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Study on the Tracking Performance of the Vascular Interventional Surgical Robotic System Based on the Fuzzy-PID Controller

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***Abstract* - In recent years, minimally invasive interventional surgery with catheter as the important surgical instrument has been widely applied in the treatment of Cardio-Cerebrovascular disease for its small tranma, fast recovery and other many advantages in the world. But traditional intervention operation of cardiovascular disease still has many insufficient sections. the tools of operation have a poor operability, a high dependency to the doctor on the spot, and its auxiliary informations are not visualized and full-scale. At the moment of operation, The surgeons are exposed to X-ray threatening the surgeons health due to the depositing which lasts long. It is imperative to protect the surgeons from X-ray during VIS. With this system and the surgeon operates a real catheter on the master side, which can make full use of the natural catheter manipulation experience and skills obtained in conventional catheter operation. In this paper, we proposed fuzzy-PID controller to the vascular interventional surgical robotic system to solve the problem of tracking error from the slave to the master manipulator. We conducted master-slave tracking experiments to compare the performance of PID controller with fuzzy-PID controller. Experiments results showed that the fuzzy-PID controller can improve the tracking performance from the slave side to the master side and reduce the error. So the the fuzzy PID controller is suitable for the robot-assist catheter system.**

Index Terms - Minimally invasive interventional surgery. Location tracking. fuzzy control. stability.

I. Introduction

At present, cardiovascular diseases and cerebrovascular diseases have become the main threat to people's lives. They are characterized by high morbidity, high mortality, high disability rate, high recurrence rate and high cost of treatment. According to surveys, every year there are more than 16.7 million people around the world lost their lives for suffering from cardio-cerebral vascular diseases.

With the development of medical technology, Vascular Interventional Surgery (VIS) has become the most effective technique to treat vascular diseases, which is popular for the diagnosis and treatment of endovascular diseases [1]-[2]. It is a revolutionary surgical technique. Many diagnosis and medical surgery with an endoscope or a catheter are performed for the VIS [3]-[4], Because of its smaller incisions, less blood loss, decreased pain and quicker recovery, VIS has been widely adopted all over the world. Conventionally, VIS Surgeons cut an incision in the groin where a catheter is inserted, then control the catheter to the target that is under fluoroscopic guidance [5]-[6]. However, due to the narrowness and complexity of blood vessels, it is very difficult to operate a catheter which is inside the blood vessels. It is not only an extension of operating time, but also the fatigue of the operators and patients that causes the difficulty, which maybe increase the risk of the surgery. Moreover, in consideration of large number of patients who need to be treated, the problem of lacking the well-skilled doctors who can operate a catheter appropriately for the surgery is an imperative problem we need to solve. In addition, these doctors are always exposed to X-ray radiation. In order to solve these problems, an efficiency tele-surgery system should be adopted, which can assist the surgeon to operate the catheter interventional in a safe space [7].

In recent years, many research teams around the world have focused on the study of robotic catheter operation systems for vascular interventional surgery. Some other teleoperated force-reflecting systems have also been developed. These systems can realize provision of force feedback by using proximal force measurements [8]-[11]. On January 9, 2000, the United States Intuitive Surgical company successfully developed Davinei Da Vinci surgical robot, which is one of the commercial use of technology. And its design idea is through using minimally invasive methods to implement the complex surgery [12]. The UK imperial college proposed an insertion robot which can transmit catheter and implement force feedback [13]. And N.Zakaria et al used the ER (Electrorheological) fluid to realize force feedback. This system can avoid error during process of operation [14]

In this paper, some improvements have been made in the control of the slave side. The fuzzy-PID controller is added to the slave end part, which reduces the tracking error from the slave end to the master end, eliminates the chattering phenomenon and improves the stability of the system. The overall structure of the article is as follows: the first chapter is the introduction, the second chapter presents the overview of the system structure, the third chapter is the basic principles, the fourth chapter is the experiment and analysis of the results, the fifth chapter is the conclusion and future work.

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II. THE MASTER-SLAVE VASCULAR INTERVENTIONAL SURGICAL ROBOTIC SYSTEM

According to the current requirements of the vascular intervention system, we designed a set of vascular interventional robot assistance system, which can allow doctors to safe and efficient finish vascular intervention surgery operation, but also to train doctors, System components shown in Fig.1 and the master-slave intervention system shown in Fig.2.

