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# Study on Tracking Control of Vascular Interventional Surgical Robot based on Autocoupling PID

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***Abstract* –Cardiovascular and cerebrovascular diseases are the biggest killers of human health. With the development of modern science and technology, the use of robotic assisted vascular interventional surgery has become an important means to reduce cardiovascular and cerebrovascular diseases. In the traditional minimally invasive vascular interventional surgery, the doctor is exposed to a large amount of radiation for a long time, which will cause some damage to the doctor. Using surgical robots instead of doctors to operate catheters could overcome these shortcomings. In the operating room can free the doctor from the operation site and prevent radiation damage to the doctor's body. Existing research on robot system is focused on the construction of the system and the development of the related key technologies of the system control research is rarely used more open loop or simple proportional integral differential control scheme, in recent years, there are also studies the combination of PID and intelligent control, the adaptive fuzzy PID, PID neural network, and synovial control, etc., the control method has its own advantages and disadvantages. In order to solve the problem of master-slave control of vascular interventional surgical robot, the traditional PID controller was analysed, and the self-coupling PID controller was designed. In this paper, the simulation results and real experimental results are presented. It is proved that the Autocoupling PID controller can effectively improve the operation ability, effectively solve the problem that the traditional PID is difficult to set, and has a good control effect. It is verified that the Autocoupling PID can be applied to the master-slave control system of the vascular interventional robot.**

***Index Terms* –*Vascular interventional surgery robot, master-slave control, self-coupling PID controller***

## I. INTRODUCTION

Many cardiovascular and cerebrovascular diseases, such as arrhythmia, are the main application fields of vascular interventional surgery. In traditional vascular interventional surgery, the physician directly manipulates the catheter and, with the help of medical imaging, delivers the catheter through the blood vessels to the lesion for diagnosis and treatment. Compared with the traditional open surgery, it has the advantages of less injury, less bleeding, faster postoperative recovery and fewer complications. However, catheter operation requires experienced doctors to get good results through repeated trial and error, so long exposure to radiation between doctors and patients and long-term work will cause certain damage to doctors[1]. The combination of robotic technology and vascular interventional surgery can overcome the shortcomings mentioned above and promote the promotion of vascular interventional surgery[2].

The vascular interventional surgery robotic system mainly consists of two parts: the master side and the slave side. The doctor performs surgery on the master side outside the operating room, and the computer collects the surgical information of the doctor on the master side and transmits it to the slave side. The computer replaces the doctor to complete the interventional surgery and avoids the doctor receiving radiation[3].

In recent years, many medical teams have devoted themselves to the research of The vascular interventional surgery robotic system. At present, the relatively mature is the Sensei robot system developed by Hansen Medical. The Sensei robotic system offers four modes of remote operation, allowing doctors to choose different control modes according to their operational needs. Corindus Vascular Robotics has developed a robotic system for interventional surgery called the Corpath 200, which allows surgeons to perform surgery remotely using a joystick and a touch screen. The Corpath 200 also has navigation and positioning capabilities to accurately locate catheters and guide wires,J.Jayender et al. from the University of Western Ontario, Canada, used a 7-DOF robot as a slave catheter delivery device to build a master-slave interventional system for catheters. The robot at the slave side can follow the hand movements of the doctor at the master side, which can be regarded as an extension of human hand[4].

In the university area, Zhao Ximei proposed a three-dimensional fuzzy controller to improve the accuracy of interventional surgery. Professor Guo Shuxiang proposed a new interventional surgical robotic system. The system uses the operation mode of the combination of active and driving to realize remote operation.Beijing aerospace university and navy general hospital for vascular interventional surgery cooperation has developed a set of force feedback master-slave interventional surgery robotic system, including the main manipulator, slave manipulator, image navigation system and contact force feedback part, and the first minimally invasive vascular interventional surgery after the animal experiments, they are still in the research using the fuzzy algorithm to fusion of catheter and the contact force of the blood vessels, back to the doctor, allowing doctors to surgical face more real feeling[5].

