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A Novel Master-slave Robotic System with Close Loop Control for Vascular Interventional Surgery

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Abstract - **Cardiovascular and cerebrovascular diseases have become the first threat of human health. With the development of interventional surgery, minor trauma, safety and high efficiency have become the focus of today's technological development. However, doctors are exposed to a large amount of X-ray radiation during surgery, which causes great damage to the doctors. So master-slave interventional surgical robot systems have developed rapidly. And the accuracy of the interventional robot directly determines the safety and reliability of the operation. Therefore, this paper designs a new type of slave device and control algorithm to improve the control accuracy of the interventional robot. This paper proposes a novel master-slave robotic system with close loop control for vascular interventional surgery. By adding a rotary encoder coaxial with the guide wire holder, it is used to detect the actual rotation angle of the guidewire and a linear position sensor fixedly connected with the guidewire clamper detects the axial displacement of the guide wire to form a closed-loop control to improve guidewire rotation and linear control accuracy. The results show that with the closed loop control of the guide wire, the average following error of the linear control of the guide wire is 0.912 mm, and the linear control average error is reduced by 63.96% compared to the system without feedback. The average following error of the rotation control is 1.311°, and the mean error of the rotation control is reduced by 43.47% compared to the non-feedback system. It indicates that the closed-loop control system has a good effect on improving the control accuracy of the surgery robot.**

Index Terms – Vascular interventional surgery; Surgery robot; Control accuracy; Closed-loop control.

I. INTRODUCTION

Vascular intervention surgery is widely used in many surgical procedures due to its advantages of less bleeding, less trauma, fewer complications, safety, reliability, and rapid postoperative recovery[1]. However, long-term exposure of doctors to x-rays, and wearing heavy lead clothing increases the burden on doctors, resulting in decreased efficiency of surgery and damage to the doctor's body. This year, robotic-assisted vascular interventional surgery robots have developed rapidly. Doctors can stay away from X-rays and reduce radiation damage by using interventional surgery robot system, and get rid of the shackles of lead clothing to increase the efficiency and stability of surgery

The master-slave interventional robot system has a master-side manipulator and a slave guide wire controller. Doctors can operate the manipulators of the master-slave control system in an environment far from X-rays[2]. The computer collects the operating information of the manipulators at the master-side. The computer converts the master motion information into control instructions and sends it to the slave controller, which controls the movement of the slave guidewire. There are several representative VIS robotic systems such as the Sensei Robotic Catheter System and Artisan Extend Control Catheter by Hansen Medical [3]. The CorPath GRX System by coth lab[4]. Remote navigation catheter system called Amigo by Catheter Robotic Inc.[5]. Remote Magnetic Navigation system called the Stereotaxis Niobe by Stereotaxis Inc. [6]. Shuxiang Guo et al. [7] put forward a new kind of vascular intervention assisted robot control system, the system uses master-slave operation and remote operation can be achieved. Yu Song et al. [8] developed a force feedback-based vascular interventional robot based on MR fluids. Jian Guo et al. [9] detect the catheter distal force and a real-time force feedback device is proposed according to the principle of damping between a permanent magnet and a coil. Xuanchun Yin [10] et al. firstly introduced an operator-centered human-computer interaction design concept using MR fluids to create semi-active tactile feedback. Jin Guo [11] presented a catheter sensing unit for measuring the movement of a catheter and a force feedback unit for providing a sense of resistance. Yan Zhao put forward a novel way of detecting the slave manipulator operating force information[12]. Linshuai Zhang et al. developed a strain-based force detection device[13] and a novel clamping mechanism based on the electromagnetic braking for a catheter manipulator[14] used for the slave side of the haptic robot assisted vascular interventional surgery system. Xuanchun Yin et al. [15] proposed a remote force feedback catheter operating system based on MR fluids. Yu Wang et al. [16] developed a doctor-based operation training system based on virtual reality to provide convenience for novice doctors. Jin Guo et al. [17] proposed a new master-slave interventional surgical robot system with force feedback and a visual inspection system for force. Jian Guo et al. [18] proposed a new interventional surgery safety early warning system to improve the safety and stability of surgery. Xianqiang Bao et al. [19] developed a new type of remote interventional robot

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based on catheter and guidewire cooperation. Yuan Wang et al. [20] introduces a catheter-operated surgical system for on-line detection of catheter insertion resistance

These vascular interventional surgical robots mostly use self-entrained encoders of screw motors and servo motors as closed-loop control. At this time, they ignore the transmission errors of the mechanical structure and the accumulated errors caused by the lack of control accuracy of the control system. Ma X et al. [21] introduce a master-slave interventional robot system, and the system does not detect the movement of the guide wire or calculate the influence of the system's transmission error and cumulative error. This control method affects the control accuracy of the vascular interventional surgery system, which is not conducive to surgical safety. Therefore, for an interventional robotic system, the actual motion of the guide wire needs to be used as a feedback of the closed loop control, rather than the feedback value of the encoder of the motor. It needs more research.