The system is a master and slave system, and the operation of a blood vessel in the main side without a X- radiation environment. From the side of the scene image and the catheter tip contact force information can be feedback to the doctor by visual feedback in the form of the master manipulator can be operated by the doctor from the catheter operation force side real-time feedback to the doctor, the doctor is operating information collection into the main controller, the main controller after processing the information uploaded to the main the PC side PC. The main side of PC through LAN communication or Internet communication main side operation information from the host computer to the PC side, from the controller according to the operation information of PC from the side of the transfer to the operator from a control command, and then drive the operator from the catheter into the blood vessel, at the same time collecting feedback operation force of catheter. The IP camera is used to collect the operation spot image feedback to the operator, the matrix sensor tube is installed in the front side collision detection sensor and the catheter tip catheter wall and vascular wall contact force, the two sensor detects the force information in the main terminal PC to do the corresponding numerical and visual feedback to remind that the form is passed to the an operator.

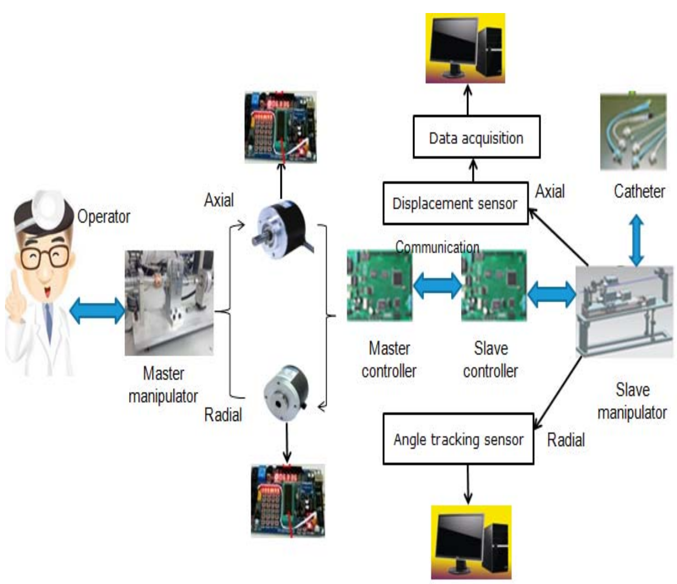

Fig.1 Master slave system operation diagram

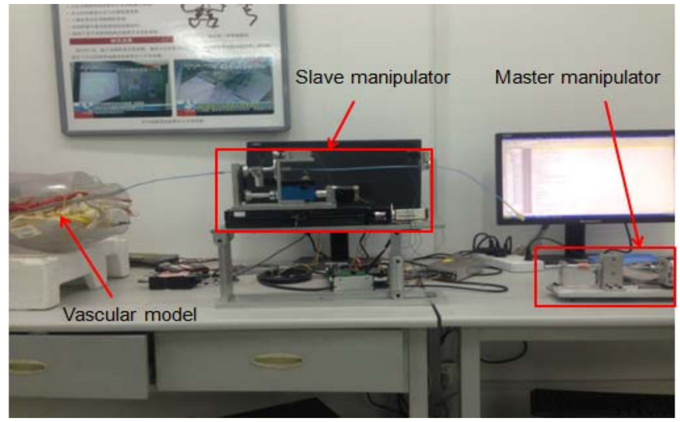

Fig.2 The master-slave vascular interventional surgical robotic system

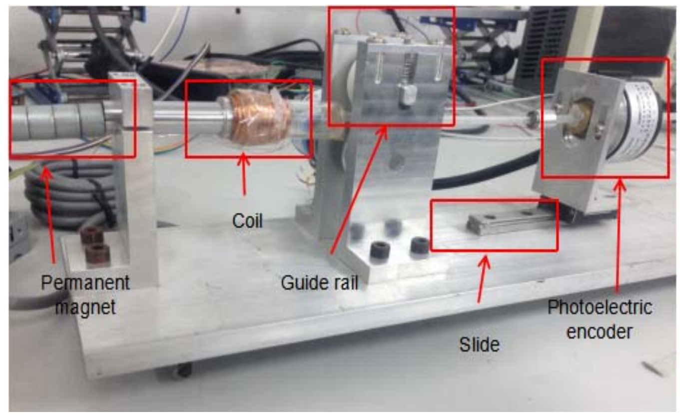

Fig.3 The master manipulator system

Fig.3 shows the master manipulator system developed by our team. Two hollow shaft photoelectric encoders are used to control the axial and radial motion. When the catheter is moving, the controller of the master collects the signal from the hollow shaft photoelectric encoder and passes it to the slave controller through the serial port. From the end of the controller, driven from the end of the catheter to do the corresponding movement. Thus, the purpose of master-slave control is achieved.

