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A Novel Vascular Interventional Surgeon Training System with Cooperation between Catheter and Guidewire

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Abstract **- To meet the surgeon's needs for vascular interventional surgery, our team studied a training system based on virtual display technology to help Surgeon perform vascular interventional training. The system is mainly composed of a virtual environment and a master manipulator. In this paper, we proposed a vascular intervention training system with a novel master manipulator and a novel virtual training environment with cooperation between catheter and guidewire. An experiment was conducted to verify the axial tracking performance between virtual environment and master manipulator, the experimental results showed that the training system has a good axial tracking effect and can help surgeon improve training effect.**

Index Terms - Virtual Reality, Master Manipulator, Cooperation between catheter and guidewire, Axial Tracking.

I. INTRODUCTION

In recent years, cardiovascular and cerebrovascular diseases have become one of the serious diseases that seriously threaten human health. High prevalence, high disability and high mortality are characteristics of the disease, and the disease occurs mostly in middle-aged and elderly people. At present, the most direct and effective method for vascular diseases is minimally invasive vascular interventional surgery. Minimally invasive vascular intervention is a procedure in which the doctor inserts the catheter into the patient's blood vessel through the forward and backward movement of the catheter and rotation, and movement in the blood vessels until the patient's focus, to achieve the treatment of related diseases [1]. Compared with traditional surgery, minimally invasive vascular intervention surgery can significantly reduce patient's pain because of its advantages such as less injury, less pain, and faster postoperative recovery [2]. Therefore, the vascular interventional surgery is widely used to treat cardiovascular and cerebrovascular diseases, and the hospital demand for vascular intervention surgeons has increased year by year.

The surgical procedure for vascular interventional surgery is: First, the doctor advances the guidewire slowly along the patient's femoral artery incision. During this process, the doctor uses a continuous X-ray photograph to determine the position of the guidewire in the blood vessel. The entrance of the guidewire. Secondly, when the guide wire reaches the lesion site of the interventional patient, the doctor will slowly deliver the interventional catheter along the guide wire that has reached the designated position, until the catheter is sent to the patient's lesion, and the insertion is stopped. At the same time, the guide wire is slowly pulled out along the catheter. Finally, the doctor releases the stent along the catheter to dilate the narrow blood vessels or inject drugs along the catheter to dissolve the thrombus [3].

Through the vascular interventional surgery process display, it can be seen that the doctor performing the vascular intervention operation needs to have a very professional surgical operation skill, which requires a large number of surgical simulation operations for the newly graduated intern to obtain due to these factors [4]. Due to the influence of these factors, it becomes difficult to further widely apply vascular interventional surgery.

Traditional interventional surgery training relies mainly on donated corpses, human models, animal experiments and patients. The donated corpses are limited and limited by blood clotting time; The human body model cannot reflect the variability and diversity of the human body structure; The anatomy of the animal is different from that of the human body, and the training environment is not ideal. Training during the operation, because of the long-term stay in the radiation environment, the need to wear heavy lead clothing, will quickly consume the trainee's physical strength, resulting in increased risk of surgery. However, as the hospitals have increased the demand for vascular intervention surgeons, the disadvantages of traditional vascular interventional training have become more apparent.

Along with the development of robotics and virtual reality technology, some shortcomings of the implementation and training of vascular interventional surgery have been solved. Aiming at the impact of long-term radiation on the health of doctors during surgery, and the risk of surgery caused by wearing fatigued lead clothing for a long time to accelerate the fatigue of doctors, the master-slave vascular interventional robot assisted system has made great progress. Due to the development of virtual reality technology research, the training system based on this research is more and more realistic, and can effectively solve some of the problems mentioned earlier.