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Because the safety of interventional surgery must be ensured, the position tracking error between master and slave control systems must be reduced during the operation. A simple and effective autocoupling PID controller is proposed, which can be applied to the master-slave control system of vascular interventional surgery. The autocoupling PID controller can reduce the tracking error and the difficulty of PID parameter tuning.

## II. INTERVENTIONAL SURGICAL ROBOTIC SYSTEM

Vascular interventional surgery robot's role is to help the doctor to control thread of push, pull, rotate, on the basis of force feedback, to see the doctor makes the doctor has more real feeling, as it is important to the precision of the control system and its stability issues, these are very important, the precision of the control system for the security and stability is related to the operation, but current control methods have their own a little and disadvantages, Aiming at the problems existing in the control system of most vascular interventional surgical robots, a master-slave control system for vascular interventional surgical robots was designed based on the predecessors. The system principle is shown in Fig. 1[6]:

This system is the vascular interventional surgical robot of our laboratory platform. It's master side and slave side can realize the cooperative operation of catheter guidewire, and the operation can be completed mainly by realizing the synchronous movement of the catheter and guide wire. The system includes a master side and a slave side. The Master side structure is shown in Fig. 2; The structure of the slave manipulator is shown in Fig. 3.

The mainpulator mainly has linear displacement sensor, bionic pipe, photoelectric encoder, winding.On the master side of the electromagnetic coil. The slave manipulator mainly includes stepper motor, stepper motor driver, Fangshen photoelectric encoder, driver, guide rail, bearing, coil and fixture, etc.

The master manipulator consists of two parts, including a guide wire manipulator and a catheter manipulator. The bionic catheter is pushed and pulled by the doctor's hands so that the signal is received through the linear displacement sensor and transmitted to the main operator to achieve the purpose of output signal[7].

The master operator is mainly used to receive the operation signal of the doctor and the feedback control signal of the main controller. At the same time, its output end is connected with the input end of the main controller to provide force feedback to the doctor. The master controller and the slave controller communicate through CAN bus, receive signals through the master controller, and then transmit them to the slave controller through communication. The slave controller outputs signals to control motor for rotation, so as to drive the guide wire to push, pull and rotate. At the same time, the PC display can display the image information collected by IP camera, and can provide real-time visual feedback to doctors. The platform is driven by a stepping motor produced by Dongfang Electric Co., Ltd. The master side information is collected by a linear displacement sensor and the slave side information is collected by a photoelectric encoder.

The master side adopts the principle of electromagnetic induction. When the doctor moves the bionic catheter, the linear displacement sensor can measure the actual displacement to be pushed by the doctor through the electromagnetic induction to achieve the purpose of collecting information, and then convert it into a signal and send it to the controller, thus sending it to the slave side. At the same time, according to the principle of electromagnetic induction, the force feedback can be realized so that doctors can feel the presence of the operation more truly[8].

The design of the master manipulator of the platform fully conforms to the ergonomic design of doctors' operating habits. The catheter operator and the guide wire operator of the main operator are placed front and back, completely in line with the actual operation method of the doctor[9].The conduit on the slider of the master side adopts biomimetic material, which enables doctors to operate the platform more realistic and more in line with the actual operation requirements. And when the doctor operates the main terminal, it can realize the accurate force feedback in real time, so that the doctor has the feeling of the operation on the spot.