III. THE DESIGN OF THE FUZZY - PID CONTROLLER

A. The basic structure of fuzzy inference

The fuzzy inference system is composed of four parts including fuzzication, fuzzy reasoning, fuzzy rules and accuracy. The functions of each part are as follows:

1) Fuzzification: The precise quantity of input is transformed into fuzzy quantity, which is completed by fuzzy module.

2) Fuzzy Reasoning: According to the fuzzy rules, fuzzy inference is used to get the fuzzy output.

3) Accuracy: The fuzzy output obtained from the fuzzy inference can be transformed into an accurate digital quantity or analog quantity that can be accepted by the actual system.

4) Fuzzy Rules: Fuzzy rules as the basis of judging output are the core of the controller.

B. The fuzzy -PID controller

With the development of computer technology and the application of fuzzy control technology, the operating personnel to adjust PID parameters experience as knowledge inventory into computer, according to the actual situation of the scene, the computer automatically adjusts the PID parameters, so that the fuzzy -PID controller appears. This controller combines classical PID control with advanced fuzzy reasoning to realize the optimal control of the system.

The fuzzy -PID controller according to the error E and the error change De to determine the PID parameters of the experience expressed by fuzzy rules: In the actual control process, according to the real-time error E and the error variation De to carry on the fuzzy inference, in order to determine the PID parameter change, the parameter is passed to the PID controller. So the fuzzy -PID controller is based on the classical PID controller, and a fuzzy controller is used to adjust the three parameters of the PID controller. So the fuzzy -PID controller is based on the classical PID controller, plus a fuzzy inference device to adjust the three parameters of the PID controller. Fuzzy inference error E and error change De as input and the three parameters of PID controller KP,KI, KD as the output meet the different time due to the control object model changes on the PID control parameter self-tuning requirements. Using fuzzy rules and fuzzy inference to modify the PID parameters online will constitute a fuzzy -PID compound controller. Structure shown in Fig.5.

The PID parameter fuzzy adaptive adjustment is based on the fuzzy relationship between the three PID parameters and error E and the change of De, continuous E error detecting and error change De in the operation of the system, the best value to calculate the three parameters according to the principle of fuzzy reasoning, transferring to the PID controller on line modified to meet different error E and error change De case control parameters for different requirements, so that the control system has good control performance.

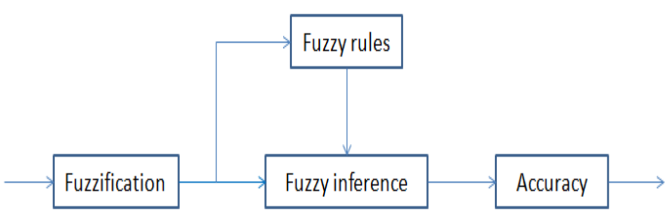

Fig. 4 The structure of fuzzy inference system

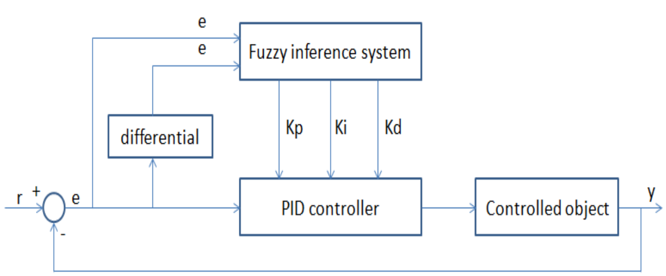

Fig.5 The structure of fuzzy -PID controller

C. References

a. Design of fuzzy controller

According to the working principle of the fuzzy -PID compound controller, e and EC taken as input, their fuzzy subsets are {NB, NM, NS, ZO, PS, PM, PB}, and the elements of the subset represent negative, big, negative, middle, negative, small, zero, small, middle and large.Its domain is [-3 3], and the quantization level is {-3, -2, -1,0,1,2,3}.Taking Kp, Ki and Kd as outputs, their fuzzy subsets are {ZO, PS, PM, PB}, and the elements in the subset represent zero, respectively, small, middle, and large.Its domain is [0 3], and the quantization level is {0,1,2,3}. The results are shown in Fig.5

b. Design of fuzzy controller

The tuning of PID parameters must take into account the effects of three parameters on the system performance at different times. According to the design experience of PID control system, the parameters of PID control system can be adjusted:

1) When the |e| is large, larger KP and smaller KD should be taken to speed up the system response and to avoid excessive overshoot of the ki=0.