In 2015, Nung Rudarakanchana and his team of the London University of Technology in the UK proposed some current perspectives about virtual reality simulation for the

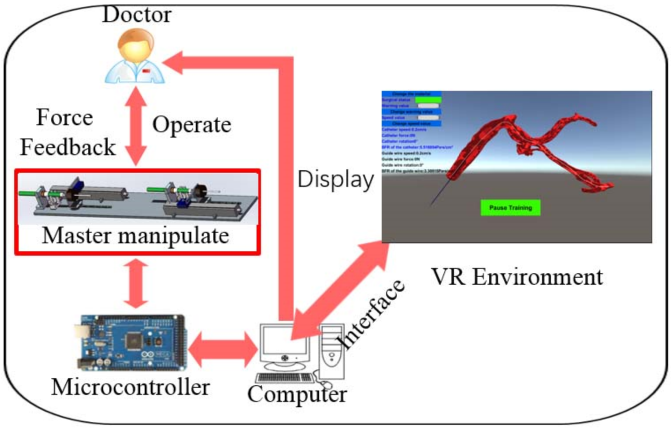


Fig.1 The concept diagram for training system

optimization of endovascular procedures [5]. In 2017, the University of Melbourne in Australia design and evaluation of a virtual reality simulation module for training advanced temporal bone surgery, and this system can effectively train doctors for sacral surgery [6]. In 2017, the team led by Professor Guo Shuxiang of Kagawa University in Japan designed an MR fluid device based on tactile interface for intravascular remote surgery, which can effectively achieve the impact force of the catheter in the blood vessel [7]. In 2017, the team of Beijing Institute of Technology in China proposed a tensor-mass method-based vascular model for interventional surgery virtual reality simulator [8]. In 2014, Shanghai Jiaotong University conducted a study on the interaction technique of virtual cardiovascular interventional surgery, which can effectively improve the training effect [9].

Under the impetus of these studies, the vascular interventional surgery training system based on VR technology has been greatly developed, and it also helps the promotion of vascular interventional surgery. Our team has been developing vascular interventional surgeon training systems based on virtual reality technology for many years, and has developed a variety of master manipulators for this system. This paper is divided into five parts. The first part introduces the progress of vascular interventional surgery and its research [10]. The second part is the training system research and design. The third part is the experiment and analysis of the training system, and the fourth part is the conclusion.

II. Overview of The Training System

A. System Overview

As shown in Figure 1, the complete training system is divided into two parts: the master side manipulator and the VR Environment.

VR-based vascular intervention surgeon training system. by using VR technology to simulate the operation of the surgery, the trainer can visually observe the operation of the operation through the display of the virtual environment interface, thereby performing a reasonable surgical simulation operation [11]. The motion information of the catheter and guide wire is sent through the serial port to the computer connected to the main controller. When the catheter model or the guide wire model and the blood vessel model collide in the VR, the generated collision force will be displayed in real time on the interface of the virtual environment, and sent to the primary controller through the serial port of the computer, and the primary controller drives the primary manipulator The force feedback device allows the trainer to feel the actual feedback .

B. Over View of the master manipulator

Number footnotes separately in superscripts. Place the actual footnote at the bottom of the column in which it was cited. Do not put footnotes in the reference list. Use letters for table footnotes (see Table I). *IEEE Transactions* no longer use a journal prefix before the volume number. For example, use "*IEEE Trans. Magn.*, vol. 25," not "vol. MAG-25."

At present, many training system main manipulators use Phantom manipulator [12], Phantom has good force feedback effect, but because the operation mode does not meet the doctor's operating habits, the interventional surgeon's excellent vascular operation experience can not be used. In response to this situation, some teams began to study the main end-manipulator of vascular interventional surgery that complies with the interventional surgeon's operating habits [13]. After years of research on the master manipulator, we designed a master manipulator that complies with the operating habits of the interventional surgeon to simulate the operation of the catheter guidewire and to achieve force feedback through electromagnetic force. The design of the main manipulator is shown in Figure 2.

