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Study on Control Strategy of Vascular Interventional Surgery Robot based on Adaptive Smith Predictor

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***Abstract* –When doctors perform cardiovascular and cerebrovascular interventional operations, X-ray radiation will greatly increase the probability of doctors suffering from cancer. Surgery through robots can protect doctors' bodies and reduce the workload of doctors. Most of the research focus on interventional surgical robots is on traditional control algorithms. Few studies have paid attention to the delay problem of the system. Most of the vascular interventional surgery robots adopt the master-slave type, and the slave end needs to restore the action of the master end. The master-slave system cannot avoid the master-slave tracking error caused by the delay. In this paper, an adaptive Smith prediction algorithm is proposed to solve the master-slave delay and improve the tracking accuracy. This paper proves by experiments that this algorithm has a good control effect, can effectively solve the lag problem of the robot, improve the tracking performance, and ensure real-time and accuracy.**

Index Terms –Vascular interventional surgery robot, Master-slave control, Adaptive smith predictive control

I. INTRODUCTION

In recent years, due to various reasons such as work pressure, cardiovascular and cerebrovascular diseases have become more and more frequent. Vascular interventional surgery can effectively treat cardiovascular and cerebrovascular diseases. It has the advantages of quick recovery and easy acceptance by patients. The requirements are extremely high, and the doctor needs to perform surgery under X-rays for a long time, which is very unfriendly to the doctor[1]. Therefore, a lot of research has been carried out at home and abroad to solve the problems existing in the operation. At present, the mainstream method is to perform interventional surgery through interventional surgery robots, so that doctors can be relieved.

Vascular interventional surgery robots are generally of master-slave design. The doctor operates the master-end robot in a separate room, and the slave-end robot reproduces the movements of the master-end. In this way, the problems existing in previous operations can be perfectly solved [2].

The surgical robot developed by the Hansen medical team has become very famous in recent years. The robot can provide a variety of operation modes for doctors, and doctors can flexibly choose which mode to perform surgery through changes in the environment and their needs [3]. The University of Western Ontario, Canada has independently developed a robot for interventional surgery. This robot can complete the autonomous navigation and precise positioning of the catheter through its own algorithm. It has up to 7 degrees of freedom. The action of the end operator to complete the twisting and pushing of the catheter.

In terms of robot control, Zhao Ximei and his team used three-dimensional fuzzy control to achieve precise master-slave tracking and achieved very good control results. Guo Shuxiang and his students designed a new type of manipulator in structure, which adopts The magnetorheological fluid can realize the force feedback function, which is of great significance. The slave end can reproduce the force on the catheter at the master end. With the joint efforts of other universities, Beihang University has developed a set of vascular interventional surgery system after several years of research. This system consists of a master operator, a slave operator, and visual equipment. It is worth mentioning that , This device has achieved good results in animal experiments. In addition, it uses a fuzzy algorithm to make the force feedback more realistic in the doctor's hand. The doctor is like operating the catheter by himself.[5].

Will the master-slave robot inevitably cause tracking errors due to the delay? The delay is mainly composed of the acquisition time of the master-hand information and the response time of the motor. Excessive delay will seriously affect the doctor's operating experience and cause safety hazards. This paper proposes Integrate the improved adaptive Smith algorithm and fuzzy control to achieve a better control effect, achieve accurate master-slave tracking, and eliminate master-slave tracking errors caused by time delays [6].

II. INTERVENTIONAL SURGICAL ROBOTIC SYSTEM

The vascular interventional surgery robot can free the doctor from the traditional operation in the past. The doctor can operate the master end in another room to complete the control of the robot slave end. In this case, the synchronous control strategy of the master control is very important. The control strategies currently studied have their own shortcomings. This paper adopts the combination of fuzzy control strategy and Smith to achieve a better control effect. The control block diagram of this platform is shown in Figure 1. [7]:

The main end of the surgical robot designed by our team is shown in Figure 2, and the slave end is shown in Figure 3. Like other teams, it still adopts the master-slave structure. The slave end restores the actions of the master end according to the control strategy. The master end can be realized through the slave end. Force feedback, the doctor can have a very real force touch [8].