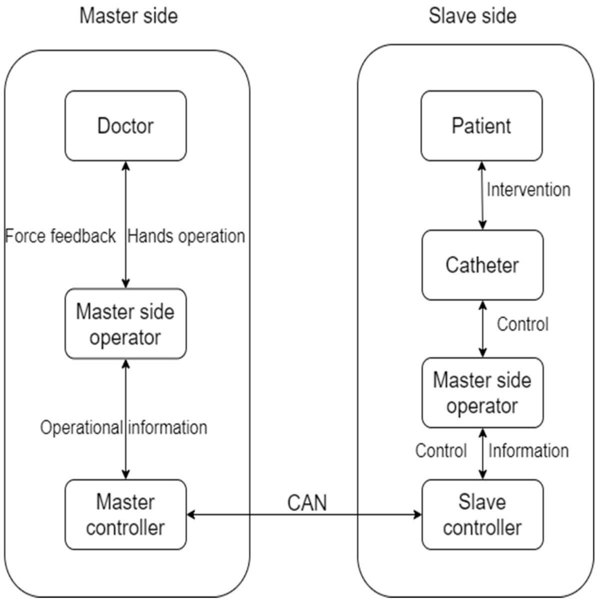

Fig. 1 Control System of Vascular Interventional Surgical Robot.

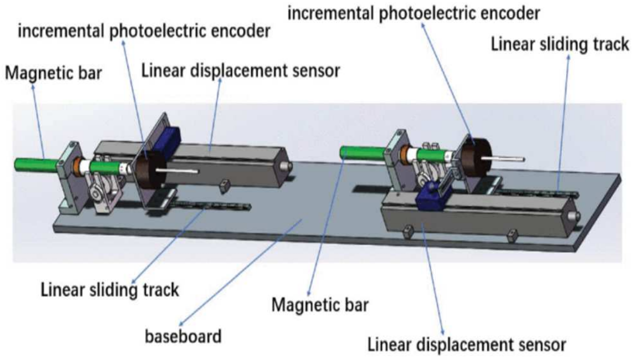

Fig. 2 The master manipulator

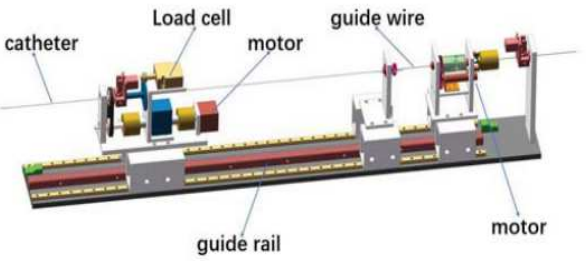

Fig. 3 The slave manipulator

## III. CONTROL ALGORITHM OF MASTER-SLAVE SYSTEM

### A. *Traditional PID Control Algorithm*

In the control process, the PID controller (also called PID controller) which is controlled according to the proportion (P), integral (I) and differential (D) of the deviation is the most widely used automatic controller. It has the advantages of simple principle, easy realization, wide application, independent control parameters, simple parameter selection, etc[9].

Conventional PID control system model is shown in Fig. 4:

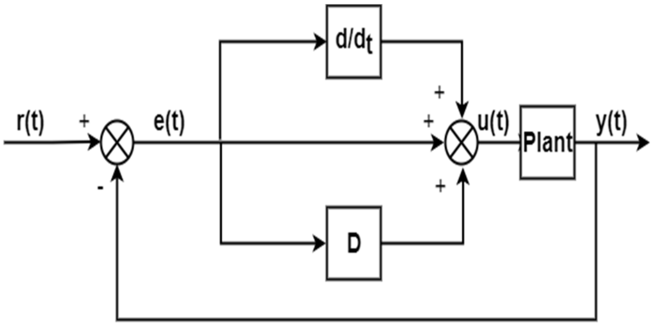

Fig. 4 Conventional PID control block diagram

In PID control, R(t) is the input, Y(t) is the output, the error between the input and output is E(t), P,I and D three terms after a certain multiple amplification of the algebraic sum is the control signal U(t). P represents that the proportional coefficient is proportional to the current error. If the error between input and output is positive and large, then the output is positive. After adopting proportional control, if there is residual error, the error control effect accumulated in history can be increased to eliminate the residual error. I stands for integral control, which sums up historical errors and accumulates them to form an accumulation of past errors. D stands for differential control, which can predict the future trend of error change according to the change rate of the current error, so as to reduce the error by controlling the change rate of the error.