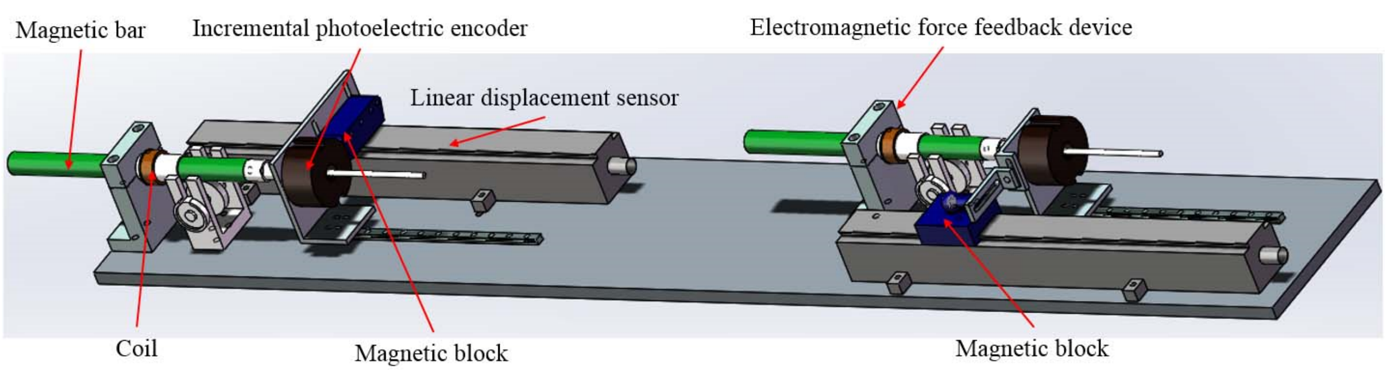


Fig.2 Overview of the master manipulator

The whole main end manipulator is 1000mm long. The front end and the rear end are respectively the catheter manipulator and the guide wire manipulator. The data acquisition principle and the force feedback mode are the same, and the linear displacement sensor and the push mechanism installation sequence and the magnetic block style are modified. Achieve a distinction.

The radial rotational displacement of the catheter and guidewire side is based on a light-increasing electrical encoder with a hollow shaft with a resolution of 2,500 lines. The axial displacement information is collected by Novetechnik's linear displacement sensor. In order to distinguish, the catheter part adopts the suspension magnetic block, and the guide wire part adopts the rail type magnetic block. The functions of the two are the same, and there are differences in the fixing manner. The linear slide adopts PNY linear slide rails with a total field of 200mm and features low friction. Although the accuracy of the linear displacement sensor is very high, it is a 0-10V analog output, and the Arduino Mega 2560 analog input voltage used by the master controller is 0-5V, which needs to be stepped down. After the processing, the output voltage has voltage fluctuations.

To eliminate the fluctuation, we use the Kalman Filter algorithm. Kalman Filtering algorithm is an algorithm that uses the linear system state equation to estimate the state of the system through input and output of the system. The Kalman Filter is capable of estimating the state of a dynamic system from a series of data in which measurement noise is present, given the known variance of the measurement. Simply put, the Kalman Filter is an optimized autoregressive data processing algorithm. For solving a large part of the problem, he is the best, the most efficient and even the most useful. Because it is easy to implement by computer programming, and can update and process the data collected in the field in real time, Kalman filtering is the most widely used filtering method at present, and has been well applied in many fields such as communication, navigation, guidance and control.

The Kalman filter can be divided into a time update equation and a measurement update equation, also known as prediction equations and correction equations. Time update equation: The state variable prior estimate and the error covariance prior estimate are estimated based on the state estimate at the previous moment.

$$\hat{X}_{\bar{k}} = A\hat{X}_{k-1} + BU_{k-1} \quad (1)$$

$$P_{\bar{k}} = AP_{k-1}A^T + Q \quad (2)$$

Measurement update equation: responsible for constructing improved a posteriori estimates by combining a priori estimates with new measured variables. Time update equations and measurement update equations.

