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RESEARCH PAPER

Tracking Performance Evaluation of a Novel VR-based Robot-assisted Catheter System

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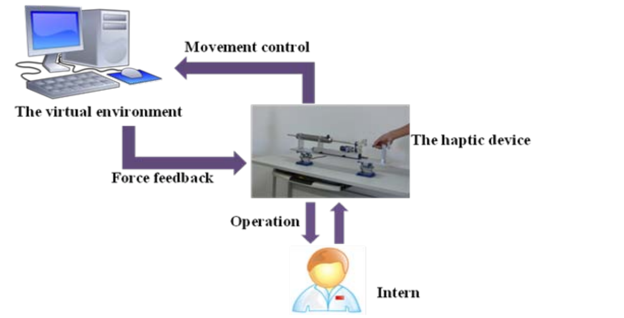
Abstract - This paper proposed a novel virtual reality (VR)-based robot-assisted catheter system which can be used to train the novice. The whole system is composed of the virtual environment and the master manipulator. The virtual environment including catheter model and vascular model is established using three-dimensional reconstruction method. A novel master manipulator which has high-precision motion information detecting unit has been designed and applied to the VR catheterization training system. The master manipulator can allow the surgeon operator the medical catheter directly to complete insertion or rotation motion, which can help surgeon to use the skills acquired in the traditional vascular interventional surgery (VIS). A damper based on magneto rheological fluid (MRF) is applied to the master manipulator to realize the tactile feedback. The tracking performance evaluation experiments have been done. The results indicated that the axial tracking error is lower than 0.2mm and the radial tracking error is lower than 3.6°. The results indicated that the synchronous tracking precision of the system is very high, which can meet our design requirement.

Keywords: Virtual reality (VR), Magneto rheological fluid (MRF), Synchronous tracking, Vascular interventional surgery (VIS), Tracking performance

I. INTRODUCTION

In recent years, vascular interventional surgery (VIS) has become more and more popular for the diagnosis and treatment of endovascular disease, such as aneurysm, infarction, embolization and so on [1]. Because it has many advantages, such as less incision, short hospital stay, less recovery time and so on [2]. And many diagnosis and medical surgery with a catheter or an endoscope are executed for minimum invasive surgery in recent years [3]. During endovascular catheterization the neurosurgeon inserts the catheter from femoral artery of a patient to diseased position. During catheterization it requires a surgeon who has good skills and experiences to operate catheter inside the body where direct observation is not possible. Especially cerebral aneurysm surgery, it is difficult for unskilled surgeons to insert the catheter to the diseased position safely in the case of that the blood vessels of brain are narrow and fragile. The Fig.1 shows the diagram of the VR-based robotic catheter system, the neurosurgeon operates the master manipulator to control the motion (including axial motion and radial motion) of catheter in VR environment, when the catheter contacts to the blood vessel in VR environment, the feedback force can be transmitted to the master manipulator which is a haptic device, then neurosurgeon can feel the feedback force through catheter connected with master manipulator, base on the force feedback, the neurosurgeon decide to insert or rotate catheter so as to enhance the safety during VIS.

Fig.1 The diagram of the VR-based robotic catheter system



Many relative researches and products for the VIS have been done. And these virtual reality systems can help to train the unskilled surgeons and provide objective assessment for laparoscopic cholecystectomy and stenting of the carotid artery [4]. And there are a lot of outstanding achievements among them. One of those influential researches is a robotic catheter placement system called Sensei Robotic Catheter System designed by Hansen Medical. This system can provide the surgeon higher stability and more accurate force in the progress of catheter placement. This system improves manipulation precision and reduces radiation exposure to the surgeon. Arizona State University proposed a training system for orthopedic drill bone surgery. The system aims to provide high precision location and force information. And this system has passed the validation of senior doctors [5]. Mr Hu et al have presented a virtual reality simulator for training with force feedback in minimally invasive surgery which allows generating realistic physical-based model of catheter and blood vessels, and enables surgeons to touch, feel and manipulate virtual catheter inside vascular model through the same surgical operation mode used in actual VIS [6]. Sungmin Seung et al developed a tele-operation master-slave system for minimal invasive brain surgery [7]. Yili Fu et al proposed a master-slave catheterization system for positioning the steerable catheter [8]. Magneto rheological Fluid Damper is proposed and optimized [9]-[10]. In aforementioned researches it has no applications of MRF to VR-based robotic catheterization.