Its structural material is mainly aluminum alloy, which has the advantages of strong hardness and not easy to deform. The main end is mainly composed of sliders, gears, sensors, motors, etc. The principle can realize the force feedback function and increase the doctor's experience.

The main end manipulator is divided into two parts, one is the catheter manipulator and the other is the guide wire manipulator. Through the cooperation of the two manipulators, various surgical methods can be realized. The two manipulators control the corresponding slaves respectively. End effector, through cooperation with each other, the intervention of the catheter guide wire is finally completed.

The specific control process of the master-slave robot is to collect the operation information of the doctor's hand through the linear displacement sensor, and then transmit the information to the controller. The master controller and the slave controller communicate through the CAN bus and send control instructions to the slave controller. Then the slave controller controls the motor and then controls the slave manipulator to complete the surgical action. The slave manipulator is equipped with a force sensor, and the detected force is sent back to the master end, and then the master end force feedback device generates a feedback force to the doctor's hand to realize the force Feedback function [9].

The realization of the master-end force feedback uses the principle of electromagnetic induction. When the linear displacement sensor detects the displacement signal of the master-end, it transmits the signal to the control motor of the slave-end. The motor controlled by the slave-end controls the forward movement of the manipulator, and the catheter follows the manipulator. When the pressure sensor on the slave side detects a forceful change, it transmits the signal to the master manipulator, and the master manipulator operates on the principle of electromagnetic induction. A force opposite to the propulsion direction will be generated to realize the function of force feedback [10].

The master-slave platform is completely ergonomic in structural design. The two sliders on the slave end simulate the movements of the human hand to complete the push motion of the catheter and guide wire. Put the catheter and guide wire on the clamp, and the clamp can clamp the catheter. When the push action is started, the catheter on the main test slider is made of bionic material, and the doctor pushes it into the patient's body, delivering medicines and surgical instruments from the catheter to complete the treatment of the patient[11].

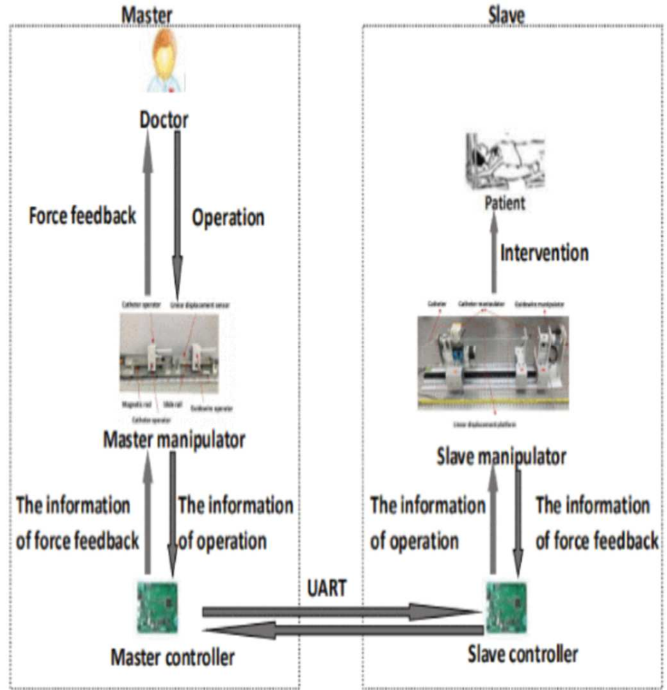

Fig. 1 Control System of Vascular Interventional Surgical Robot.