Kalman filter state update equation:

$$K_k = \frac{P - H^T}{HP_kH^T + R} \quad (3)$$

$$\hat{X}_k = \hat{X}_{\bar{k}} + K_k(z_k - H\hat{X}_{\bar{k}}) \quad (4)$$

$$P_k = (I - K_kH)P_{\bar{k}} \quad (5)$$

Where $\hat{X}_{K-1}$ and $\hat{X}_K$ are the posterior state estimate value after k-1 and k, $\hat{X}_{\bar{K}}$ is the a priori estimate value at time k, Pk-1 and Pk are the posteriori estimation covariance at times k-1 and k, $P_{\bar{K}}$ is the priori estimate covariance at time k, H is the state variable to the observed transformation matrix, zk is the observation value, Kk is the filter gain matrix, A is the state transition matrix, Q is the process excitation noise covariance, R is the measurement noise covariance, B is the matrix that converts the input into state, ($z_K - H\hat{X}_{\bar{K}}$) is the actual observations and residuals of predicted observations.

The force feedback device is composed of a 200mm magnetic bar and a coil, and the force feedback is generated by the principle of Ampere. According to the Ampere force formula F=nBIL , when the magnetic induction intensity B the coil length and the number of turns of the coil are determined, Force feedback can be achieved by controlling the magnitude of the current to control the amperage [14]. The magnetic bar used in the force feedback device has a magnetic bar intensity of 6000 Gs, coil's length is 10 mm and coil's number of turns of 480.

C. *VR environment*

In the vascular interventional training system, in order to simulate the true effect of blood vessels, most teams use VR technology [15] and conduct various researches on vascular modeling [16] and tactile information feedback [17].

In this study, the virtual environment of the vascular intervention surgeon training system is developed using the game engine Unity 3D. The software supports multiple formats to facilitate the import of various 3D reconstructed vascular models. The underlying rendering supports Direct and OpenGL for better visual display. Support NVIDIA PhysX physics engine, which can simulate the physical characteristics of objects.

The vascular model in the training environment was analyzed using a brain medical CT image acquired by the Radiation Department of Kagawa University, Japan. A three-dimensional model of the brain blood vessel was obtained by Mimics three-dimensional reconstruction, and a vascular construction training system was intercepted [18]. The catheter and guide wire are hinged models made by 3Dmax, which are separately distinguished by making blue and green skins.

As shown in Fig. 3, the VR training system includes a position simulation of the catheter guide wire in the blood vessel, and the left side shows data such as the movement speed of the catheter guide wire during the training, the rotation angle, and the collision force of the touching blood vessel. The blood vessel in the figure is a partial interception of the model of the three-dimensional reconstruction of the brain blood vessels. The blue model is a catheter model of the hinge structure, and the light green model is a guide wire model of the hinge structure.

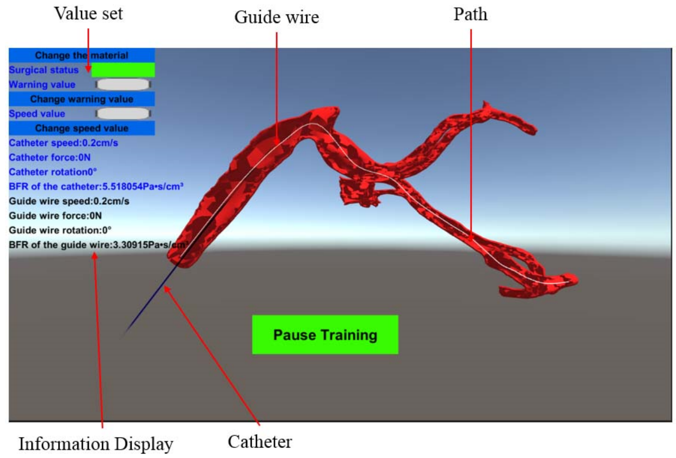


Fig.3 VR training environment

The white trajectory in the vessel model is the planned path. In the eyes before the lab, when you are doing virtual environment operations, the object information in the scene is known. Therefore, the three-dimensional object path planning problem in the virtual environment is mainly to obtain an optimal barrier-free path from the starting point to the ending point. In this system, we set the starting point of the path to the blood vessel entrance, set the next bend of the blood vessel as the end point, and so on until the final end point of the blood vessel. In this process, the blood vessel wall is regarded as an inaccessible obstacle [19].

