changed or the contact force is not reduced in time, the vessel wall is likely to be punctured and dangerous in the process[6]. But under the force control, the goal is to control the contact force of the robot end.When the robot generates excessive force, it will intelligently adjust the position trajectory to reduce the contact force and ensure safety. This is the benefit of force control, also known as active compliance control[7].

The compliance control is to obtain the control signal from the force sensor, and use this signal to control the robot to contact the environment and make a compliant motion without conflicting with the environment. Compliance control can be divided into active compliance control and passive compliance control[8]. Passive compliance control uses auxiliary mechanical structures to enable the robot to naturally comply with external forces when it is in contact with the environment[9], while active compliance control uses force feedback information to use active control strategies to achieve robot force control. Due to the shortcomings of passive compliance control, such as slow dynamic response and poor robustness, active compliance control has gradually become the focus of compliance control research. In the basic active compliance control, it can be divided into explicit force control, force/position hybrid control, impedance control, admittance control, etc. For example, using PID force control for the force controller part of the robot alone can be called explicit force control, which separates the force controller and the position controller, but this method splits the relationship between force and position. The control method is not very effective in practice, and some feedforward links are often added to it, and the stability is low. The force/position hybrid control is to control force and position at the same time. The method is mainly to decompose the Cartesian space of the robot's end-effector coordinates into a position subspace and a force subspace according to the actual task requirements. The force/position hybrid control is intuitive and easy to implement, but it has many shortcomings. For the vascular interventional surgical robot, it cannot be simply decomposed into orthogonal position subspace and force subspace, so the force/position hybrid control is not suitable for this study. The characteristic of impedance control is that it does not directly control the

978-1-6654-0853-0/22/$31.00

force between the robot and the contact environment, but according to the relationship between the position of the robot end and the force at the end, the displacement is input and the force is output[10]. However, due to the large inertia and frictional force of the master-slave collaborative robot, it is difficult for the operator to achieve precise movement even if the end is equipped with a force sensor, and the requirements for modeling accuracy are high, so impedance control is usually only suitable for Interactions in a rigid environment, such as grinding and polishing, cargo picking and placing, are difficult to meet the accuracy requirements of a flexible environment, such as the vascular interventional surgery robot studied in this paper. However, position-based impedance control, also called admittance control, is a control method of inputting force and outputting displacement[11], which is more suitable for flexible environments. Therefore, in order to make full use of force information during motion control and improve system compliance and safety, the active compliance control method selected in this paper is admittance control for vascular interventional surgery robots.

This paper is divided into five chapters: The first part is the introduction. The second part is an overview of the platform of the surgical robot system. The third part is the design of the admittance controller. The fourth part is simulation experiment and result analysis. The last part is the conclusion and the future work.

II. Overview Of The Platform

In order to protect doctors and improve the safety of vascular interventional surgery, our team designed a master-slave vascular interventional surgery robot with force feedback function, which mainly includes two parts: a master robot and a slave robot[12]. During the operation, we can place the slave robot at the patient, and the doctor can obtain visual feedback and force feedback information outside the operating room, then operate the master manipulator, issue operating instructions, and then transmit it to the slave manipulator through the communication channel , so that the catheter guide wire can be controlled to complete the operation commands such as advancing, retreating, and rotating, and finally it can realize the master-slave cooperative control. At the same time, the force sensor at the slave manipulator can detect the force information of the catheter and the guide wire moving in the blood vessel, and realize the function of force feedback through the feedback force reproduction device at the master manipulator[13].

The master-slave vascular interventional surgery robot designed by our team is simple to operate, conforms to the operating habits of doctors, and can realize the coordinated operation of catheter and guide wire[14]. The master manipulator of the system is mainly divided into two parts: the catheter manipulator and the guide wire manipulator. The master-slave vascular interventional surgery robot designed by our team is simple to operate, conforms to the operating habits of doctors, and can realize the coordinated operation of catheter and guide wire11. The master manipulator of the system is mainly divided into two parts: the catheter manipulator and the guide wire manipulator. It has two linear displacement sensors, which adopt a non-contact measurement method. The displacement measurement is realized by the suspended magnetic block above the sensor, and the information of the axial displacement of the catheter and the guide wire can be measured respectively. At the same time, two photoelectric encoders are used to measure the radial rotation information of the catheter and the guide wire, which are respectively packaged inside the catheter manipulator and the guide wire manipulator. The force feedback part of the master manipulator is mainly composed of a magnetic rod and two coils, and the force feedback is realized based on the principle of electromagnetic induction[15]. The master manipulator is shown in Fig. 1.