The traditional PID control algorithm is shown as follows[10]:

$$u(t) = k(e(t) + 1 / T_1 \int_0^t e(t)dt + T_D de(t) / dt) \tag{1}$$

The traditional PID controller can also be written in the following form[11]:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d de(t) / dt \tag{2}$$

$K_p$ is the proportional gain, $K_i$ is the integral gain, and $K_{d6}$is the gain.

### B. *Autocoupling PID Control Algorithm*

Since decoupling PID is on the basis of traditional PID to make some improvements, in theory it is also the sum of the proportion, integral, differential gain three formation control signal, but the fact is due to the speed factor according to certain proportion relationship instead of the PID, so between coupled together, by traditional PID independent parameters into the decoupling PID coupling parameters, so as to make the three gain there is a relationship between constitute control signal, the control method solves the problems of traditional PID parameters of the positive definite are harder to, greatly optimize the positive definite speed, and on the accuracy and stability also has a good effect[12].

The block diagram of the autocouplingPID control system is shown in Fig. 5:

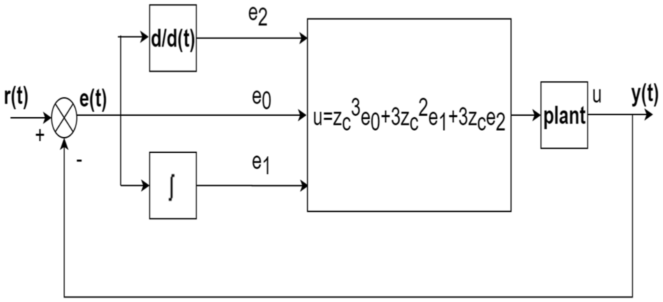

Fig. 5 Autocoupling PID control block diagram

As can be seen from Fig. 4, the difference between the autocoupling PID and the traditional PID is that it has different processing methods for input signal processing.

It can be seen from the block diagram that the controller error model of the autocoupling PID is shown in formula (3).

$$u(t)=z_c^3 e_0 + 3z_c^2 e_1 + 3z_c e_1 + 3z_c e_2 \tag{3}$$

According to the controller error model, it can be seen that the difference between autocoupling PID and traditional PID is that they have different processing methods for input signals. Autocoupling PID also has three parameters of proportional integral derivative, but in fact they are all replaced by one parameter, namely the speed factor $Z_C$.

Where $Z_c$ is called the velocity factor and is greater than 0. At the same time, $Z_C$ has a large setting margin. In order to improve the dynamic response speed and anti-interference ability of the control system, the larger $Z_C$ is required to be, the better. However, if $Z_C$ is too large, the gain weight $Zc^3$ of the integral link will be large. Therefore, in order to ensure fast response speed and strong anti-disturbance ability, as well as to avoid overshot and oscillation due to integral saturation, an adaptive velocity factor model is derived,as shown:

$$z_c = \alpha / T_t \left[1 - 0.9 \exp(-\beta t)\right] \tag{4}$$

Among them:

$$0<\alpha<100, \beta=1/T_t \tag{5}$$

$T_t$ is the transition time from dynamic to steady state, which is the time required for the system to be stable from startup. For a fast system, the larger alpha is, the larger the velocity factor will be and the better the system control effect will be. α is usually within the following range:

$$10<\alpha<100 \tag{6}$$

For slow systems, α is usually in the range:

$$0<\alpha<10 \tag{7}$$

The larger alpha is, the faster the response speed is and the stronger the anti-jamming ability is. Otherwise, the selection range of $Z_C$ can be decided quickly in this way.Compared with the traditional PID controller, the autocoupling PID has only one speed factor. By means of $Z_C$, three different physical links of proportion, integration and differentiation are closely coupled together to form control signals. Therefore, the traditional PID needs to set $K_p$, $K_i$ and $K_d$, while the autocoupling PID only needs to set one parameter Zc, and there is the following relationship between $Z_c$ and $K_p$, $K_i$ and $K_d$.