When the catheter or guide wire moves along the path to the bend of the blood vessel, collision detection occurs when it touches the vessel wall. Here, the collision detection algorithm of the AABB axial bounding box is used. The collision detection algorithm can quickly detect the collision and achieve the real-time requirement of the system due to the simple calculation. When a collision is detected, a spring-damper force feedback model is used. Based on previous laboratory studies, we obtain a formula (6) for the collision force [20]:

$$F_{collision} = \frac{E \cdot S \cdot \Delta X}{X} \tag{6}$$

Where E is the elastic modulus of the blood vessel wall, S is the contact area of the catheter or guide wire with the blood vessel, X is the thickness of the blood vessel wall, and X is a vascular shape variable.

When the catheter or the guide wire collides with the blood vessel, the value of the collision force is displayed on the left side and sent to the main controller, and the main controller generates the ampere force to simulate the collision force according to the data driving force feedback device. When the collision force exceeds the set warning value, the left surgical state will change from green to yellow to remind the manipulator that when the force of the puncturing blood vessel is exceeded, the surgical state will change from yellow to red to indicate the surgical failure.

In the virtual reality training environment, we cut the blood vessel into 30 segments, each segment is approximately equivalent to a cylinder, and the blood flow resistance of the catheter and the guide wire in each segment is calculated by the Poiseu leaf formula and visualized on the screen. display. At the same time, through the Stokes theorem to the blood vessel viscous resistance simulation of the blood vessel part entering the catheter and the guide wire, and through the force feedback device of the master operator, the tactile feedback is generated, and the visual feedback is also performed on the interface [21].

When the virtual environment interacts with the host controller, because Unity 3D supports poor serial communication and also improves data processing speed, we use the window program developed by C#, which integrates TCP/IP server, serial communication, data processing and Database, which implements processing, storage, and transfer of data.

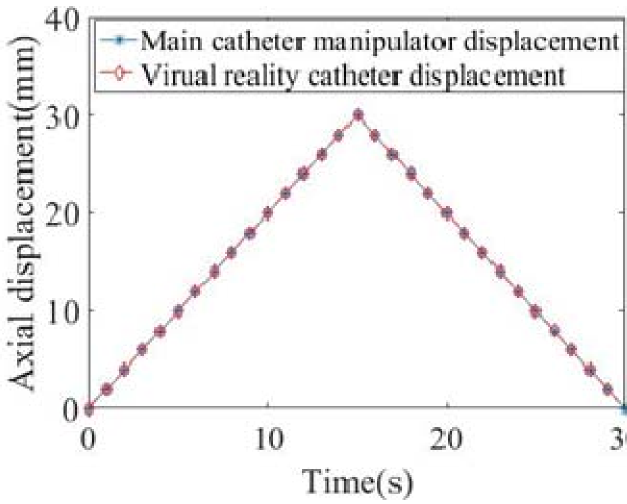
III. EXPERIMENTAL AND RESULTS

In order to verify the axial tracking effect of the virtual environment on the master manipulator, the catheter and guide wire axial position tracking experiments of the main-end operator were performed on the catheter and the guide wire in the virtual environment. The experimental setup is shown in Figure 4. The main end of the catheter and the guide wire operator displacement are collected by a laser range finder, and the main controller uses the Arduino.