In order to solve aforementioned problems in relative researches and products, the robot-assisted catheter system for the VIS has been proposed, it can be used to train the unskilled surgeons, and meanwhile, it can solve the problem that the skilled neurosurgeons are lack.

This paper proposed a novel VR-based robot-assisted catheter system which can be used to train the novice. The whole system is composed of the virtual environment and the master manipulator which is a haptic device. And the virtual environment including catheter model and vascular model is established using three-dimensional reconstruction method. We have done experiments of the synchronous tracking both axial motion and radial motion, the experimental results indicated that the synchronous tracking precision of the system is very high, which can meet our design requirement.

This paper is organized as following: the part two is an introduction of the VR-based robotic catheterization system, part three is the experiments and results, and the experiments of the synchronous tracking both axial motion and radial motion have been done. Part four concludes the paper. Part five is acknowledgements.

II. THE VR-BASED ROBOTIC CATHETERIZATION SYSTEM

A. The VR-based robotic catheterization system

Our research team has been proposed and designed the robotic catheter system in previous study [11]-[14]. Fig.2 shows the VR-based robotic catheterization system, the VR-based robot-assisted catheter system mainly contains two parts: the virtual environment and the master manipulator. The surgeon operates the master manipulator which is shown in the Fig.2 on the master side to insert or rotate the catheter on the slide stage, as if the surgeon operates a catheter directly beside the patient. At the same time, the motion information (including axial motion and radial motion) of the catheter will be detected by the master controller on the master side and transmitted to the virtual reality environment. And furthermore, the catheter in the virtual reality environment will perform a synchronized movement with the catheter in the real environment. The surgeon can operate the catheter directly to execute insertion motion or rotation motion, which can help the surgeon use the skills acquired in the traditional interventional surgery. The motion information is gathered by DSP controller. The master manipulator uses a damper based on the MRF to realize the force feedback. The MRF can be used to realize force feedback for its advantages such as quick response and low power consumption. The force information in the virtual reality environment will be transmitted to the master manipulator and transmitted to surgeon's hand. And the controller will control the damper to generate a corresponding force to realize the force feedback. The operator can feel the feedback force actually through the medical catheter connected with master manipulator, and the surgeon can decide whether insert or rotate the catheter depending on the feedback force. The VR-based robot-assisted catheter system can be used to train the unskilled surgeons to improve their operant level so that it can improve the safety of the surgery. Fig.3 shows the functional block diagram of the whole VR-based catheterization training system, it indicates the relationship between operator and VR system, and furthermore, it gives the flow chart of the control information.

Fig.2 The VR-based robotic catheterization system

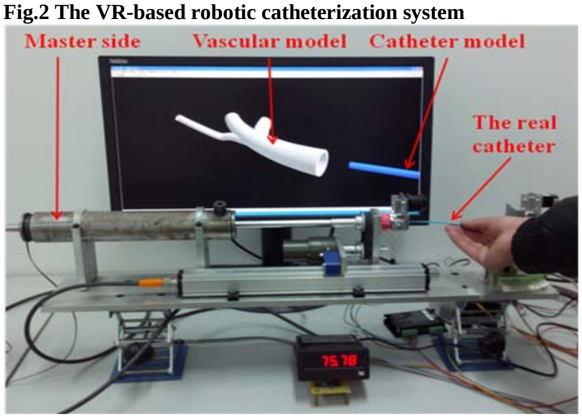
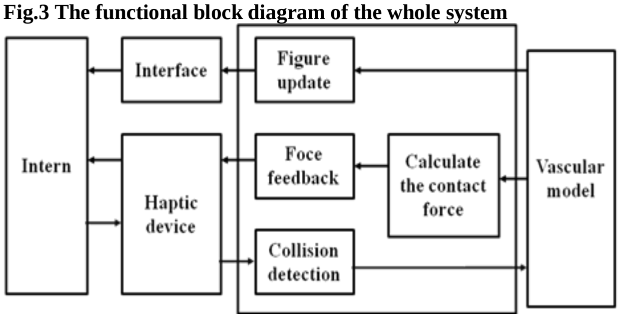