The slave manipulator structure of the system mainly includes a linear displacement platform, a slave catheter manipulator, and a slave guide wire manipulator[16] . There are four clamps in the slave manipulator, which are used to hold the catheter and the guide wire respectively, and the four clamps can realize the coordinated movement of the catheter and the guide wire at the same time, including actions such as pushing and rotating. The motor used is the stepper motor of Japan Oriental Motor AR series. The force sensor part uses a load sensor to measure the force on the catheter and guide wire in the blood vessel. The slave manipulator is shown in the Fig. 2.

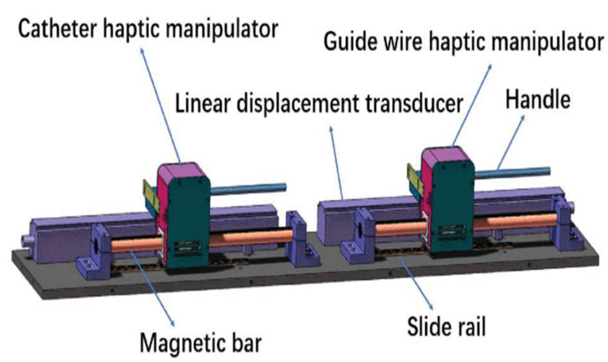

Fig. 1 The master manipulator

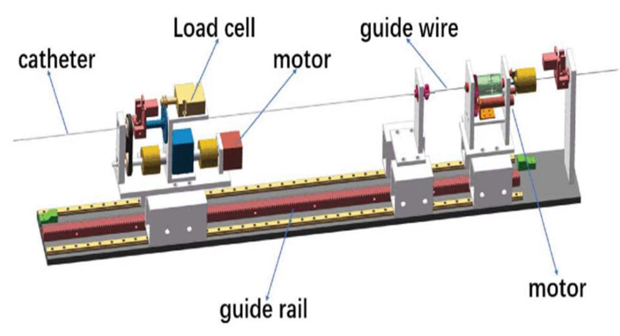

Fig. 2 The slave manipulator

III. Design Of The Admittance Controller

A. Overview of the Admittance Control Principle

In 1985, Neville Hogan put forward a complete theory of impedance control after summarizing and researching the experience of predecessors[17]. Since then, impedance control has been widely used in compliance control and other fields. The core idea of impedance control is to establish the dynamic relationship between the position of the robot end manipulator and the contact force, and then select appropriate impedance parameters to control the contact force, so that the mechanism exhibits compliance.

According to the impedance control theory, the contact model between the robot end manipulator and the environment can be represented by a mass-spring-damping system[18], as shown in Fig. 3.

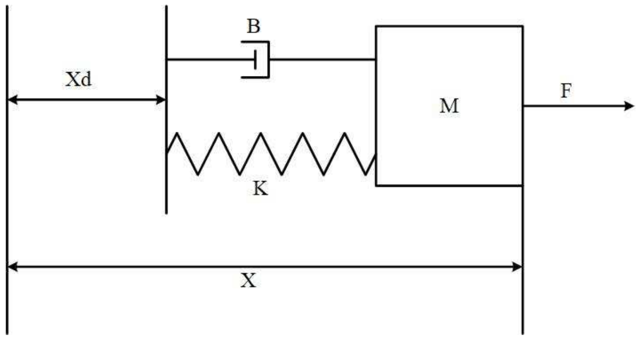

Fig. 3 The mass-spring-damping system

The system can be written as the following differential equation:

$$F = M(X'' - Xd'') + B(X' - Xd') + K(X - Xd) \tag{1}$$

Among them, F is the external force on the end of the robot, X is the end position,, Xd is the desired end position, M is the mass coefficient, B is the damping coefficient, and K is the stiffness coefficient.