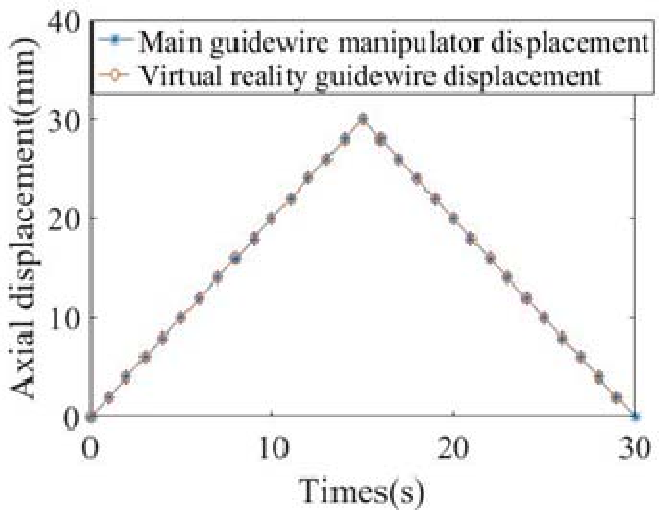
In the experiment, we firstly push the forward and backward movements of the catheter at the master manipulator at a constant speed. The motion displacement of the catheter is measured by a laser range finder, and the red diamond dotted line in Fig. 5(a) is obtained. The catheter in the virtual environment performs the tracking motion, and the catheter displacement data in the virtual reality data feedback is obtained through the relay program, and the blue star solid line in Fig. 5(a) is obtained.

Then we perform the same operation on the master guide wire manipulator, and the guide wire in the virtual environment performs tracking motion. The displacement of the guide wire measured by the laser range finder is shown by the red diamond-shaped dotted line in Fig. 5(b). The displacement of the guide wire in the virtual reality is shown by the solid line with blue star in Fig. 5(b).

Fig.4 Axial tracking experiment



(a) Catheter axial displacement tacking curve



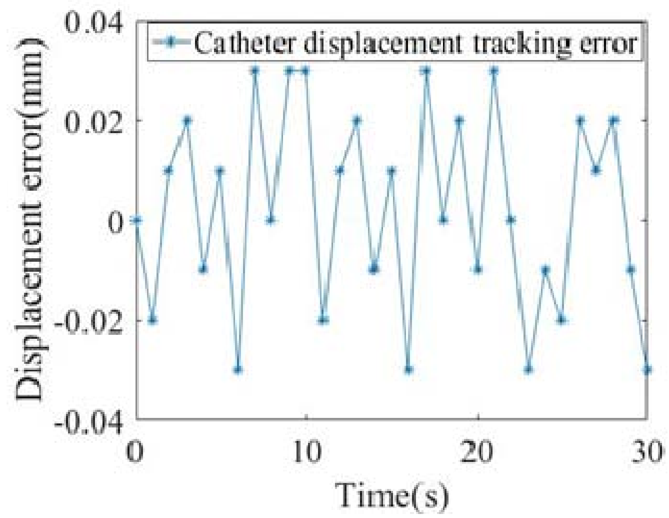
(b) Guide wire axial displacement tacking curve

Fig.5 Catheter and guide wire axial displacement tracking curve

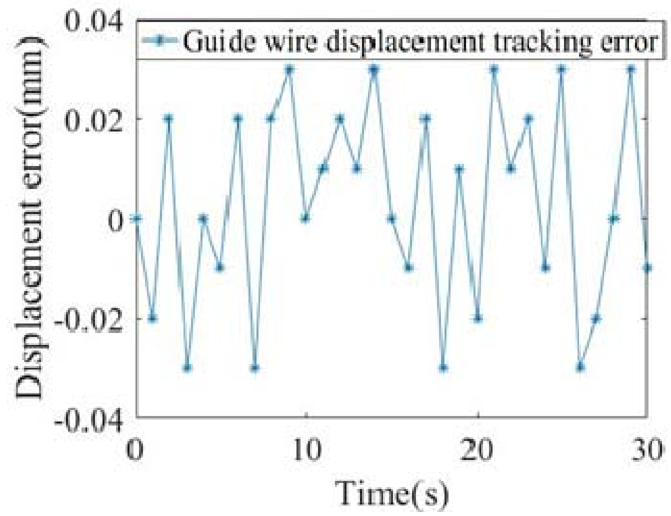
It can be seen from the displacement tracking curve of the catheter and the guide wire in the virtual environment in the figure that the catheter and the guide wire in the virtual environment have a very good tracking effect on the axial displacement of the catheter and the guide wire of the main end operator.