$$\begin{aligned} k_i &= z_c^3 \\ k_p &= 3z_c^2 \\ k_d &= 3z_c \end{aligned} \tag{8}$$

The control effect of the designed controller is simulated in the MATLAB Simulink environment, and the traditional PID is also simulated and compared. According to the dynamics model of the master-slave manipulator of the vascular interventional surgical robot, a second-order linear system is adopted for simulation:

$$G(S)=\frac{1}{1.2S^2+8S+1} \tag{9}$$

The simulation block diagram is shown in Fig. 6:

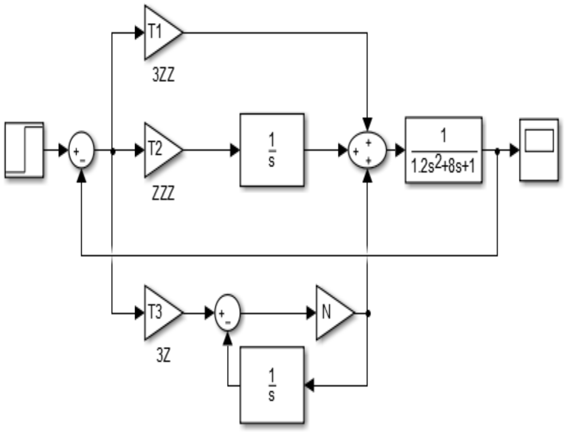

Fig. 6 Block diagram of autocoupling PID logic controller

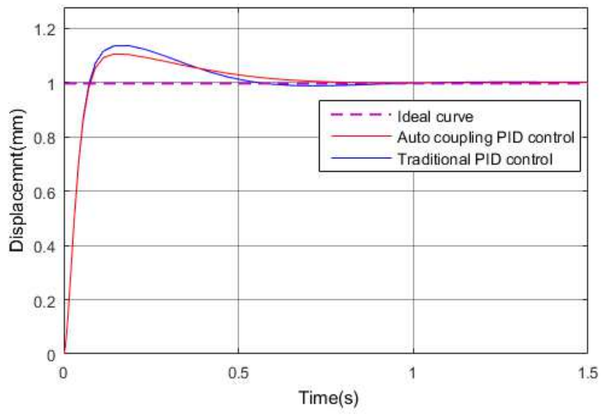

Fig. 7 Step response position tracking comparison.

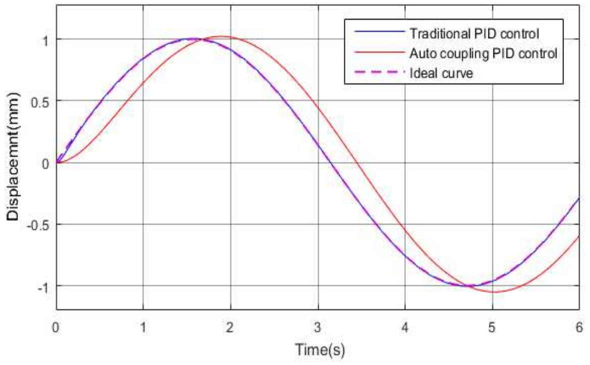

Fig. 8 Sinusoidal response position tracking comparison.