2) When |e| is medium, the smaller KP and the appropriate KD should be taken to make the system have a smaller overshoot, and take the appropriate ki with a smaller static error.

3) when the |e| is small, a larger KP and Ki should be taken so that the system has good steady-state performance. Kd value should be appropriate to avoid the system in the vicinity of the equilibrium point of shock.

The two input variables are divided into 7 fuzzy subsets: NB, NM, NS, ZO, PS, PM and PB.The output is divided into 4 fuzzy subsets: ZO, PS, PM and PB. According to the rule of PID parameter adjustment, the fuzzy rules table for three parameters of KP, Ki and KD are set out in Table I, Table II, Table III.

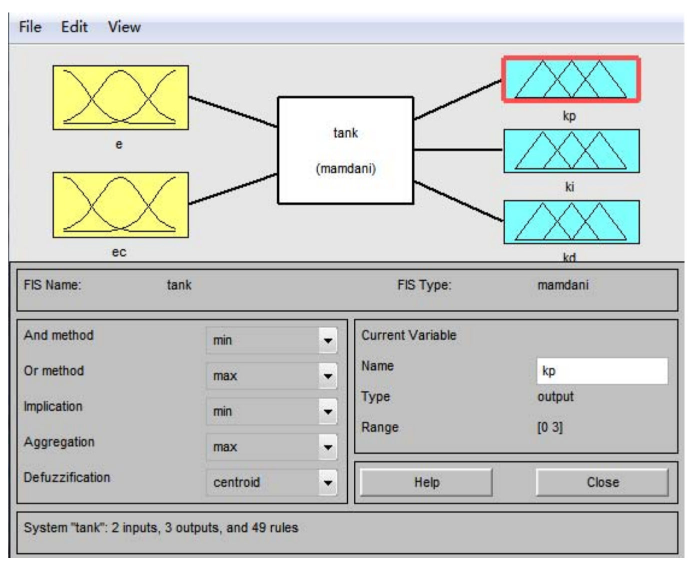

Fig.6 The new fuzzy inference system in the FIS Editor window

TABLE I
FUZZY RULES OF PARAMETER KP

kp		Ec						
		NB	NM	NS	ZO	PS	PM	PB
	NB	PB	PB	PM	PS	PM	PB	PB
	NM	PB	PB	PM	PS	PM	PB	PB
	NS	PB	PM	PS	ZO	PS	PM	PB
e	ZO	PB	PM	PS	ZO	PS	PM	PB
	PS	PB	PM	PS	ZO	PS	PM	PB
	PM	PB	PM	PM	PS	PM	PB	PB
	PB	PB	PM	PM	PS	PM	PB	PB

TABLE II
FUZZY RULES OF PARAMETER KI

ki		Ec						
		NB	NM	NS	ZO	PS	PM	PB
	NB	ZO	PS	PB	PB	PB	PS	ZO
	NM	ZO	PS	PB	PB	PB	PS	ZO
	NS	ZO	ZO	PM	PB	PM	ZO	ZO
e	ZO	ZO	ZO	PM	PB	PM	ZO	ZO
	PS	ZO	ZO	PM	PB	PM	ZO	ZO
	PM	ZO	PS	PB	PB	PB	PS	ZO
	PB	ZO	PS	PB	PB	PB	PS	ZO

TABLE III
FUZZY RULES OF PARAMETER KD

kd		Ec						
		NB	NM	NS	ZO	PS	PM	PB
	NB	PS	PS	PM	PB	PM	PS	PS
	NM	PS	PS	PM	PB	PM	PS	PS
	NS	PS	PM	PB	PB	PB	PM	PS
e	ZO	PS	PM	PB	PB	PB	PM	PS
	PS	PS	PM	PB	PB	PB	PM	PS
	PM	PS	PS	PM	PB	PM	PS	PS
	PB	PS	PS	PM	PB	PM	PS	PS

c. Simulation and results

The mathematical model of the simulation object transfer function is (1) ,whose fuzzy factors are Ke = 0.9 and Kec = 0.1. The solution fuzzy factors are K1 = 3, K2 = 1.2 and K3 = 0.01. The initial PID values are Kp = 4, Ki = 3 and Kd = 1.5.Sampling period is T = 0.01s .