It can be seen from the formula that the realization method of impedance control is to adjust the force generated at the end by measuring the difference between the current position and the target position, that is, the input is displacement and the output is force. Therefore, impedance control requires that we can obtain accurate position information and control the joint moment of the robot[19]. Moreover, when there is no contact with the environment, the position control is open-loop, so the requirements for modeling are relatively high. If the modeling error is large, the accuracy of the position will be affected. So the control strategy depends on the accuracy of the dynamic model.

This paper will study the position-based impedance control. The position-based impedance control is also called the admittance control, which corresponds to the impedance control. It adjusts the motion of the robot by measuring the force on the end, that is, the input force and the output displacement. For admittance control, it is divided into two parts, one part is the inner loop responsible for motion control, which is generally realized by PID control, and the other part is the outer loop responsible for force control[20]. Since the current research on motion control is very mature, and the force information can be measured by force sensors, the admittance control is easier to realize and more suitable for the research in this paper.

The differential equation for the admittance control is:

$$M(X'' - Xd'') + B(X' - Xd') + K(X - Xd) = F \tag{2}$$

Laplace transform is performed on the differential equation, and after sorting, we can get:

$$X = Xd + \frac{F}{MS^2 + BS + K} \tag{3}$$

Based on the above schematic diagrams and formulas, the principle of admittance control can be summarized as follows: it combines force information with the inner loop of motion control, and takes the force information F as the input of the admittance controller, The force information F is used as the input of the admittance controller, and the force information is converted into the position correction amount X-Xd through the admittance control model, and after the new desired position is obtained, the position control is performed, that is, the force is controlled by the change of the position amount. Therefore, the admittance control can be used to control the contact force and position at the same time, so that the original rigid contact becomes a flexible contact.

B. Design of Admittance Control System

The block diagram of the vascular interventional surgery robot system based on admittance control designed in this paper is shown in Fig. 4:

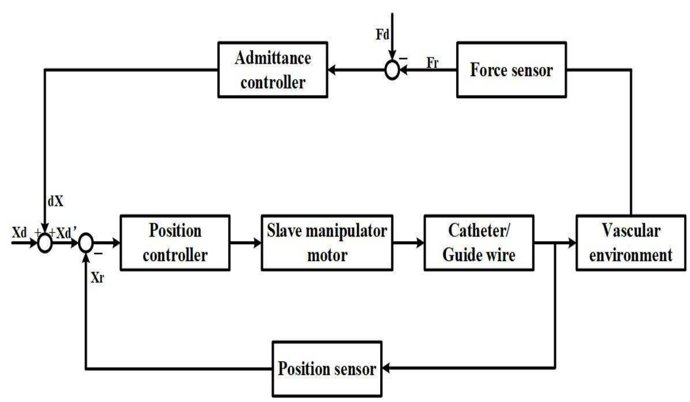

Fig. 4 The admittance control system block diagram

The force controller part shown in Fig. 4 adopts admittance control, and the position controller part adopts PID control. Most of the research on admittance control is to use it to track the contact force and position at the same time to achieve the function of accurate tracking. In this paper, the principle of admittance control is used to innovate, and the desired force Fd is set as the safety threshold of the desired feedback force, that is the contact force between the catheter and the guide wire can be limited within the safety threshold, so the input F of the admittance controller designed in this paper is Fr-Fd. The size of the safety threshold Fd is set as follows: the safety threshold is 350 mN for the guide wire and 450 mN for the catheter [21], the safety threshold can also be set according to the surgeon's surgical experience and data during the actual operation.

The control process of the vascular interventional surgery robot system based on admittance control is as follows: when the catheter and the guide wire move in the blood vessel, excessive contact force is generated due to its own reasons or external changes, and the actual force Fr detected by the force sensor exceeds the safety threshold Fd. At this time, the admittance controller is activated. The admittance controller has three parameters that can be set, so that it can output an appropriate size of the position correction dX by adjusting the parameters. The desired position Xd of the master side superimposes the position correction amount dX at this time to obtain a new desired position Xd', and then the photoelectric encoder of the slave side can measure the actual position Xr, so that the PID controller is used for master-slave motion control. This method reduces the force by changing the amount of displacement until the contact force measured by the sensor falls within a safe threshold.