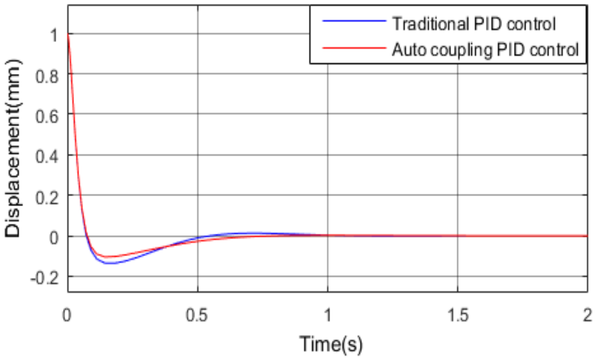

Fig. 9 Step response position tracking error comparison

We can see from Fig. 7 since autocoupling PID controller has good control system for step response performance, convergence within 1 s and its maximum error is less than 0.1, according to the positive definite rules setting. Found that it has good control effect, and easy to setting, see from Fig. 8 as the decoupling PID controller of the sinusoidal signal tracking also has good control effect which can be seen from the Fig. 9 the same since the decoupling PID controller to control the step signal tracking error with good effect, can make error within 1 s to 0 and the previous step response.

## IV. EXPERLMENTAL RESULTS AND ANALYSIS

In this paper, the platform shown in Fig. 10 was used for experiments. We use NDI to collect displacement data. The

NDI camera will collect the position information of the two rigid bodies. Then the displacement of the master and slave side is compared and the error of the master and slave side is calculated. The test platform used tubes with a diameter of 5.0mm and a length of 140mm. In order to reduce the cumulative error caused by the driving part, the platform uses a stepper motor to drive the catheter for displacement. Fig. 11 shows the simulated blood vessel used in the experiment. The operation path, starting point and end point are marked in the figure. Due to the characteristics of the vascular interventional surgical robot of this experimental platform, we will try our best to imitate the operation methods of doctors in the experiment.