$$G(S) = \frac{10}{2S^2 + 3S + 1}$$

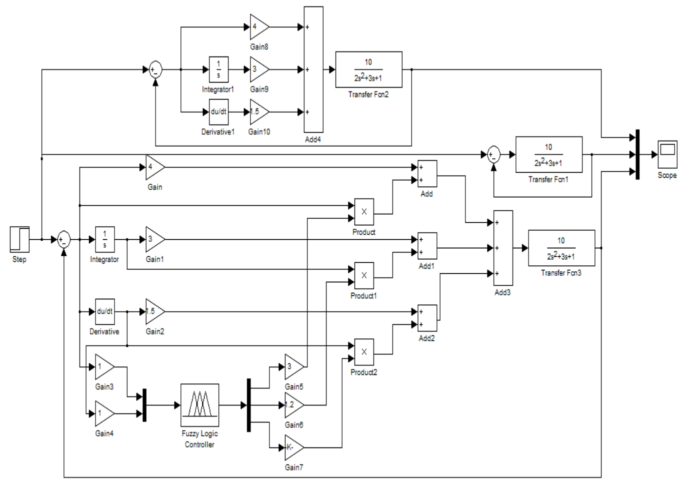

Fig.7 Simulation experiment diagram

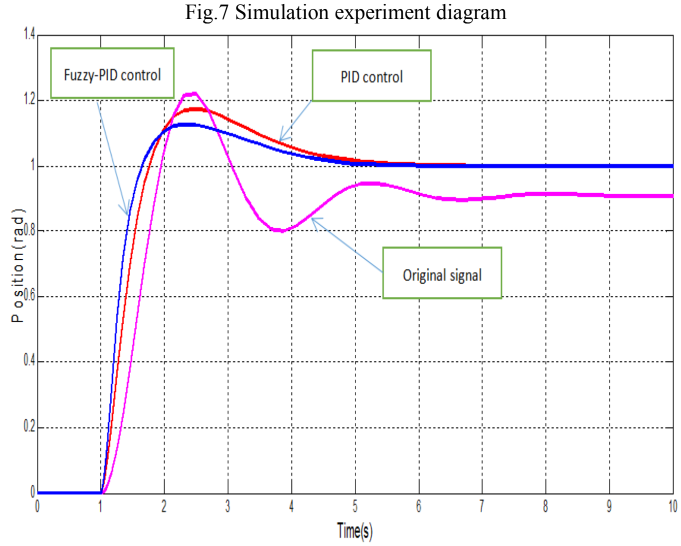

Fig.8 Original signal curve, conventional PID control curve and fuzzy PID control curve

As shown in Fig.8, the pink curve represents the original signal, blue curve represents the signal by the conventional PID controller and the red curve represents the signal by the fuzzy -PID controller adjusted curve. From the simulation results, we can see that under the original signal in the balance, there are a greater fluctuation and the conventional PID controller and fuzzy -PID composite controller can make the original signal to achieve a faster balance. When t=2.5s, the red curve fluctuation is small, which shows that the fuzzy -PID controller has smaller overshoot, and thus has better stability. In addition, the red curve in the t=5s achieve a balanced state, while the blue curve in t=6s to achieve a balanced state, indicating that the fuzzy -PID composite control can make the signal to achieve a faster balance.

To sum up, when an identical signal is passed by the conventional PID controller and the fuzzy -PID composite controller. Compared with the conventional PID controller, the fuzzy -PID controller has better stability, smaller overshoot and shorter balance time.

IV. EXPERIMENTS AND RESULTS

It is proved that fuzzy -PID composite controller improve the tracking performance from the slave controller to the master manipulator. First, we made five sets of master-slave tracking experiments. Fig.9 is the structure of the slave. Taking the left end of the slide rail as the reference, when the main end is forward or backward fixed value, the initial value and the final value of the sliding rail movement are read out through a ruler, and the moving distance is obtained.Curve of displacement from the slave to the master is shown in Fig.10.Error curve of master-slave tracking is show in Fig.11 and the average and variance of the displacement is show in Fig12.