In order to perform precise motion control when the force is within the safety threshold, the admittance control is activated when the actual force Fr detected by the force sensor is greater than the safety threshold Fd. However, when the actual force F is less than the safety threshold fd, the input of the admittance controller is 0, and only simple motion control is performed, so the flow chart of the admittance control system is shown in the Fig.5 :

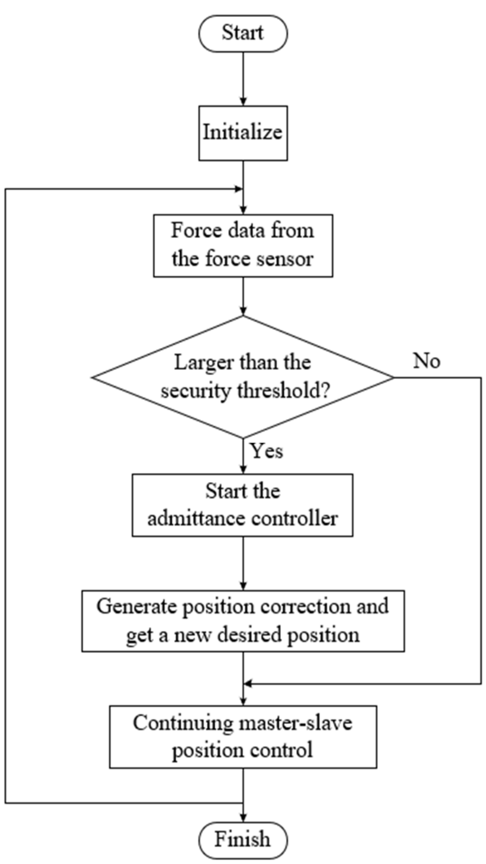

Fig. 5 The flow chart of the admittance control system

IV. SIMULATION EXPERIMENT RESULTS AND ANALYSIS

A. The Simulation Experiment Setup

In order to verify the feasibility of admittance control, this paper uses Simulink to build a simulation with admittance control and a simulation without admittance control for comparison.

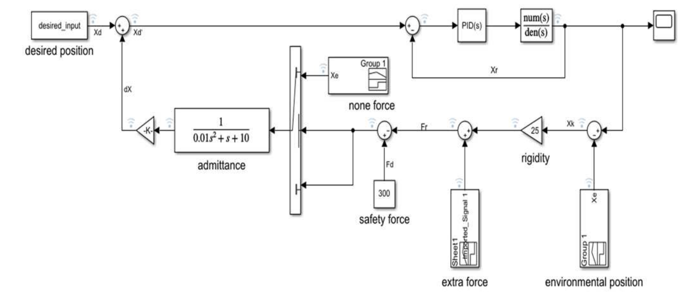

Fig. 6 The simulation diagram with admittance control

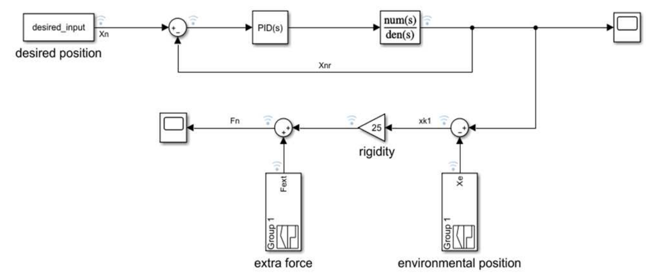

Fig. 7 The simulation diagram without admittance control

In the simulation built in this paper, it is assumed that the desired input position Xd is 1.25t+sin(t), the environmental position Xe is t, and the environmental stiffness is 25. As for the admittance controller part, after analyzing each parameter and performing several simulation experiments with different size parameters, it is finally concluded that the effect is better when the parameter M is 0.01, B is 1, and K is 10. In addition, since the output position correction value is small, a proportional link is added. The position control part in the simulation adopts PID control. In vascular interventional surgery, external disturbances are unknown, in order to simulate more realistic, this paper uses the measured continuous external force disturbance for simulation analysis.