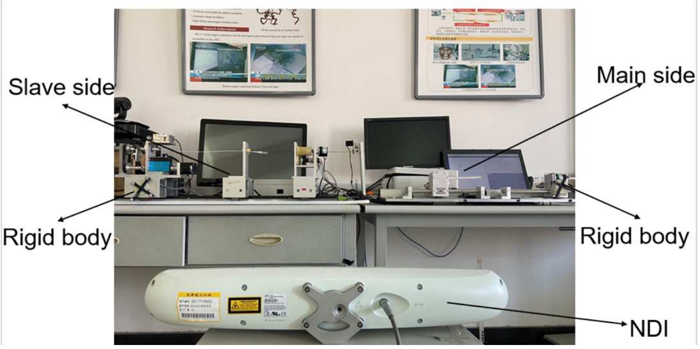

Fig. 10 Master slave displacement experiment

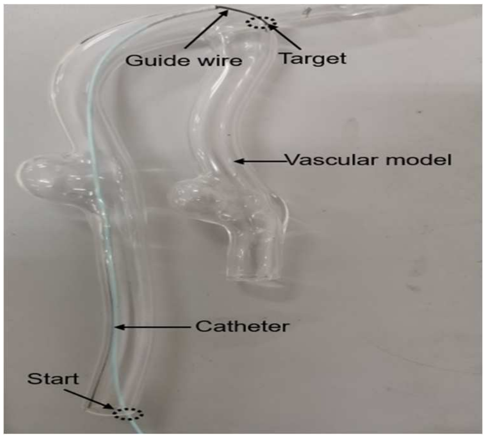

Fig. 11 Simulated vascular experiment diagram

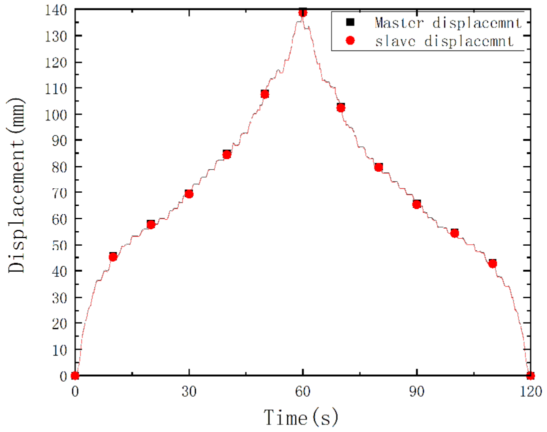

Fig. 12 Comparison between master displacement and slave displacement

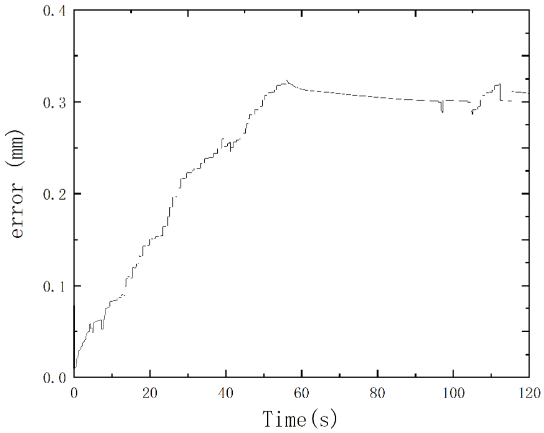

Fig. 13 Master-slave displacement tracking error

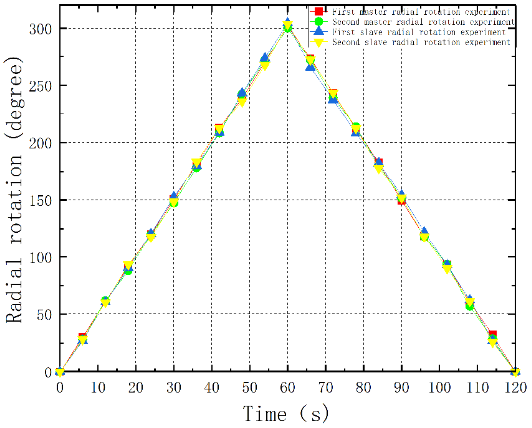

Fig. 14 Radial rotation data

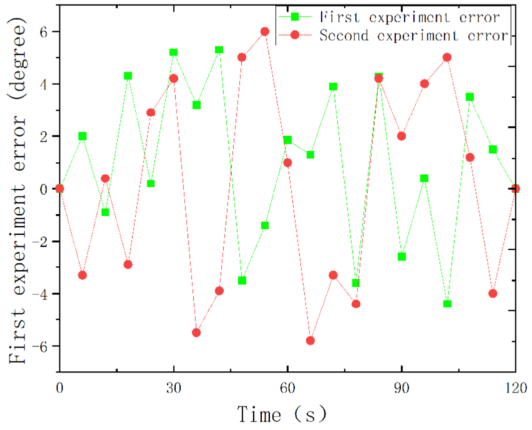

Fig. 15 The radial rotation error

Fig. 12 represents the tracking findings between the master-slave displacements that basically coincide with each other. Fig. 13 represents the displacement error between the master side displacement and the slave side displacement with the movement of the master side displacement. Fig. 14 represents that the master slave encoder rotates 60° each time, and rotates 5 times until the forward rotation reaches 300°. Reverse rotation 5 times from 300° to 0°. Fig. 15 shows the final average error of each radial test. From Fig. 12, we can see that the tracking displacement between the master and slave is very high, indicating a good control effect. According to Fig. 13, we can see that the movement error with the displacement of the master gradually increases. But the final error will eventually reach about 0.3mm. The minimum radial error is about 1.8°, the maximum error is less than 6°. It can be seen from Fig. 15 that the maximum average error is 2°, and the minimum average error is 0.57°. It can be observed from the above that the autocoupling PID has a good control effect in both axial and radial directions.

## V.CONCLUSION

An autocoupling PID controller for the master-slave control system of a vascular interventional robot was proposed. However, there were still many shortcomings in the current study, which need to be further improved. First of all, the mathematical models of interventional surgical robots were not very accurate. In this paper, it were simply analyzed that the system was a second order system, and the exact system model was not given. Secondly, in the simulation experiment of this paper, the selected parameters were only given by the author and were not optimized by algorithms such as optimization algorithm. Finally, the effect of the control algorithm still needs to be verified in the experiment.

## ACKNOWLEDGMENTS

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