In this paper, a master-slave operating system based on closed-loop control with guidewire movement is proposed to improve the operation accuracy of the interventional robot. In section II, design of the proposed slave device and detailed introduction of closed-loop feedback algorithm is elaborated. In section III, the performance evaluation experiments are conducted and the result is discussed. In section IV, the research work is concluded and the future work is pointed out.

II. DESIGN OF THE CLOSED-LOOP CONTROL SYSTEM

A. Over view of catheter/guide-wire operation closed-loop feedback control system

In the interventional operation, the operation accuracy of the catheter and the guide wire has a great influence on the quality of the operation. Based on this consideration, the guide wire rotation accuracy and linear operation accuracy are very important factors. Minimizing the transmission error of the system, keeping the movement of the slave end consistent with the master-side operation is critical for surgery. This paper proposes a master-slave operating system based on closed-loop control with guidewire movement. In order to prevent the influence of mechanical transmission on the detection of the rotation and displacement of the guidewire, rotating detection device and guide wire rotate together and rigidly connected with the guidewire holder. The sensor for detecting the linearity of the guidewire is also rigidly connected with the guidewire holder.

Firstly, in terms of structure, the position information detected by the rotary encoder and the linear position sensor is consistent with the motion information of the guidewire. To prevent the effect of mechanical transmission errors on the detection of the rotation angle and the linear displacement of the guidewire. For the influence of the detection of the rotation angle and the linear displacement of the guide wire, the rotary encoder is fixed on one end of the guide wire holder to ensure that the rotary encoder and the guide wire holder perform a rotary motion.This structure avoids the influence of the gear gap on the rotation angle detection of the guide wire when the rotating gear is being driven. Ensure that the angle information detected by the rotary encoder is the actual motion information of the guidewire. At the same time, in the detection of the linear motion information of the guide wire, the linear position sensor is rigidly connected with the guidewire holder instead of detecting the linear motion displacement of the screw guide. The linear position sensor is performed along with the guide wire holder. At this time, the displacement data detected by the linear position sensor is the actual position information of the guide wire.

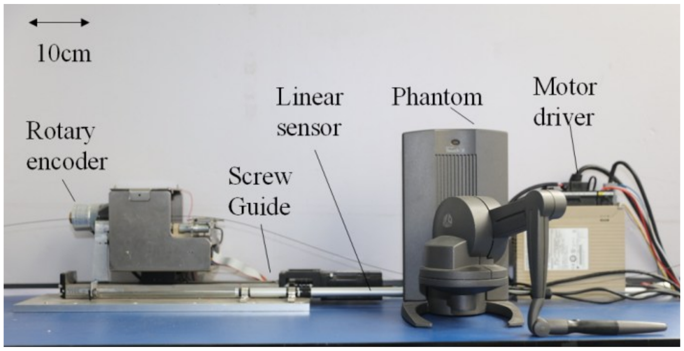


Fig. 1. Master-slave system structure

By fixing the rotary encoder and the linear position sensor on the end position of the guide wire drive, following the guide wire together, the guide wire movement detection error caused by the mechanical transmission error is avoided. The rotary encoder and the linear position sensor detect the motion information of the guide wire for closed-loop feedback. On the one hand, this closed-loop solution solves the transmission error of the system. On the other hand, this closed-loop control can solve the accuracy problem of the guidewire motion control and solve the system's cumulative error.

B. Closed-loop control principle

The master-side computer collects the position information of the phantom, converts the position information into control commands, and sends it to the slave ARM(Advanced RISC Machine) micro control system. The ARM micro control system receives the control command sent from the computer and sends pulse signals to the motor driver. The motor driver controls the voltage value of the motor according to the number of pulse signals sent by the ARM micro control system so as to control the rotation angle of the motor. The motor drives the guide wire holder to move through the transmission structure. The rotary encoder rotates along with the guide wire holder. The ARM micro control system collects the voltage signal of the rotary encoder, converts it into angle information and sends it to the master-side computer. The linear position sensor follows the guide wire holder and performs a linear motion. The Agilent digital multimeter collects the voltage signal from the linear position sensor and sends the voltage signal to the computer. The master-side computer sends control command to the ARM micro control system by comparing the posture information of the phantom with the data of the guidewire fed back from the digital multimeter and ARM micro control system.