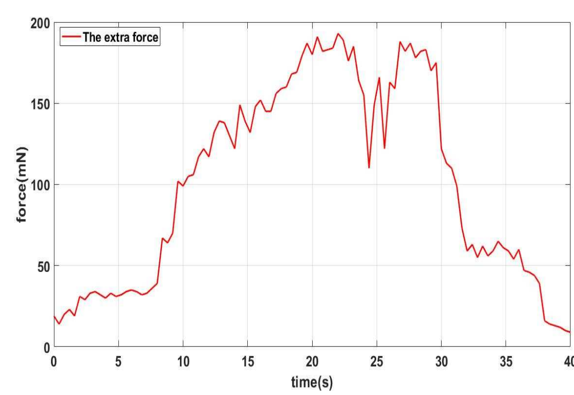

Fig. 8 The extra force set in simulation

B. The Simulation Experiment Results and Analysis

In this simulation experiment, the force safety threshold Fd is set to 300mN. The force safety threshold can be changed and lowered to accommodate all vascular interventional surgical robots, or force control can also be performed using fiber optic sensors at the end of the catheter. When comprehensive force Fr exceeds 300mN, the admittance control is performed, but when Fr falls below 300mN, the input is 0, and the admittance control is stopped at this time.

This simulation experiment uses the wireless signal Data Inspector for data collection and analysis, which is convenient and concise. Fig. 9 is a force comparison chart, the red solid line is the comprehensive force generated with admittance control, the blue dotted line is the force without admittance control and the desired force threshold is 300mN. Fig. 10 is the displacement comparison chart, this figure contains the displacements with admittance control, the displacements without admittance control, and the respective desired displacements.

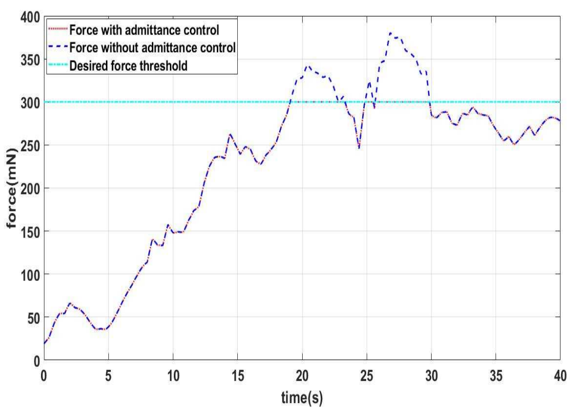

Fig. 9 Force comparison with and without admittance control chart

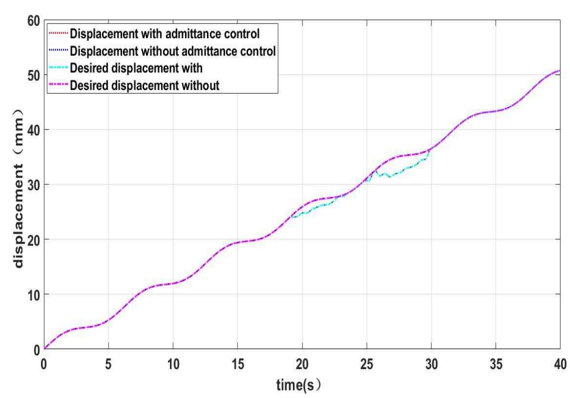

Fig. 10 Displacement comparison with and without admittance control chart

From the above simulation experiment results, it can be seen that the comprehensive force value is greater than the safety threshold of 300mN at 19.1-23.3s, 24.9-25.5s and 25.7-29.9s, and the admittance controller adjusts the displacement in real time. When the displacement is changed, the force value decreases and is always controlled below the safety threshold of 300mN. At 23.3-24.9s, 25.5-25.7s and 29.9-40s, the force has always been within the safety threshold, so the admittance control stops working and only the motion control is carried out, as shown in Figure 9 and Figure 10, the force with admittance control and displacement with admittance control are basically the same as the force without admittance control and displacement without admittance control . After 40s, if the force is greater than the safety threshold of 300mN, the admittance control will still be activated.

In order to reflect the effectiveness of the admittance control, the error is obtained by comparing the force output when the admitting control is performed with the desired force threshold of 300mN, and for more intuitive purposes, the error when the admitting control is not performed is set to 0.

