Proceedings of 2019 IEEE
International Conference on Mechatronics and Automation
August 4 - 7, Tianjin, China

Study on Robust Control for the Vascular Interventional Surgical Robot

Jian Guo[1], Shuai Yang[1]

[1]*Tianjin Key Laboratory for Control Theory & Applications in Complicated Systems and Biomedical Robot Laboratory*
Tianjin University of Technology
Binshui Xidao 391, Tianjin, China

jianguo@tjut.edu.cn;
923756066@qq.com;

Shuxiang Guo[1,2*] , Cheng Meng[1] , Lei Qi[1]

[2] *Intelligent Mechanical Systems Engineering Department*
Kagawa University

2217-20, Hayashi-cho, Takamatsu 761-0396, Japan

*Corresponding author: guo@eng.kagawa-u.ac.jp;
535109737@qq.com; 1561549149@qq.com;

***Abstract* -With the rapid development of surgical robot technology, more and more requirements on control precision were raised upon the surgical robots. For master-slave controlled surgical robot, the error of displacement between master side and slave side affects the safety and success rate of interventional surgery. A robust control algorithm is proposed to reduce the displacement error between master side and slave side. In this paper, the system identification technology is used to establish the mathematical model of the interventional robot system, which is expressed in simunlink, and a robust controller is used to optimize its performance and improve its system stability. Stability analysis was carried out by using lyapunov function method and experimental method, and the experimental results showed that the system with robust control algorithm has better performance .**

Index Terms - Vascular intervention robot, robust control, lyapunov function method, stability

I. INTRODUCTION

At present, with the rapid increase of the incidence of cardiovascular diseases, vascular interventional surgical technology is particularly important. Compared with traditional technology, vascular interventional surgical technology have many huge advantages, such as relatively small trauma to patients, less blood loss during surgery and faster postoperative recovery. But the disadvantages are also obvious. Doctors need to be in a bad working environment for a long time and wear heavy protective clothing, which greatly increases the probability of doctors' mistakes in the operation process. With the development of robot technology, robot-assisted vascular intervention has become a research hotspot.

The robotic vascular interventional surgery system mainly includes two parts, the master side and the slave side. The doctor will operate the master side outside the surgery room, and then the computer will collect and transmit the operation information of the doctor on the master side to the slave side, which will complete the vascular interventional surgery in place of the doctor. Currently, the relatively mature vascular interventional surgical robot system mainly includes Sensei x robot system designed by Hansen Medical [1], which integrates 3D electronic anatomical mapping (EAM) technology into the robot system to optimize the navigation function of the catheter in the system. Yu Song [2] et al. developed a vascular interventional surgical robot based on force feedback of MR fluid. This system proposed a remote force feedback technology based on MR fluid, which improved the authenticity of operating the slave side. For master-slave control surgical robots, the physiological tremor of the hand affects the accuracy and success rate of robot-assisted surgery. Rui Shen [3] et al. proposed a physiological tremor recognition algorithm to improve the success rate of vascular interventional surgery in this way. Yu wang [4] put forward a kind of closed loop system to improve the precision of vascular interventional robot, Yu wang and others think that involved in major error mainly comes from the error of mechanical transmission system, therefore they add a rotary encoder, it is used to detect the actual rotation Angle guide and a linear position sensor fixed and thread clamping circuit inspection guide line to form the axial displacement of closed loop control to improve rotary and linear control precision. In this paper, the closed loop link is added to optimize the mechanical structure to improve the control precision, to make up for the error caused by mechanical transmission. The existing problems of the system are shown as follows:

(1) The structure of the system is too complex because of error compensation by changing the mechanical structure.

(2) No control algorithm is used to reduce the system error .

In order to solve these problems, this paper proposes a robust control algorithm for the vascular Interventional surgical robot, which can reduce the uncertainty of mechanical transmission from the perspective of algorithm. This method can reduce the overall system error more comprehensively, instead of only aiming at the error of the transmission structure.