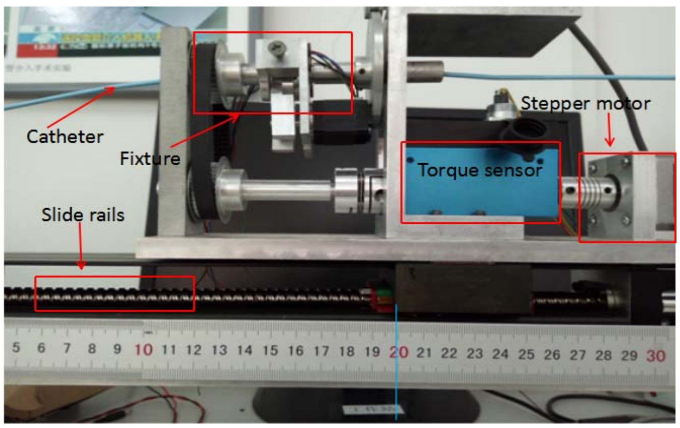

Fig.9 Structure of the slave manipulator

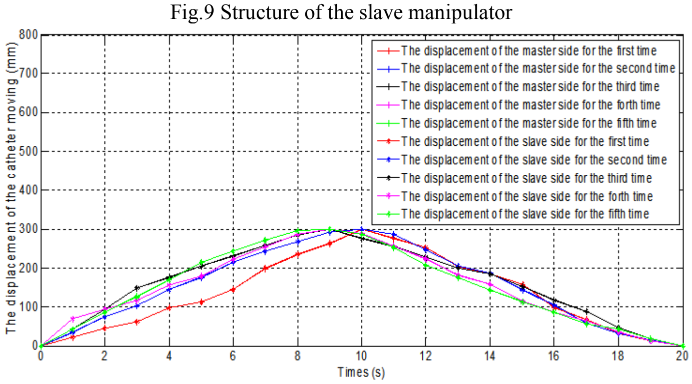

Fig.10 Curve of displacement from the slave to the master

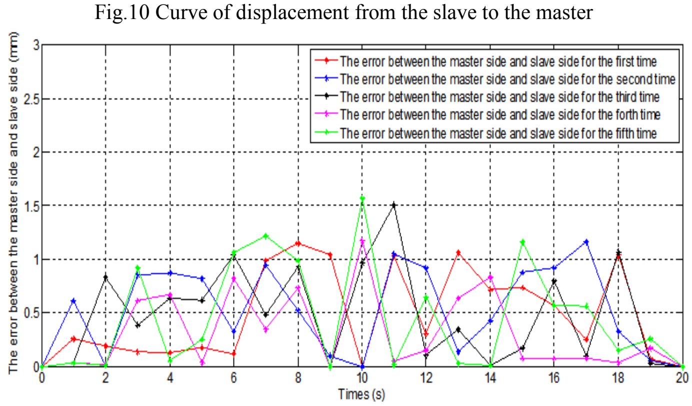

Fig.11 Error curve of master-slave tracking

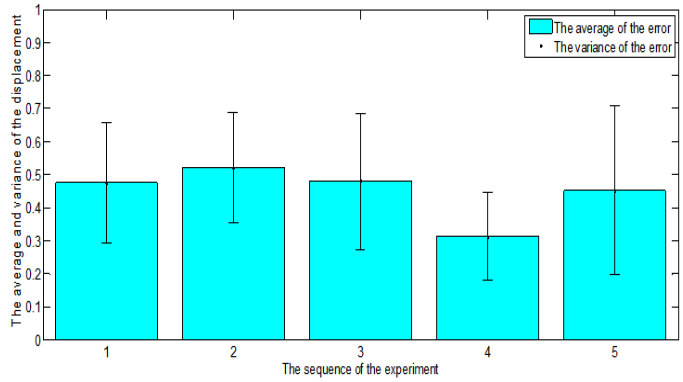

Fig.12 The average and variance error of the master-slave tracking

As can be seen from Fig.10 Fig11 and Fig.12,Although the master-slave tracking performance is great,there is still a big error. Because of the fuzzy relation fuzzy -PID controller to constantly adjust the PID between the three parameters and the error E and the change of De, continuous e error detecting and error change De in the operation of the system, the best values of the three parameters according to the principle of fuzzy reasoning, are passed to the PID controller online modification to meet different error E and error the changes of De under the condition of the control parameters of the different requirements, so that the control system has good control performance. We write a good driver PID control program added to the stepper motor. Through experiments. The optimal control parameter are obtained . The experimental results curve are shown in Fig.13 Fig.14 and Fig.15.