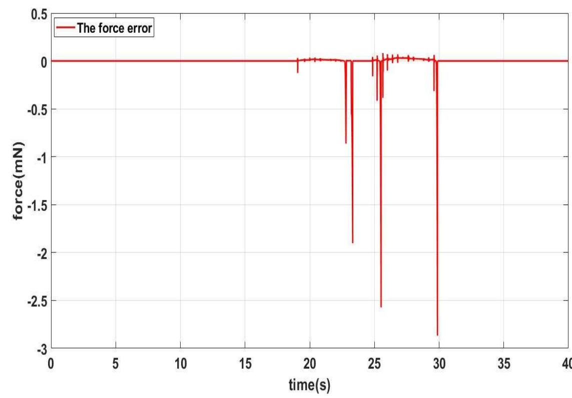

Fig. 11 The force error with admittance control

As can be seen from Fig. 11, there will always be a large error close to -3mN at the end of the conduction control, which indicates that the force reduction at this time is within the safety force threshold, while the maximum positive error is only 0.08mN, which is in line with the requirements of vascular interventional surgery.

Through the above analysis , we could conclude that the simulation experiment results verified that the admittance control can limit the contact force of the catheter guide wire in the blood vessel within the safety threshold. Therefore, it can improve the compliance and safety of the vascular interventional surgical robot system.

V. Conclusions And Future Work

In order to make full use of the feedback force information in the motion control of the vascular interventional surgical robot and avoid excessive contact force, this paper proposed a control strategy based on admittance control. When the contact force exceeded the safety threshold, the admittance control was activated, and adjusted the desired displacement in real time, and then performed motion control to reduce the contact force. The simulation experiment results showed that the admittance control could limit the contact force within a safe threshold, thereby it could improve the safety and compliance of the system.

The future work will be to study the use of intelligent control methods combined with admittance control, such as fuzzy admittance control, and apply it to this platform.

ACKNOWLEDGMENTS

This research is supported by National Natural ScienceFoundation of China (61703305、62103299), Key Research Program ofthe Natural Science Foundation of Tianjin (18JCZDJC38500)and Innovative Cooperation Project of Tianjin Scientific and Technological (18PTZWHZ00090).

REFERENCE

[1] Linshuai Zhang, Shuoxin Gu, Shuxiang Guo and Takashi Tamiya, "A Magnetorheological Fluids-based Robot-assisted Catheter/guidewire Surgery System for Endovascular Catheterization", *Micromachines*, Vol. 12, No. 6, 2021.

[2] Xiaoliang Jin, Shuxiang Guo, Jian Guo, Peng Shi, Masahiko Kawanishi and Hideyuki Hirata, "Active Suppression Method of Dangerous Behaviors for Robot-Assisted Vascular Interventional Surgery", IEEE Transactions on Instrumentation & Measurement, Vol. 71, pp: 1-9, 2022.

[3] Wei Zhou, Shuxiang Guo, Jin Guo, Zhengyang Chen and Fanxu Meng, "Kinetics analysis & ADRC-based controller for a String-driven Vascular Intervention Surgical Robotic System", *Micromachines micromachines*-1692488, Vol. 13, No. 770, 2022.

[4] Shuxiang Guo, Jinxin Cui, Yan Zhao, Yuxin Wang, Youchun Ma, Wenyang Gao, Gengsheng Mao and Shunming Hong, "Machine learning-based Operation Skills Assessment with Vascular Difficulty Index for Vascular Intervention Surgery", *Medical & Biological Engineering & Computing*, Vol. 58, No. 8, pp: 1707-1721, 2020.

[5] Jian Guo, Xiaoliang Jin, Shuxiang Guo and Qiang Fu, "A Vascular Interventional Surgical Robotic System based on Force-Visual Feedback", *IEEE Sensors Journal*, Vol. 19, No. 23, pp: 11081-11089, 2019.

[6] Yan Zhao, Huiming Xing, Shuxiang Guo, Yuxin Wang, Jinxin Cui, Youchun Ma, Yu Liu, Xinke Liu, Junqiang Feng and Youxiang Li, "A novel noncontact detection method of surgeon's operation for a master-slave endovascular surgery robot", *Medical & Biological Engineering & Computing*, Vol. 58, No. 4, pp: 871-885, 2020.