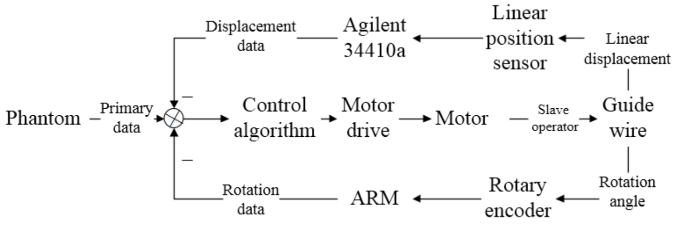


Fig. 2. Control flow chart

Through the closed-loop control to increase the accuracy of the guide wire movement control, the key issue is to check the precise and accuracy of the output value of the system. In terms of the rationality of the detection structure, as shown in Figure 1, the rotary encoder and the linear position sensor are connected to the motion terminals of the guide wire holder. In terms of test data accuracy, the pulse number of the rotary encoder is detected by the ARM micro control system. ARM micro control system detect the phase difference and level difference of the two-phase voltage generated by the rotary encoder. Each revolution of the rotary encoder, the ARM micro control system detect 10,000 pulses and the detection accuracy of the rotation angle is 0.036°. The voltage value of the linear position sensor is detected by the Agilent 6-bit half-digital multimeter. The output range of the linear sensor is 10V and the detection distance is 30cm. The digital multimeter's voltage detection accuracy is 0.1mv, so the detection accuracy of the linear displacement of the guidewire is 3μm. This accuracy is sufficient to meet the needs of interventional surgery.

C. *Closed-loop feedback algorithm*

The ARM micro control system sends to the master computer the two adjacent moments (T1, T2) (T1 before, T2 behind) of the actual rotation angle of the guide wire (BR1, BR2). The Agilent digital multimeter sends the master computer the actual straight line position of the guide wire (BZ1, BZ2). The master actor phantom sends the line position (AZ1, AZ2) and the rotation angle (AR1, AR2) to the master computer. When the slave movement speed is in a threshold interval (CR1, CR2) (CZ1, CZ2), that is, CR1<BR2-BR1<CR2, CZ1<BZ2-BZ1<CZ2. At this time, the control instruction received from the master computer is

$$p = K(A1-B1)*K+A2-A1 \tag{1}$$

The coefficient K depends on the speed of the guide wire at T2, and the speed of the guide wire is inversely proportional to the value of K. Through the closed-loop feedback of the attitude of the guide wire movement, the transmission error of the mechanical structure and cumulative error of insufficient system control accuracy will be reduced.

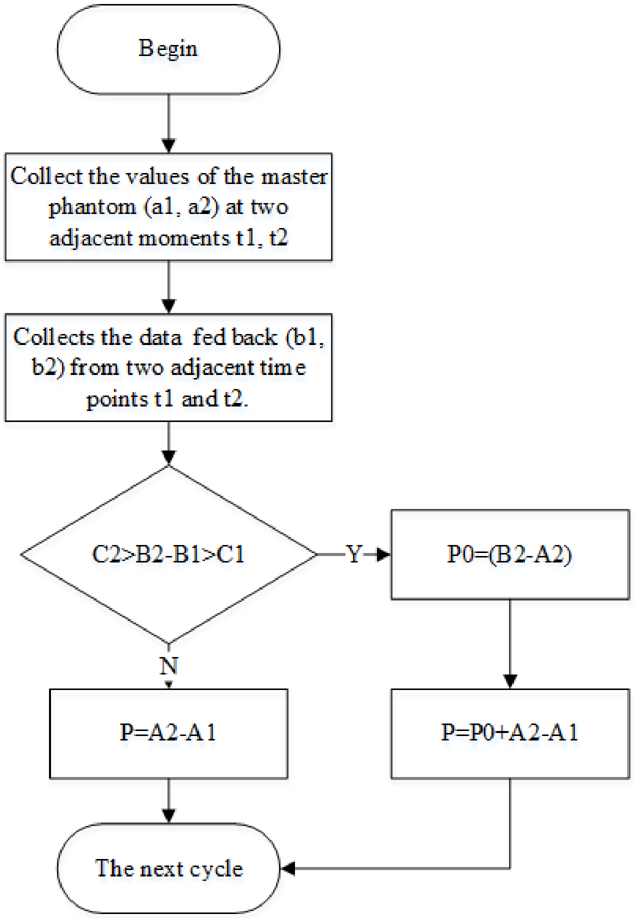
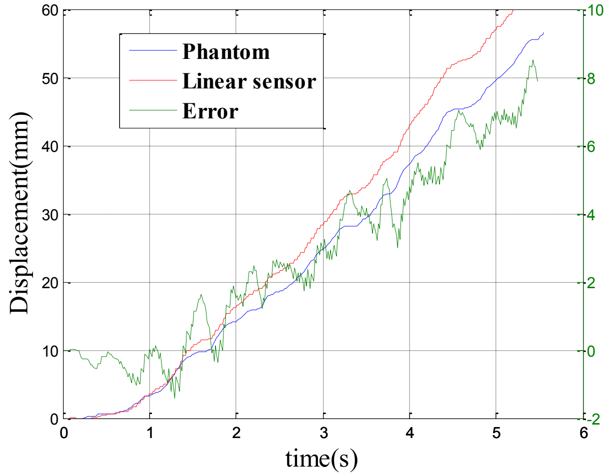