Fig.3 The functional block diagram of the whole system



B. The designed master manipulator

The master manipulator is used to collect the motion information of the catheter and realize the force feedback. Fig.4 shows the developed master manipulator connected with medical catheter which is operated by suegeon. The master manipulator consisted of two units: the motion information gathering unit and the force feedback unit. The motion information mainly contains the axial movement information and the radial movement information of the catheter. The axial movement information is detected by the linear displacement sensor. The linear displacement sensor adopts the magnetic induction principle to realize the displacement measurement. Therefore, there is no contact between the sliding block and the sensor, which can reduce the friction to increase the precision of the system. The sliding block of the linear displacement sensor and the piston rod of the damper are fixed together, which can guarantee the axial movement of the catheter is synchronous with the sliding block. Therefore, the linear displacement sensor can detect the axial motion information of the catheter accurately. The radial movement information of the catheter is detected by the photoelectric rotary encoder. The photoelectric rotary encoder is connected with the piston rod of the damper through a synchronous belt, which can guarantee the rotation motion of the catheter is synchronous with the photoelectric rotary encoder. The damper based on the MRF is used to realize the force feedback. The damper consists of a piston twined with the coil and an outer casing. A certain damping force will appear once a certain current flow through the coil when piston moving in the damper. According to the above principle, we can control the damping force though controlling the current flowing through the coil. And the intern will feel the feedback force through the master manipulator applying the MRF. The force feedback can improve the veracity of the training to the surgeon.

Fig.4 The novel manipulator based on MRF

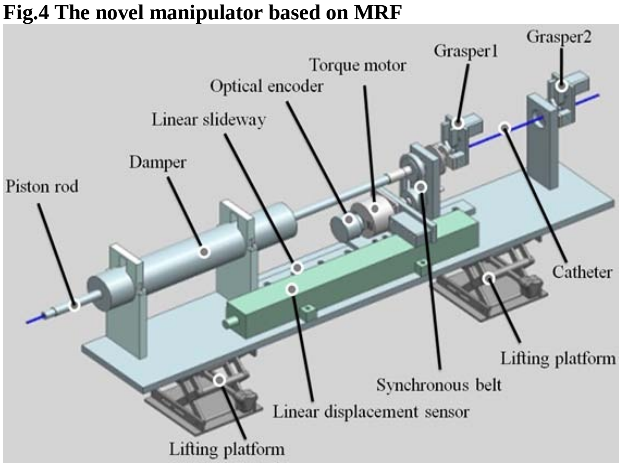
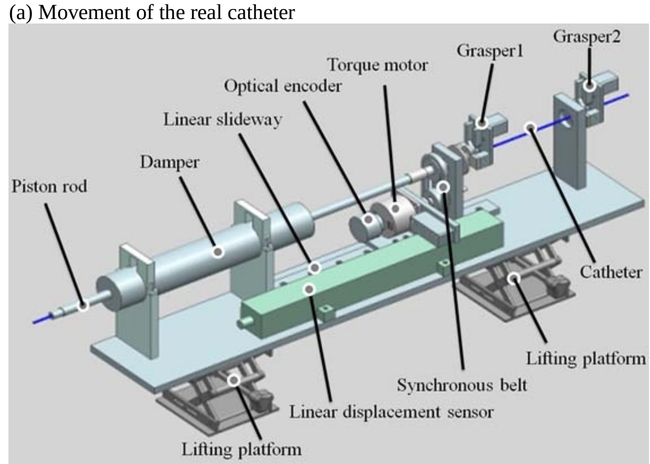
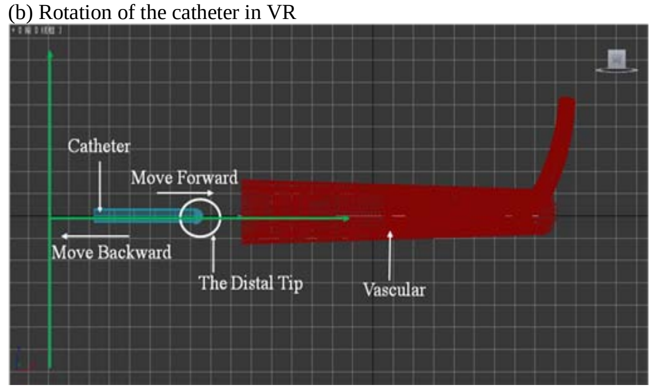