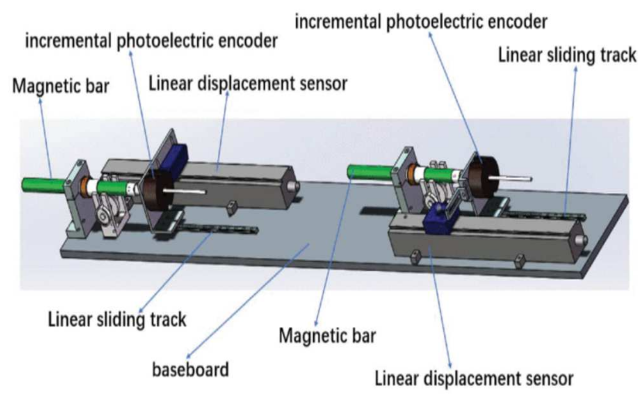

Fig. 2 The master manipulator

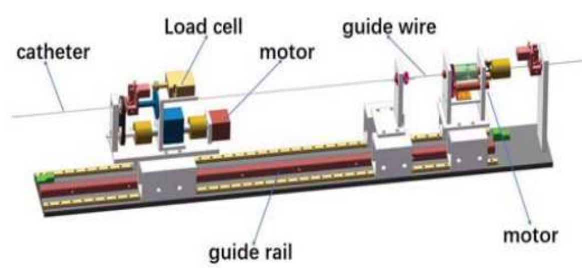

Fig. 3 The slave manipulator

III. Control Algorithm of Master-Slave System

A. *Smith Predictive Control*

In order to solve the pure lag term contained in the closed-loop characteristic equation, Smith et al. changed the pole value and characteristic root of the characteristic equation of the system by adding an estimation compensation link to the traditional PID feedback control loop, which greatly improved the control performance of the whole system. The block diagram of the traditional smith prediction compensation control system is shown in Fig. 4[12]:

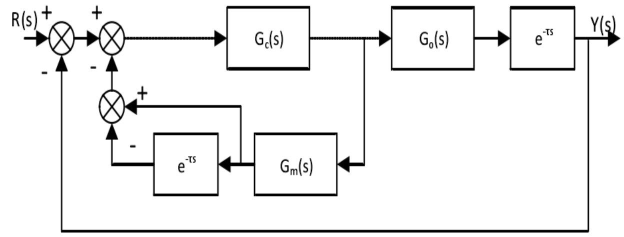

Fig. 4 Conventional Smith control block diagram

Among them, $G_m(s)$ is the estimated model transfer function of the controlled object,$e^{-\tau_m s}$ is the time delay factor of estimated compensation, and represents the transfer function of the pure lag part of the controlled object in the estimated model. It can also be seen from the figure that the control method of Smith's prediction compensation is to connect a link inversely parallel in the actual system. This link has a time delay compensation factor. Through the function of predicting the future state of the system, the time delay of the time delay system is calculated. The delay is sent to the controller of the overall system in advance, which theoretically can completely eliminate the influence of the time delay on the system. The transfer function of the entire system output to the input is:

$$\phi(s) = \frac{Y(s)}{R(s)} = \frac{G_c(s)G_0(s)}{1+G_c(s)[G_m(s)(1-e^{-\tau s})+G_0(s)e^{-\tau s}]} e^{-\tau s} \quad (1)$$

When the actual controlled model and the estimated model are completely matched, $G_0(s) = G_m(s)$, $\tau=\tau_m$, The transfer function $\emptyset(s)$ of the system can be obtained:

$$\phi(s) = \frac{Y(s)}{R(s)} = \frac{G_c(s)G_0(s)}{1+G_c(s)G_0(s)} e^{-\tau s} \quad (2)$$

Its characteristic equation:

$$1 + G_c(s)G_0(s) = 0 \quad (3)$$

It can be seen from the characteristic equation that after the Smith predictor lag compensation, it further shows that the system is no longer affected by the time delay factor. Therefore, for the controlled system with lag, the stability of the system can be improved and improved to a certain extent after the introduction of Smith predictor.