II. OVERVIEW OF PLATFORM

This system is a cooperative operation device of catheter and guidewire in vascular interventional surgery. The device is divided into the master side and the slave side, and its feature is that it can control the catheter and guidewire at the same time and carry out cooperative operation. The overview of vascular Interventional robot control system as shown in Fig 1 The structure of master side part as shown in Fig 2(a) ; The structure of slave side as shown in Fig 2(b); The master operator is divided into a catheter operating device and a guide wire operating device, and the doctor uses both hands to control the device. The left and right control both master side and slave side. The input side of the master operator receives the signal operated by the doctor's hands and the feedback control signal of the master controller, and its output side is connected with the input end of the master controller and provides force feedback to the doctor at the same time. Referred to the input end of the master controller receives the master operator of information and feedback from the controller's operation, between master controller and the controller through the CAN bus communication, the output of the master controller and the master operator input connection, output to the master operator of the feedback control signal, while the output of the master controller is described from the controller and the input side of the connection, the master operator of operating information transmission from the controller; The PC display displays the image information collected by the IP camera and provides real-time visual feedback signals to the surgeon. The IP camera collects real-time motion images from the field operator, and its output end is connected with the master terminal PC display screen via the Internet; The input end of the controller receives the doctor operation information transmitted by the master controller and the force information of the catheter and guide wire collected by the sensor on the operator, and then the output end connects to the master controller and transmits the force information to the master controller through the CAN bus, and the master controller controls the master operator to provide force feedback to the doctor. The platform realizes force feedback through electromagnetic induction principle. In order to reduce the cumulative error, the platform uses the stepper motor produced by dongfang motor company for driving, and the information acquisition function is mainly completed by photoelectric encoder and linear displacement sensor.

The master operating device of this system adopts ergonomic design conforming to the operating habits of doctors. The catheter operating device and the guide wire operating device in the master operator are placed in front and back, which is completely in line with the actual operating mode of doctors. When doctors operate this platform, their hands touch the bionic catheter, making the operation more authentic and in line with the actual operation requirements. The real-time and accurate force feedback delivered by the doctor when operating the master manipulator enables the doctor to feel that he is in the field for operation. The doctor makes operation decisions based on the force feedback and visual feedback, which can effectively improve the safety of surgery. The system adopts the way of matching the guide rail and rack-rack from the operator's axial push unit, which is simple and stable in structure and can push for a long distance. Moreover, each module is independent from each other without interference, and can move independently or cooperate with the controller, which meets the operation requirements in actual surgery.

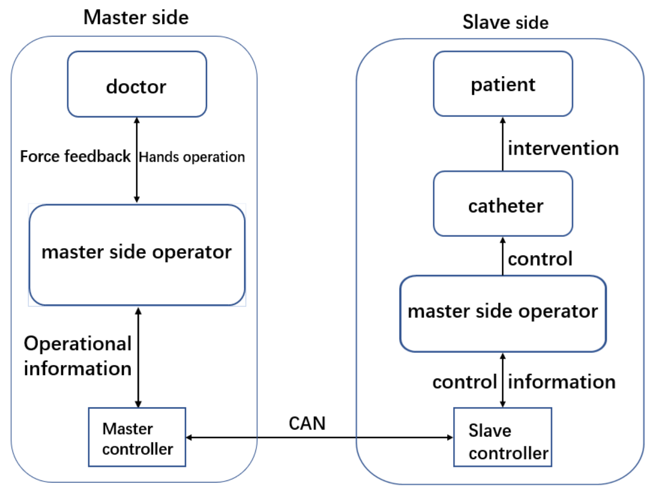
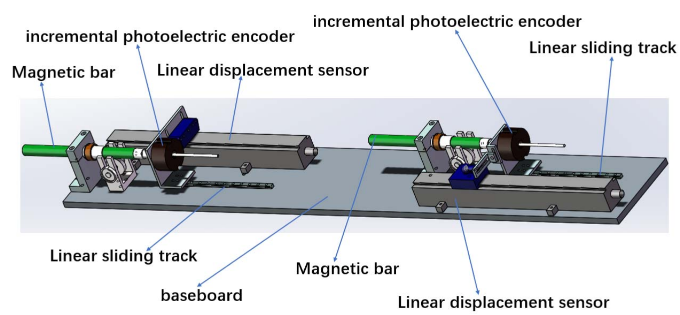
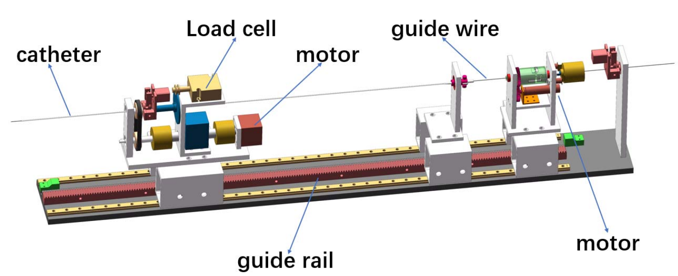