We conducted a more depth analysis of the axial motion tracking of the catheter and the guide wire, and obtained the displacement tracking error of the master catheter manipulator and the virtual environment catheter, and the displacement tracking error of the master guide wire manipulator and the virtual environment guide wire. These error curve is shown in Fig. 6(a) and Fig. 6(b). It can be seen from Fig. 6 that the maximum value of the axial tracking error of the catheter and the guide wire is not more than 0.03 mm, and the absolute error average is about 0.018 mm.

Through the previous axial displacement experiment, the error of the virtual environment tracking master manipulator is no more than 0.03mm. In the whole system, the movement of the virtual environment is mainly based on the data collected



(a) Catheter axial displacement tracking error curve



(b) Guide wire axial displacement tracking error curve

Fig.6 Catheter and guide wire axial displacement tracking curve

by the master manipulator, so this error is mainly due to Data error acquired by linear displacement sensor. After research, this error is mainly due to the linear displacement sensor voltage is 0-10V, we use the main terminal controller Arduino Mega 2560 can only accept 0-5V voltage, the linear displacement sensor voltage partial pressure processing, due to the voltage divider resistance accuracy, and the Kalman filter algorithm is used to eliminate the error of the linear displacement sensor data. The error is not high and the accuracy fully meets the requirements of system research.

The previously used master manipulator is connected to the photoelectric encoder by the transmission structure, and converts the displacement amount into the rotation amount of the photoelectric encoder. Here, the maximum error of the measurement is 2 mm due to the close cooperation between the photoelectric encoder and the main end. The error is around 1.24mm [22]. The error of the new master manipulator is much lower than the previous master.

IV. Conclusions and Future Work

This paper proposed a vascular interventional surgeon training system is compatible with the surgeon's operating habits. This system using a master manipulator and virtual reality technology that. Based on the previous virtual environment, the training system adds the operation of the guide wire and proposes the processing of the data, and integrates it into an external program. At the same time, the operation of the guide wire is controlled by various degrees of freedom, the detection and simulation of the collision force. The data shows that splitting into child threads runs in parallel, improving the response speed of the virtual environment. We also added the effect of blood flow on the viscous resistance of the catheter and guidewire. Compared with the previous master manipulator and training system, the new design main-end operator improves the axial displacement acquisition accuracy, and the virtual environment is more functional and the running speed is improved. Finally, an experiment was conducted to verify the axial tracking performance between virtual environment and mast manipulator， and the axial displacement tracking experiment showed that the system has good axial tracking performance and can help improve training effect.

In future work, we control the coil current change through the drive circuit to solve the magnetic rod center close to the magnetic rod center. Point-of-failure problems and magnetic deflection problems through the center point magnetic field.

Acknowledgment

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References

[1] X. Yang, H. Wang, Z. Xu Z. "Calibration and operation of a positioning robot used for minimally invasive vascular interventional surgery", Progress in Modern Biomedicine, pp.1-13, 2013.

[2] L. Zhang, S. Parrini, C. Freschi, V. Ferrari, S. Condino, M. Ferrari, D. Caramella"3D ultrasound centerline tracking of abdominal vessels for endovascular navigation", International journal of computer assisted radiology and surgery, vol. 9, no.1, pp.127-135, 2014.

[3] J. Guo, X. Jin, S. Guo, "Study of the Operational Safety of a Vascular Interventional Surgical Robotic System", Micromachines, vol. 9, no. 3, 2018.

[4] Y. Wang, S. Guo, Y. Li, T. Tamiya, Y. Song, "Design and evaluation of safety operation VR training system for robotic catheter surgery", Medical & Biological Engineering & Computing, vol.56, no.1, pp.25-35, 2017.

[5] N. Rudarakanchana, I. Van Herzeele, L. Desender, N. JW Cheshire. "Virtual reality simulation for the optimization of endovascular procedures: current perspectives", Vascular Health and Risk Management, pp.195-202, 2015.