B. Adaptive Smith Predictive Control Algorithm

The traditional smith prediction control is very sensitive to the model error, and it can play a good role only when the controlled object model is established accurately, and there is a transmission delay on the network when the vascular interventional surgery robot is teleoperated. T The delay is mainly due to the fact that the movements of the main hand need to be collected by sensors, and the motor needs corresponding time, and the use of conveyor belts and connecting rods in many parts of the mechanism will also cause a response delay in the structure. However, the traditional Smith has very high requirements on the accuracy of the controlled object model, resulting in its few industrial applications.

The block diagram of the adaptive smith predictive control algorithm is shown in Fig. 5[13]:

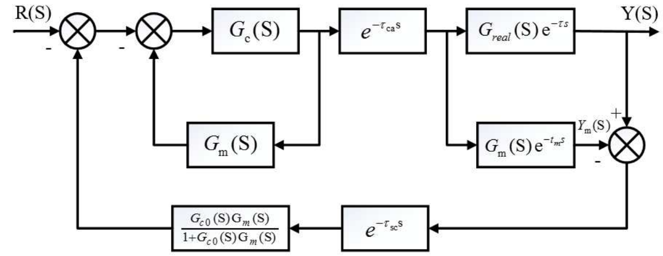

Fig. 5 Adaptive Smith control block diagram

$G_{c0}(s)$ represents a controller and $G_m(s)$ be a first-order inertial link, $\frac{G_{c0}(s)G_m(s)}{1+G_{c0}(s)G_m(s)}$ can be simplified as.

$$G_f(s) = \frac{1}{\frac{T_m}{K_c K_m}s + 1} = \frac{1}{t_f s + 1} \quad (4)$$

T_m is the predictor time constant, Kc is the gain of $G_{c0}(s)$, and K_m is the predictor gain.Its transfer function becomes as follows:

$$\frac{Y(s)}{R(s)} = \frac{G_c(s)e^{-\tau ca s}G_{real}(s)}{1+G_c(s)G_m(s)+G_c(s)e^{-\tau ca s}(G_{real}(s)-G_m(s))e^{-\tau sc s}\frac{1}{t_f s+1}} \quad (5)$$

When the controlled object is established accurately and the estimated model has no errors, $G_{real}(s) = G_m(s)$, The transfer function of the system at this time is as follows:

$$\frac{Y(s)}{R(s)} = \frac{G_c(s)e^{-\tau ca s}G_{real}(s)}{1 + G_c(s)G_{real}(s)} \quad (6)$$

It can be seen from the transfer function that the improvement has no effect on the stability of the system. The denominator of the transfer function adds an a at the end. Adjusting b can change the follow-up of the characteristic equation of the closed-loop system to achieve the purpose of improving the system performance. When there is an error between the models, the characteristic equation of the system is as follows[14]:

$$1 + G_c(s)G_m(s) + G_c(s)e^{-\tau ca s}(G_{real}(s) - G_m(s))e^{-\tau sc s}\frac{1}{t_f s + 1} = 0 \quad (7)$$

Adjust the value of a according to the size of the error. When the output of the error integral steady-state value changes within a certain range, a should take a larger value, and when the error integral steady-state value output has been developing to infinity, a should take a Smaller value[15], which is equivalent to adding a low-pass filter in each feedback channel, which can reduce the influence of model error on system stability and improve real-time performance. In this way, the failure of the predictor caused by the model error can be effectively solved by adjusting the coefficients of the filter. By updating the coefficients of the filter, the predicted model and the real model can be effectively made consistent to improve the control effect and eliminate the oscillation and overshoot of the system to reduce the adjustment time of the system to achieve effective control.