Fig.1 The overview of vascular interventional surgery robot control system



(a) The structure of master side



(b) The structure of slave side

Fig.2 The structure of vascular interventional surgery robot

III. THE DESIGN OF ROBUST CONTROLLER

A. *Analyses of Data and Error*

For actual dynamic systems, it is generally impossible to completely model accurately, and there are many uncertainties, including parameter uncertainty, unmodeled dynamics and various disturbances [5].It is difficult to accurately express the actual working state of a control system by establishing a mathematical model based on the traditional first-principles method. In order to obtain a more accurate mathematical model, we use a more accurate method of system identification to establish the mathematical model of the system [6]. System identification technology is based on the time function of input and output to determine the mathematical model describing the behavior of the system. In this way, the important parameters representing the behavior of the system can be estimated, and a mathematical model that can imitate the real behavior of the system can be established.

1800 groups of input and output data were measured through NDI .The error is shown in Fig.4. The curve of data will appear on the platform because we shift it periodically in order to imitate the behavior pattern of doctors operating the master side.

Fig.4 express the displacement error , we can see in the picture presents an error increases gradually, but at the end of the absolute value is stable within a certain range, as shown in figure error for high precision of vascular interventional robot system is very large, but the error finally presents the form of a bounded.

By using matlab system identification toolbox, we obtained the state space function of the system , The coefficients A B C D K of the state space function are shown below:

$$\frac{dx}{dt} = Ax(t) + Bu(t) + ke(t) \quad (1)$$

$$y(t) = Cx(t) + Du(t) + e(t) \quad (2)$$

$$A = \begin{pmatrix} -0.1015 & -0.06536 & 0.08489 & 0.01731 \\ 0.1549 & 0.001104 & 0.5088 & 0.3042 \\ -0.4446 & 0.07743 & -10.76 & 5.526 \\ 0.1422 & -0.6634 & 0.5811 & -1.504 \end{pmatrix}$$

$$B = \begin{pmatrix} 0.02483 \\ 0.1341 \\ -2.293 \\ 0.06708 \end{pmatrix} \quad C = \begin{pmatrix} 45.96 \\ 0.002055 \\ -0.3258 \\ -0.6232 \end{pmatrix}$$

$$D = (0) \qquad K = \begin{pmatrix} 0.1305 \\ -0.1723 \\ -0.1092 \\ -1.227 \end{pmatrix}$$

We set the external fluctuation as the following equation：

$$f(x) = Gx(t) + Me(t) \quad (3)$$

B. Design of Robust Controller

The characteristic of robust control method is to maintain some characteristics of the system under certain parameter perturbation. Robust control is an algorithm that focuses on control stability. Its design goal is to find the minimum requirements that must be met to ensure the safety of the control system in the actual environment. For the control of medical robot, the master requirement is stability. Through experiments, we get that the actual error fluctuates within a certain range. The robust control algorithm just meets our requirements for the controller. Modern robust control includes three master methods: sliding mode, high gain and high frequency. The three methods have different characteristics, but the master idea is to add a compensation term to the input to eliminate the bounded uncertainty. Three different ways have different characteristics, the sliding mode method with minimum steady-state error, but the convergence speed is slow, high gain method has fast convergence speed and smaller steady-state error, high frequency method in convergence speed and steady-state error has no obvious advantages, its advantage lies in the need of instantaneous input is small [9]. Compared with three different kinds of robust control, considering that the system requires high real-time performance, we choose the way of high gain with the fastest convergence speed.

First we set the error function:

$$r = x_d - x \quad (4)$$

r is the error of conduit displacement, x_d is the reference displacement and x is the actual displacement.