Fig.5 Movement along axial direction

(a) Movement of the real catheter



(b) Rotation of the catheter in VR



Ⅲ. EXPERIMENTS AND RESULTS

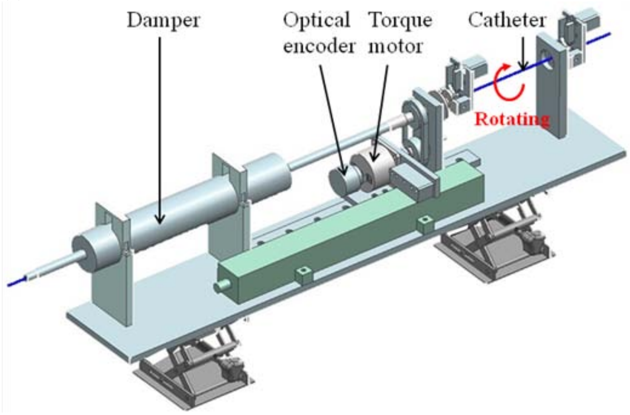
A. The experimental set up

The synchronous tracking precision of the VR robot-assisted catheter system has an important effect to improve the safety of the surgery. In this part, we will analyze the movement of the catheter. In real operation procedure, the motion of the catheter mainly contains two degrees of freedom. One is moving along the axis direction and another is rotating along the radial direction. Therefore, we will mainly detect the axial and the radial movement information of the catheter by the sensors.

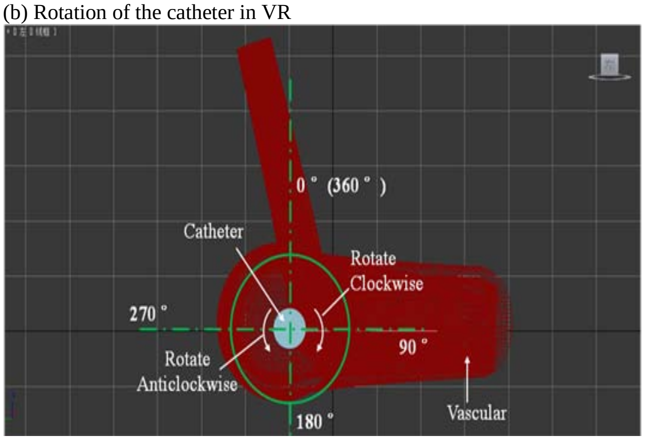
Fig.5 shows the movement along axial direction. The operator can clamp the catheter to insert the catheter. The catheter and the piston rod are fixed together while the linear displacement sensor and the piston rod are fixed together. So the movement of the catheter is synchronous with the linear displacement sensor. Therefore, the linear displacement sensor can detect the axial motion information. The detection precision of the linear displacement sensor is 0.01mm. The linear displacement sensor will detect the catheter position. Then, the DSP controller will transmit the position information to the VR system. Therefore, the catheter in the virtual reality environment will perform insertion when the operator inserts the catheter in the real environment. Furthermore, the surgeon can operate the real catheter to complete insertion, which can help the surgeon use the skills obtained in the conventional vascular interventional surgery.