In order to verify the superiority of the algorithm, this paper implements fuzzy PID and adaptive Smith prediction control algorithms in simulink respectively[16]. Through the comparison of the two algorithms, it can be seen that the introduction of the Smith predictor can reduce the overshoot and make the adjustment smaller. time, to achieve better control effect, which is extremely beneficial to the vascular intervention robot using master-slave control [17]：

$$G(s) = \frac{10}{2s^2 + 3s + 1} \tag{8}$$

The simulation block diagram is shown in Fig. 6:

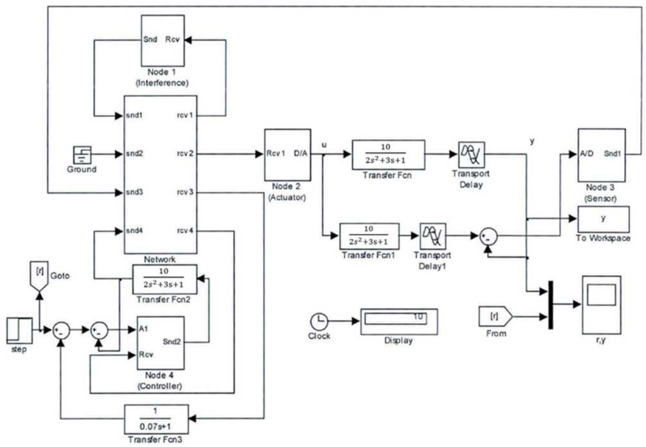

Fig. 6 The simulation diagram with adaptive smith predictor

According to the previous accumulation of the laboratory team, the main controller adopts the fuzzy PID controller, and introduces the adaptive Smith compensator designed in this paper for delay compensation[18]. The adaptive Smith can adjust the parameters of the predictor to reduce the difference between the predicted model and the actual model. To solve the problem that the traditional smith needs to accurately predict the model, and further improve the real-time performance and accuracy of the system, the simulation introduces the adaptive smith algorithm and the traditional smith algorithm to compare[19], and the final simulation comparison results are shown in Figure 7 and Figure 8[20].

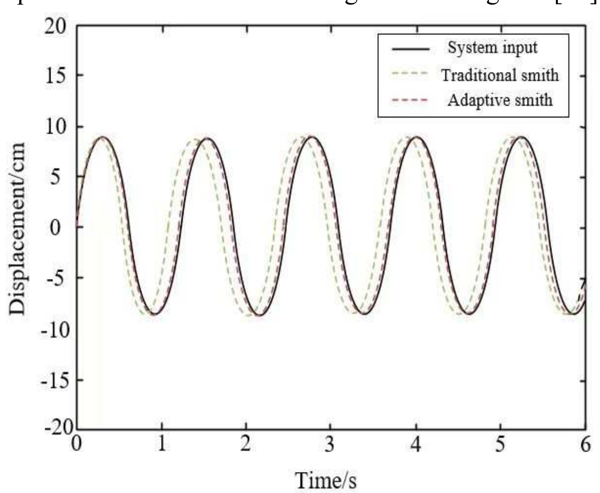

Fig. 7 Sinusoidal response position tracking comparison.

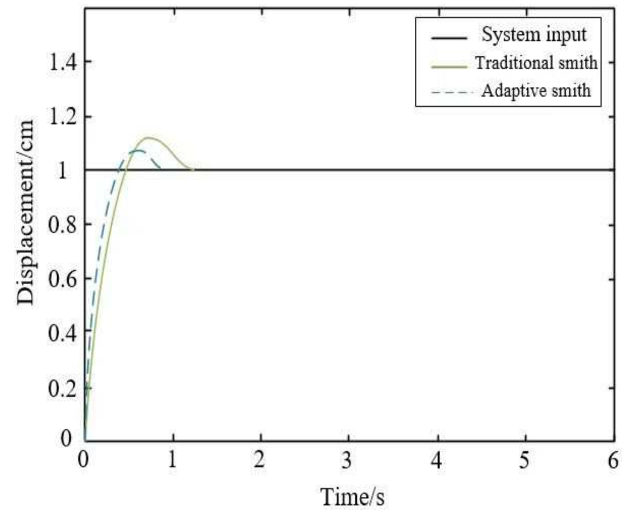

Fig. 8 Step response position tracking comparison.