Fig. 3. Closed loop feedback algorithm flow chart

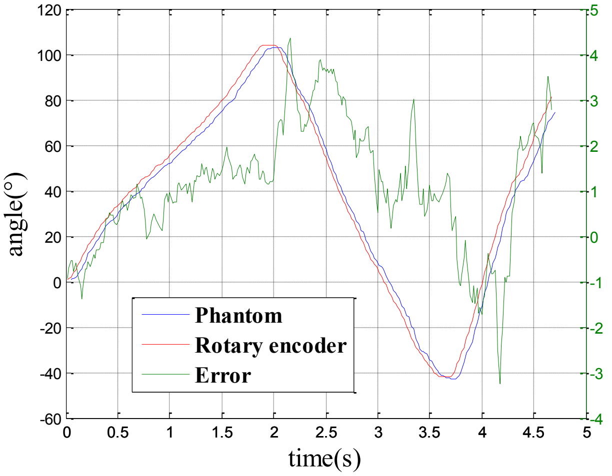
III. EXPERIMENTAL DETAILS AND RESULTS

In order to evaluate the performance of the designed catheter/guide wire axial displacement and rotation angle feedback device and the control algorithm, the phantom is used as the main end device of the interventional surgery robot to control the slave-side of the vascular interventional surgery robot system. The control accuracy of a closed-loop feedback system that does not include guidewire motion information is performed first. From the accuracy evaluation test experiment, the guidewire motion information is added to the control system to compare the performance of the closed loop system.

Figure 4 shows the control accuracy of a control system without guidewire motion feedback. It can be seen from the accuracy of the linear control that when the primary operator moves in one direction, the secondary guide wire also moves with the primary operator. However, it can be seen from the error graph that the error curve gradually increases with the increase of the number of samples, which indicates that the following error of the system gradually increases with the movement of the mater-side, mainly due to the accumulation of systematic errors in the master-slave control system. There