[6] S. Wijewickrema, B. Copson, Y. Zhou, X. Ma, R. Briggs, J. Bailey, G. Kennedy, S. O'Leary. "Design and Evaluation of a Virtual Reality Simulation Module for Training Advanced Temporal Bone Surgery", IEEE International Symposium on Computer-based Medical Systems, pp.7-12, 2017.

[7] Y. Song, S. Guo, X. Yin, L. Zhang, Y. Wang, H. Hirata, H. Ishihara. "Design and performance evaluation of a haptic interface based on MR fluids for endovascular tele-surgery", Microsystem Technologies, pp.909-918, 2017.

[8] S. Guo, X. Cai, B. 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, 2018.

[9] J. Guo, Y. Gao, S. Guo, W. Zhang, Y. Wang. "Kinematics analysis of the catheter for a novel VR robotic catheter system", IEEE International Conference on Mechatronics and Automation. IEEE, 2014:1034-1039.

[10] J. Guo, S. Guo, Y. Yu, "Design and Characteristics Evaluation of a Novel Teleoperated Robotic Catheterization System with Force Feedback for Vascular Interventional Surgery", Biomedical Microdevices, vol.18, no.5, pp.1-16, 2016

[11] Y. Mo, B. Sinopoli. "Kalman filtering with Intermittent observations: Tail distribution and critical value", IEEE Transactions on Automatic Control, vol. 57, no. 3, pp. 677-689, 2012.

[12] X. Bao, S. Guo, N. Xiao, Y. Li, C. Yang, Y. Jiang, "A Cooperation of Catheters and Guidewires-based Novel Remote-Controlled Vascular Interventional Robot", Biomedical Microdevices, vol.20, no.1, 2018

[13] S. Guo, Y. Wang ,N. Xiao, Y. Li, Y. Jiang, "Study on Real-time Force Feedback with a Master-slave Interventional Surgical Robotic System", Biomedical Microdevices, vol.20, no.2, 2018

[14] Y. Yu. "Design and Evaluation of a Novel Force Feedback-based Master Manipulator for the Robot-assisted Vascular Interventional Surgery System", Tianjin University of Technology, 2017.

[15] Y. Wang, S. Guo, B. Gao, "Vascular Elastcity Determined Mass-spring Model for Virtual Reality Simulators" International Journal of Mechatronics and Automation, vol.5, no.1, pp1-10, 2015.

[16] Y. Wang, S. Guo, T. Tamiya, H. Hirata, H. Ishihara, "A Blood Vessel Deformation Model Based Virtual-reality Simulator for the Robotic Catheter Operating System" Neuroscience and Biomedical Engineering, vol.2, no.3, pp.126-131, 2015.

[17] Y. Wang, S., T. Tamiya, H. Hirata, H. Ishihara, X. Yin, "A virtual-reality simulator and force sensation combined catheter operation training system and its preliminary evaluation", The International Journal of Medical Robotics and Computer Assisted Surgery, vol.13, no.3, 2016.

[18] J. Guo, Y. Cheng, S. Guo. "Three-dimensional reconstruction of brain blood vessels and algorithm implementation", Journal of Harbin Engineering University, vol. 40, no. 4, pp. 1-6, 2019.

[19] Y. Cheng, "The vascular interventional surgery doctor's training system based on catheter path planning'', Tianjin University of Technology, 2018.

[20] S. Guo, L. Yan, J. Guo. "Force feedback-based robotic catheter training system for the vascular interventional surgery", International Conference on Mechatronics and Automation, pp. 2197-2202, 2016.

[21] S. Guo, Q. Zhan, J. Guo, C. Meng, X. Jin, "Vascular Environment Modeling and Verification for The Virtual Vessel Interventional Surgery Training System", International Conference on Mechatronics and Automation , pp. 1087-1092, 2018.

[22] L. Yan, "The vascular interventional surgery doctor's training system based on tactile telepresence", Tianjin University of Technology, 2017