According to the results of previous experiments, we found that the uncertainty of the system would take a bounded form:

$$f(x) \le \rho \quad (5)$$

Take the derivative of equation (4) and substitute the equation of state in equation (1) into:

$$\dot{r} = \dot{x}_d - \dot{x} = \dot{x}_d - f(x) - Bu \quad (6)$$

$$\text{Let } Bu = \dot{x}_d + kr + \frac{1}{\theta}\rho^2 r, \theta > 0$$

Through lyapunov function method [6] to verify whether the system is stable after adding new input, we introduce lyapunov function:

$$v = \frac{1}{2} r^2 \quad (7)$$

The lyapunov function is positive definite. To determine the stability of the system, we need to prove that it is semi-negative definite [10]. The derivative of equation (7) can be obtained:

$$\dot{v} = r\dot{r} = r\left(\dot{x}_d - \dot{x}\right) \quad (8)$$

Substitute equation (5) into equation (7):

$$\dot{v} = r[\dot{x}_d - f(x) - \dot{x}_d - kr - \frac{1}{\theta}\rho^2 r] = -rf(x) - kr^2 - \frac{1}{\theta}\rho^2 r \quad (9)$$

$$\dot{v} \le \rho|r| - kr^2 - \frac{1}{\theta}\rho^2|r|^2 = -ke^2 + \rho|r|(1 - \frac{1}{\theta}\rho|r|) \quad (10)$$

Formula (10) has two situations:

Case1： $\rho|r| > \theta$

$$\text{so}\; 1 - \frac{1}{\theta}\rho|r| < 0,\; \dot{v} \le -kr^2 \quad (11)$$

To solve the differential equation of equation (11), we will introduce s(t)＞0 and substitute equation (7) into equation (11) to obtain:

$$\dot{v} + 2kv = -s(t) \quad (12)$$

The general solution of the differential equation (12) is:

$$v(t) = v(0)\exp(-2kt) - \exp(-2kt)\int_0^t \exp(2k\tau)s(\tau)d(\tau) \quad (13)$$

$$v(t) \le v(0)\exp(-2kt) \quad (14)$$

Can be obtained through formula (13) and (14):

$$|e(t)| \le |e(0)|\exp(-kt) \quad (15)$$

Through the above proof, we can obtain that the system presents an exponential asymptotically stable state.

Case2： $\rho|r| \le \theta$

$\text{so}\; 1 \ge 1 - \frac{1}{\theta}\rho|r| \ge 0$,

Let's multiply both sides of this $\rho|\gamma|$

,get $\theta \ge \rho|r| \ge \rho|r|(1 - \frac{1}{\theta}\rho|r|)$ (17)

Through equations (17) and (7), we can obtain:

$$\dot{v} \le -2kv + \theta \quad (18)$$

We introduce the $q(t) > 0$,get $\dot{v} + 2kv = \theta - q(t)$ (19)

The general solution of the differential equation and we get:

$$\frac{1}{2}r^2(t) \le \frac{1}{2}r^2(0)\exp(-2kt) + \frac{\theta}{2k}[1 - \exp(-2kt)] \quad (20)$$

By taking the square root of both sides of equation (20), we can get:

$$|r(t)| \le \sqrt{|r(0)|\exp(-2kt) + \frac{\theta}{k} - \frac{\theta}{k}\exp(-2kt)} \quad (21)$$

State of the system is globally uniformly ultimately bounded [12].

IV. EXPERIMENTS

In order to evaluate the control performance of the robust control algorithm for the platform, this section describes adding the robust controller of the previous section to the existing experimental platform. In this paper, the platform as shown in Fig.3 was used for experiment. We used NDI to collect displacement data. NDI's camera was going to collect the position information of two rigid bodies. After that, the displacement of the master side and slave side is compared and the error of the master and slave end was calculated. The test platform uses a catheter with a diameter of 5.0f and a length of 140mm. In order to minimize the cumulative error generated by the driving part , the platform uses a stepping motor to drive the catheter for displacement. Because of the characteristics of the vascular interventional surgical robot, we will try our best to imitate the way doctors operate in the actual operation [11]. In the experiment, we will not use continuous propulsion, but a method of segmenting propulsion with short intervals. The sampling time is one minute and the sampling interval is 0.001s. In order to compare the error, we will compare the error value after adding the algorithm with the error value without adding the algorithm, and calculate the corresponding maximum value and average value for comparison.