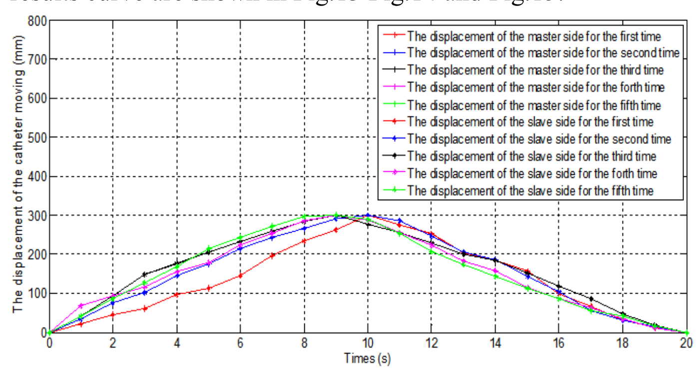

Fig.13 Curve of displacement from the slave to the master

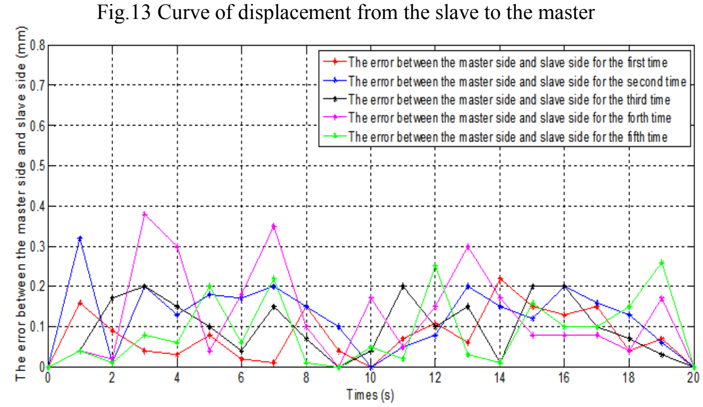

Fig.14 Error curve of master-slave tracking

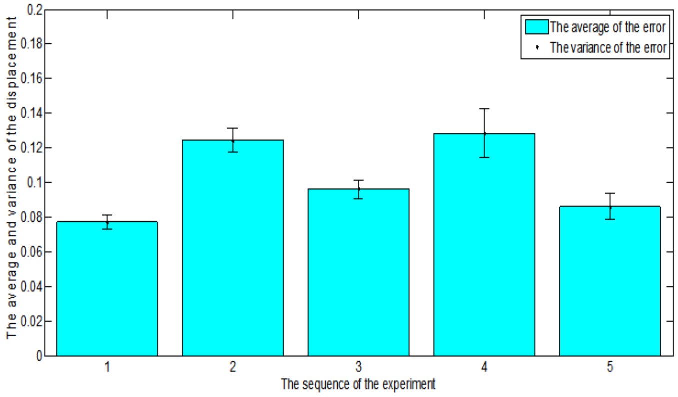

Fig.15 The average and variance error of the master-slave tracking

Compared with Fig.13,Fig.14 and Fig.15, it can be seen that the error of the master-slave tracking system is significantly smaller than that of the improved system. But there is still a certain error, because the system from the slave of the stepper motor is not very high accuracy and other hardware structures are not accurate due to the error

V. CONCLUSIONS AND FUTURE WORK

In order to improve the tracking performance from the slave side to the master side, We proposed a fuzzy -PID controller for the vascular interventional surgery robotic system to solve the problem of tracking error from the slave to the master manipulator. We conducted master-slave tracking experiments to compare the performance of PID controller with fuzzy -PID controller. The experimental results showed that the tracking performance of the fuzzy -PID controller is better than PID controller. The tracking error was reduced obviously. Therefore, the fuzzy -PID controller is suitable for the robot-assist catheter system.

In the future study, we will look for more accurate motor to replace the stepper motor and use the experimental platform to carry out a number of animal experiments.

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