Fig.6 Rotation along radial direction

(a) Rotation of the real catheter



(b) Rotation of the catheter in VR



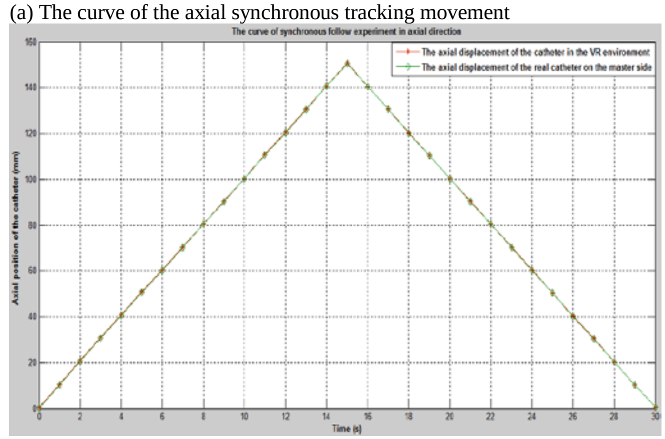
The Fig.6 shows the rotation motion of the catheter. The operator can hold the catheter to perform the rotation motion of the catheter. The catheter is connected with the piston rod while the pulley is fixed on the piston rod. Furthermore, the photoelectric rotary encoder is connected with the piston through the synchronous belt. So the radial movement of the catheter is synchronous with the photoelectric rotary encoder. Therefore, the photoelectric rotary encoder can detect the rotation information of the catheter. And the precision of the photoelectric rotary encoder is 0.036°. The DSP controller will collect the rotation information. Then it will transmit the information to the virtual reality system. And the application will realize the rotation motion of the catheter in the virtual reality environment, which can realize the synchronous rotation motion of the catheter between the virtual reality environment and the reality environment.