As can be seen from the figure, the introduction of the adaptive smith algorithm can improve the tracking performance and ensure real-time performance. When the estimated model does not match the time model, adjusting the f value can compensate for the impact of the model mismatch, which is better than the traditional smith in solving the delay.

IV. Experimental Results And Analysis

In order to further verify the effectiveness and superiority of the algorithm, this paper uses a laboratory platform to conduct intervention experiments. The platform used is shown in Figure 9. Then, NDI is used to collect the master-slave displacement under the same time series, and the master-slave error is compared. The blood vessel model used for the interventional experiment, the length is 6mm and the length is 145mm. The start and end points of the catheter are marked in Figure 10. We use a 42 stepper motor as the drive, and then the NDI data at the same time For comparison, in the interventional experiment, we tried our best to make it exactly the same as the doctor's hand operation during interventional surgery, so as to simulate the real surgical environment

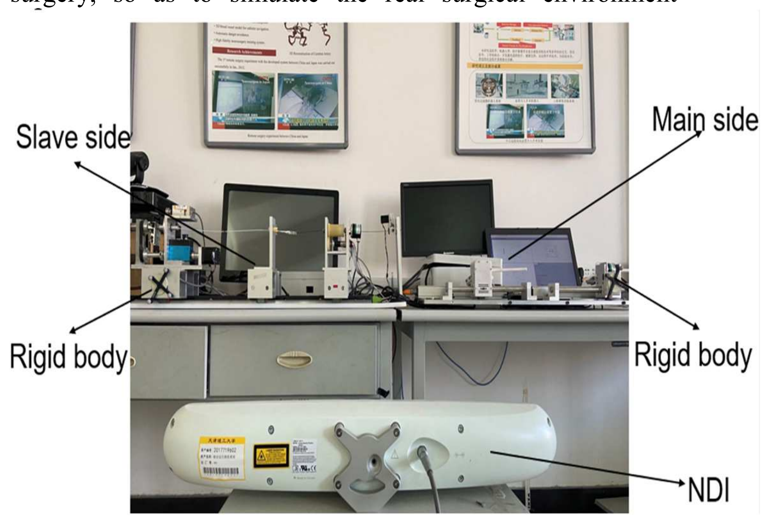

Fig. 9 Master slave displacement experiment

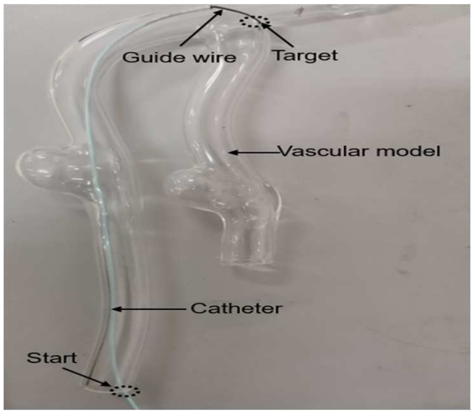

Fig. 10 Simulated vascular experiment diagram

The experimental master-slave radial displacement tracking curve is shown in Figure 13, and the master-slave radial tracking error is shown in Figure 14.The average error is 0.22mm and the maximum error is 0.37mm, and the minimum error is 0.17mm. From the figure we can find that the master-slave axis has a good tracking effect after being integrated into the adaptive smith control, which can effectively improve the real-time performance.