Fig.4 Master slave displacement experiment

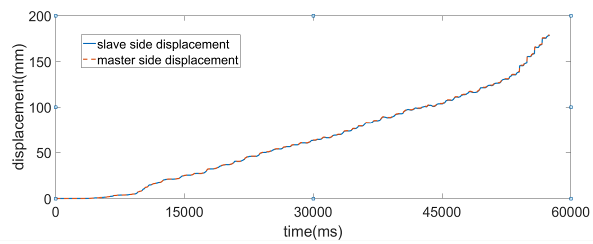


Fig.4 Master-slave displacement before modifiability

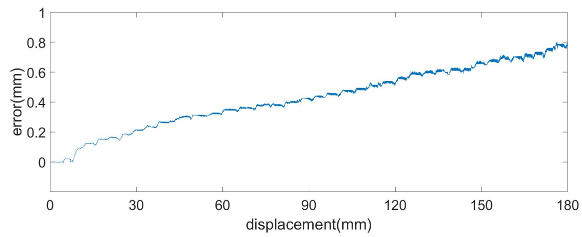


Fig.5 The error before modifiability

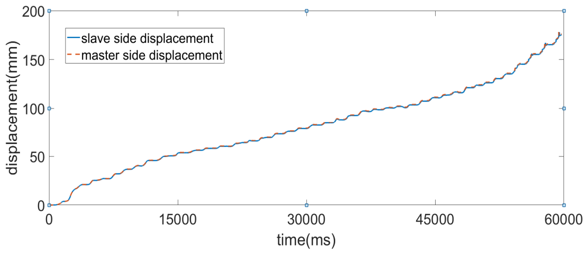


Fig.6 Master-slave displacement after modifiability

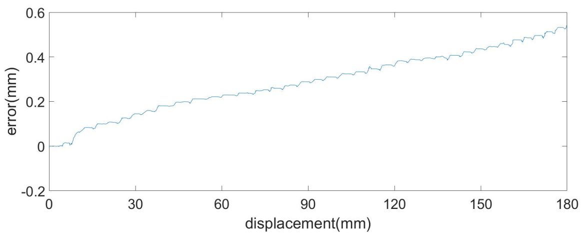


Fig.7 The error after modifiability

V. Results And Analysis

We can find that the stepper motor is used to avoid the cumulative error of the driving part, the data in the Fig 4 shows that the cumulative error of the mechanical transmission part still exists [13]. The error still shows a trend of increasing gradually. This kind of accumulated error is undoubtedly fatal in the vascular interventional robot which requires high control accuracy. We see from the chart [3], is pushed by piecewise experiment, in advance to stop the interval of time, error have no change, by looking at Fig.2 and Fig.3 of jitter, we found that the two images of jitter is approximately the same size, figure error in the interval of carrying forward the jitter mainly comes from the instrument measuring inaccuracy . Fig.4 and Fig.6 are the displacement tracking curves obtained from the experiment. According to the experimental results, the error curves of Fig.5 and Fig.7 are obtained . By comparing Fig.5 and Fig.7, it is obvious that after the robust controller is added, the error is obviously smaller and the trend of error accumulation is also decreasing. It indicates that the system maintains better performance after adding robust control algorithm under the same disturbance. [14]. In table I, we compare the maximum and average error before and after the addition of robust control. By comparing the average, we can see the average level of an error. By comparing the maximum, we can see the safety level of the vascular interventional surgical robot system. The thickness of the internal carotid artery wall is generally 8%-10% of its vascular diameter, while the vascular model diameter of some patients is 6mm. Did not add the robust controller maximum error is close to 1 mm, this for vascular interventional surgery was very dangerous, after add robust control, the biggest error in 0.5199 mm, according to references [14], we learned that the people of the artery wall thickness is 0.6 mm, and we get the maximum error is far less than the thickness of vessel wall, is our error in the range of security.

TABLE I
DATA COMPARISON BEFORE AND AFTER ALGORITHM ADDITION

	with algorithm	Without algorithm
Maximum（mm）	0.5199	0.7892
Average （mm）	0.3382	0.4656

VI. Conclusions and Future Work

This paper proposed a robust controller for vascular interventional surgical robot. By using this control algorithm, the vascular interventional surgical robot system could push the catheter into the blood vessel more accurately, safely and stably. Stability analysis was carried out by using lyapunov function method and experimental method, and the experimental results showed that the system with robust control algorithm had better performance . In the future work, we still need to further improve the rotary accuracy of the catheter and study the precision of the coordinated operation of the catheter guide wire.