B. Experimental results

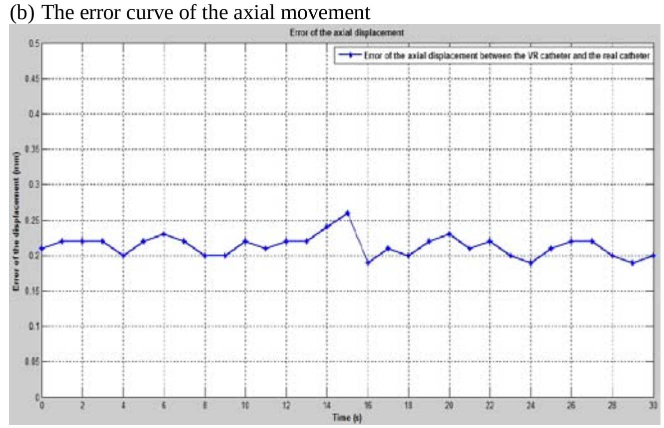
1) The axial direction

Fig.7 The experimental results of the axial insertion

(a) The curve of the axial synchronous tracking movement



(b) The error curve of the axial movement

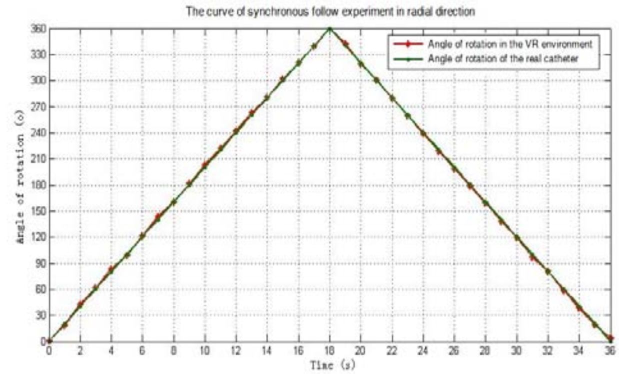


In order to analyze the axial synchronous tracking performance between real medical catheter connected with master manipulator and the catheter in VR environment, an axial movement experiment has been done. In the experiment, we recorded two aspects axial movement information: the real axial position information in the real environment detected by the linear displacement sensor and the axial position information of the virtual catheter in the virtual reality environment provided by the virtual reality software. The Fig.7 shows the results of the tracking experiment. The Fig.7 (a) is the axial synchronous tracking movement experimental results, and Fig.7 (b) is the error curve. From the figure we can see that the axial position error is lower than 0.2mm, and the error has relatively small fluctuations in the vicinity of 0.2 mm. The stability of the axial movement of the VR system is good. During the traditional VIS surgeon’s operating error using catheter in axial motion is more than o.2mm. So that the proposed VR-based robotic catheterization training can meet our design requirement.

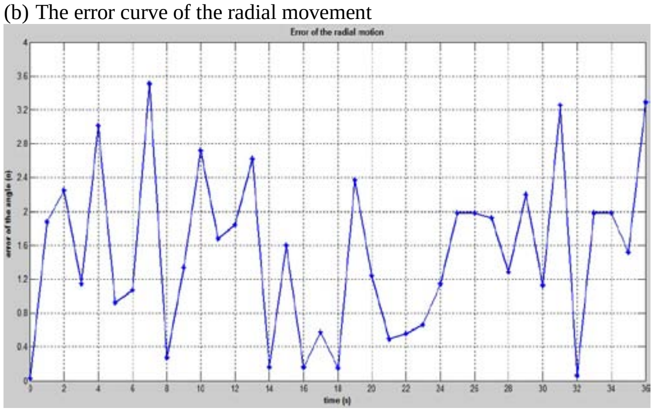
2) The radial direction

Fig.8 Experimental results of the radial rotation

(a) The curve of the synchronous tracking experiment in radial direction



(b) The error curve of the radial movement



A radial movement experiment was done for purpose of analyzing the radial synchronous tracking performance of the VR-based robotic catheterization training system. In the experiment, we recorded two aspects radial movement information: the real radial position information in the real environment detected by the photoelectric rotary encoder and the radial position information of the virtual catheter in the VR environment provided by the virtual reality software. And the results are shown in the Fig.8. The Fig.8 (a) shows the result of the radial synchronous tracking experiment, and Fig.8 (b) shows the error curve. As is shown in the Fig.8, we can see that the radial position error is lower than 3.6°, and the error large fluctuations compared with the axial movement, but the stability of the radial movement of the VR system is satisfactory. Because during the traditional VIS surgeon's operating error using catheter in radial motion is more than 5°. So that the proposed VR-based robotic catheterization training can meet our design requirement.

Ⅳ. CONCLUSIONS

In this paper, we proposed a novel VR-based robot-assisted catheter system. And we have a brief introduction of the novel VR-based robotic catheter system. We did the experiments to evaluate the synchronous tracking performances of the developed system, and the experimental results indicated that the developed system has a good synchronous tracking performance. The error of the axial synchronous tracking movement is lower than 0.2mm. Furthermore, the stability of the axial movement of the VR system is good. The error of the radial synchronous tracking movement is 3.6°. The results indicated that the synchronous tracking precision of the system is very high, which can meet our design requirement. In the future, we will use the novel VR system to train unskilled neurosurgeons and medical students.

Competing interests

The authors declare that they have no competing interests.

Author's contributions

Jian Guo
He completes the data processing and paper writing partly and paper modification.
Lin Shao
He completes experiments and the paper writing partly.
Shuxiang Guo
He completes the guidance of the paper.
Qiang Gao
He completes the guidance of the format of the paper.

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