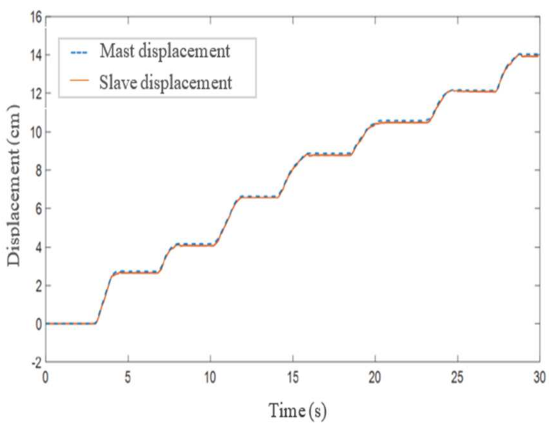

Fig. 11 Master-slave axial displacement

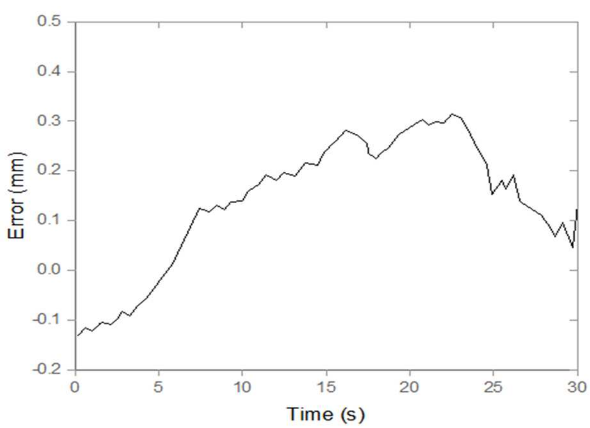

Fig. 12 Master-slave displacement tracking error

Figure 13 shows the tracking results between the master and slave radial displacements that are basically consistent.

Figure 14 shows the radial displacement error between the master side displacement and the slave side displacement as the master side displacement moves. The radial error varies between -1.9° and +1.9°. From the figure we can find that the master-slave radial tracking effect is good after being integrated into the adaptive smith control, which can effectively improve the real-time performance.

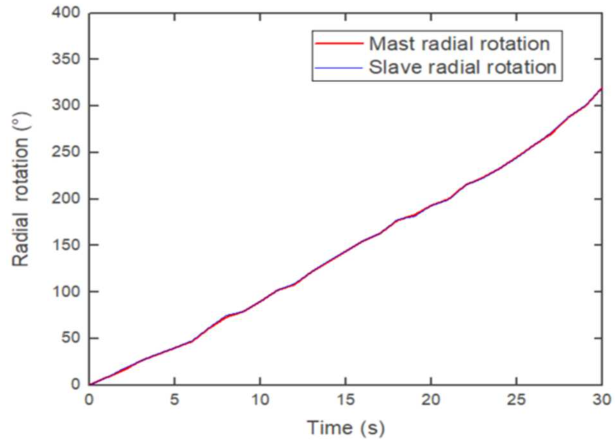

Fig. 13 Master-slave radial displacement

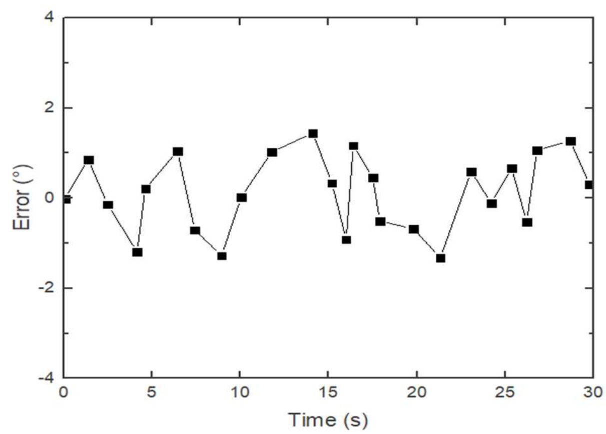

Fig. 14 The radial rotation error

V. CONCLUSION

Because it is difficult to accurately establish the prediction model, the traditional Smith prediction control algorithm is difficult to use in practice. The adaptive Smith prediction control algorithm can reduce the error between the prediction model and the real model through the change of parameters. The experimental and simulation results show that The adaptive smith prediction control algorithm can effectively eliminate the pure lag link, effectively improve effectively reduce master-slave tracking error and ensure the master-slave tracking performance.

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