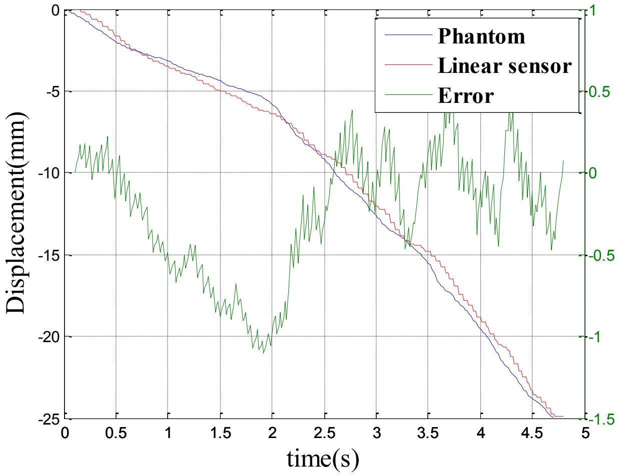


(a) Linear accuracy

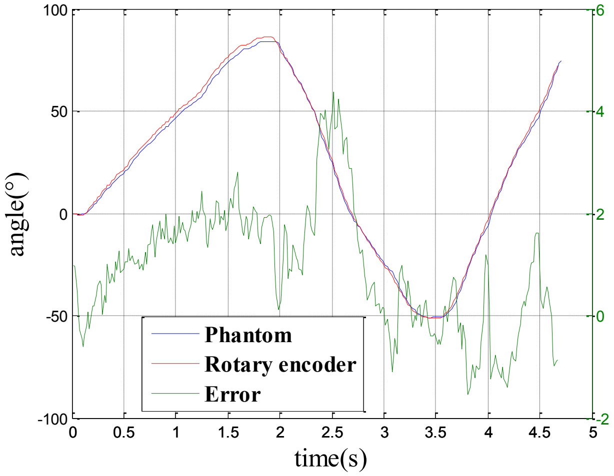


(b) Rotation accuracy

Fig. 4. Accurate experiment without guidewire motion feedback



(a) Linear accuracy



(b) Rotation accuracy

Fig. 5. Accurate experiment with guidewire motion feedback

TABLE I.
THE FOLLOWING ERROR OF THE SYSTEM WITHOUT GUIDEWIRE MOTION FEEDBACK AND WITH GUIDEWIRE MOTION FEEDBACK

	Without feedback	With feedback
Linear error(mm)	2.532	0.912
Angle error(°)	2.320	1.311

is error in the control accuracy between the master and the slave, this error will gradually increase with the movement of the master. At the same time, the transmission error of the slave structure will also increase the following error.

From the accurate experiment without guidewire motion feedback, it can be seen that the error curve is consistent with the movement trend of the main-end operator. This also shows that under the control system without guidewire motion feedback, the following error of the system change with the angle of the master-side movement. At the same time, it can be seen from the rotation accuracy experiment in Figure 4 that when the main phantom moves in the opposite direction, the following error of the system will suddenly increase. This is due to the transmission error caused by the transmission gap between gears.

Figure 5 shows that the error value does not increase with the displacement of the master-side operator in the control system with guidewire motion feedback. This is due to the addition of the slave guidewire motion feedback in the control system. It is because that the system will add an error correction command to the control command at the next control instruction, which can reduce the following error between master-side manipulator and the slave-side guidewire. In the rotation accuracy Accurate experiment with guidewire motion feedback , it can be seen that the error value does not follow the movement trend of the master-side manipulator, because the role of closed-loop feedback, so that the follow-up error is stable in a suitable range, and does not rotate with the master-side.

Ten sets of experiments are performed for each of the operation. Comparing the control accuracy without guidewire motion feedback and the control accuracy with guidewire motion feedback, the maximum value of the linear control error without feedback is 7.031mm, the mean value is 2.532mm of linear motion, and the maximum error of the feedback control system is 1.866mm, the mean value is 0.912mm. Xianqiang Bao and Shuxiang Guo et al. [22] put forward a master-slave interventional robot system. The maximum linear error of the catheter or guidewire tracking performance is 1.58mm. The clinical experiment is successfully conducted with their robot system. The error of this paper is in the same order of magnitude, so the accuracy of the proposed control system meets the clinical needs. The maximum value of the feedback error without control is 4.364°, the average error is 2.320°, the maximum value of the rotation control error with feedback is 4.290°, and the average error is 1.311°. The average error of the linear control is relative to the system without guidewire motion feedback was reduced by 63.96%, and the rotation accuracy was reduced by 43.47% compared to the system without guidewire motion feedback.

Ⅳ. CONCLUSIONS

This paper proposes a device and control system based on guidewire motion information. The structure of the whole device is compact and does not affect the movement of the guide wire in the experiment. A closed-loop feedback system is designed based on the guidewire motion. The experimental results show that the maximum value of the linear control error of the control system the control accuracy with guidewire motion feedback is 1.866 mm, the mean error is 0.912mm. The maximum value of the rotation control error with feedback is 4.290°, and the average error is 1.3117°. The average error of the linear control is relative to the system without guidewire motion feedback was reduced by 63.96% and the rotation accuracy was reduced by 43.47% compared to the system without guidewire motion feedback. This device and control system can meet the requirements of clinical surgery. According to the analysis above, the accuracy of the closed-loop feedback control of the entire device depends on the detection accuracy of the guide wire. Therefore, in the future work, a more accurate linear sensor and a more accurate rotary encoder can be used to improve the accuracy of the closed-loop feedback.

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