[7] Barkana, D. Erol T, "Design and implementation of a control architecture for robot-assisted orthopaedic surgery," *The International Journal of Medical Robotics and Computer Assisted Surgery*, Vol. 6, No. 2, pp: 42-56, 2010.

[8] H. Sang , S. Wang , J. Li , C. He , L Zhang and X. Wang, "Control design and implementation of a novel master-slave surgery robot system, " *MicroHand A. Int J Med Robot*2, Vol. 7, No. 3, pp: 334-47, 2011.

[9] A. Lopes and F. Almeida, "A force-impedance controlled industrial robot using an active robotic auxiliary device", *Robotics and Computer-Integrated Manufacturing*, Vol. 24, No. 3, pp: 299-309, 2008.

[10] G. E. Dongming, S. Guanghui, Z. Yuanjie and S. Jixin, "Impedance control of multi-arm space robot for the capture of non-cooperative targets," *Journal of Systems Engineering and Electronics*, Vol. 31, No. 5, pp: 1051-1061, 2020.

[11] F. Ferraguti et al., "An Energy Tank-Based Interactive Control Architecture for Autonomous and Teleoperated Robotic Surgery," *IEEE Transactions on Robotics*, Vol. 31, No. 5, pp: 1073-1088, 2015.

[12] Cheng Yang, Shuxiang Guo, Xianqiang Bao "An Isomorphic Interactive Device for the Interventional Surgical Robot after In Vivo Study", *Micromachines*, Vol. 13, No. 1, 2022.

[13] J. Guo, S. Feng and S. Guo, "Study on the Automatic Surgical Method of the Vascular Interventional Surgical Robot Based on Deep Learning," *Proceedings of 2021 IEEE International Conference on Mechatronics and Automation, Takamatsu, Japan*, pp: 1076-1081, 2021.

[14] J. Guo, L. He, and S. Guo, "Study on Force Feedback Control of the Vascular Interventional Surgical Robot based on Fuzzy PID," *Proceedings of 2020 IEEE International Conference on Mechatronics and Automation, Beijing, China*, pp: 1710-1715, 2020.

[15] S. Guo, Q. Zhan, J. Guo, C. Meng, and L. Qi, "A Novel Vascular Interventional Surgeon Training System with Cooperation between Catheter and Guidewire," *Proceedings of 2019 IEEE International Conference on Mechatronics and Automation, Tianjin, China*, pp: 1403-1408, 2019.

[16] J. Guo, C. Meng, S. Guo, X. Jin, and C. Sun, "A Novel Bilateral Control Strategy for Master-slave Vascular Interventional Robots," *Proceedings of the 2018 IEEE International Conference on Robotics and Biomimetics, Kuala Lumpur, Malaysia*, Vol. 1, No. 10, pp: 471-476, 2018.

[17] Hongan N. "Impedance Control An Approach To Manipulation: 'Part I-theory, Part II-implementation, Part III- Applcation," *Asme Journal of Dynamic Systems Measurement & Control*, Vol. 107, No. 1, pp: 304-313, 1985.

[18] K. Ba, B. Yu, G. Ma, Q. Zhu, Z. Gao and X. Kong, "A Novel Position-Based Impedance Control Method for Bionic Legged Robots' HDU," *IEEE Access*, Vol. 6, No. 1, pp: 55680-55692, 2018.

[19] A. Toedtheide, T. Lilge and S. Haddadin, "Antagonistic Impedance Control for Pneumatically Actuated Robot Joints," *IEEE Robotics and Automation Letters*, Vol. 1, No. 1, pp: 161-168, 2016.

[20] C. Yang, G. Peng, Y. Li, R. Cui, L. Cheng and Z. Li, "Neural Networks Enhanced Adaptive Admittance Control of Optimized Robot–Environment Interaction," *IEEE Transactions on Cybernetics*, Vol. 49, No. 7, pp: 2568-2579, 2019.

[21] C. Yang, S. Guo , X. Bao , N. Xiao,L. Shi, Y. Li and Y. Jiang, "A vascular interventional surgical robot based on surgeon's operating skills," *Medical & Biological Engineering & Computing*, Vol. 57, No. 9, pp:1999-2010, 2019.