VII. Acknowledgement

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

References

[1] Yan Zhao, Shuxiang Guo, Yuxin Wang, Jinxin Cui, Youchun Ma, Yuwen Zeng, Xinke Liu, Yuhua Jiang, Youxiang Li, Liwei Shi, Nan Xiao, “A CNNs-based Prototype Method of Unstructured Surgical State Perception and Navigation for an Endovascular Surgery Robot”, *Medical & Biological Engineering & Computing,* 2019.

[2] Y. Song, S. Guo, X. Yin, L. Zhang and Y. Wang, “Design and performance evaluation of a haptic interface based on MR fluids for endovascular tele-surgery,” *Microsystem Technologies,* DOI: 10.1007/s00542-017-3404-y, pp. 1-10, 2017.

[3] Yan Zhao, Shuxiang Guo, Nan Xiao, Yuxin Wang, Youxiang Li, Yuhua Jiang, “Operating Force Information On-line Acquisition of a Novel Slave Manipulator for Vascular Interventional Surgery”, *Biomedical Microdevices*, Vol.20, No.2, DOI:10.1007/s10544-018-0275-7, 2018

[4] Shuxiang Guo, Xiaojuan Cai, Baofeng Gao, “A Tensor-Mass Method-based Vascular Model and its Performance Evaluation for Interventional Surgery Virtual Reality Simulator”, *The International Journal of Medical Robotics and Computer Assisted Surgery*, Vol.14, No.6, DOI: 10.1002/rcs.1946, 2018

[5] Y. Zhao, S. Guo, N. Xiao, Y. Wang and Y. Li, “ Operating Force Information On-line Acquisition of a Novel Slave Manipulator for Vascular Interventional Surgery,” Biomedical Microdevices, Vol.20, No.33, DOI: 10.1007/s10 544-018-0275-7, 2018.

[6] Wang, LM ; Sun, LM ; Luo, WP “ Robust constrained iterative learning predictive fault-tolerant control of uncertain batch processes” *science china-information sciences*, nov 2019.

[7] X. Bao, S. Guo, N. Xiao, Y. Li, C. Yang, R. Shen, et al. “Operation evaluation in-human of a novel Remote-controlled vascular interventional robot,” *Biomed. Microdevices*, vol.20, no. 34, DOI:

[8] L. Zhang, S. Guo and H. Yu, “Performance evaluation of a strain-gauge force sensor for a haptic robot-assisted catheter operating system,” *Microsystem Technologies*, DOI: 10.1007/s00542-017-3380-2, pp. 1-10, 2017.

[9] H. Sang, C. Yang, F. Liu, J. Yun, G. Jin, F. Chen, “A zero phase adaptive fuzzy Kalman filter for physiological tremor suppression in

robotically assisted minimally invasive surgery," *Int. J. Med. Robotics Comput. Assist. Surg* , vol. 12, pp. 658-669, 2016.

[10] Y. Wang, S. Guo and T. Tamiya, "A virtual-reality simulator and force sensation combined catheter operation training system and its preliminary evaluation," *International Journal of Medical Robotics and Computer Assisted Surgery*, Vol.13, No.3, DOI: 10.1002/ rcs.1769, 2017.

[11] B. Taheri, D. Case, E. Richer, "Adaptive suppression of severe pathological tremor by torqueestimation method," *IEEE Transactions on Mechatronics*, vol. 20, no. 2, pp. 717-727, 2015.

[12] X. Cheng, Q. Song, X. Xie, L. Cheng, L. Wang, G. Bian, ZG. Hou, T.Huang, and P. Prasong, "A fast and stable guidewire model for minimally invasive vascular surgery based on Lagrange multipliers," in proceedings of 2017 *IEEE International Conference on Information Science & Technology*, pp. 109-114, 2017.

[13] H. Rafii-Tari, C. Payne, C. Bicknell, KW. Kwok, NJW. Cheshire, C. Riga, and GZ. Yang, "Objective Assessment of Endovascular Navigation Skills with Force Sensing," *Annals of Biomedical Engineering*, vol.45, no.5, pp. 1-13, 2017.

[14] Cheng Y, "Study of the Vascular Interventional Surgery Doctor's Training System based on Catheter Path Panning ", *Tianjin University of Technology*, 2018.