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Study on Autonomous Surgical Control System of The Vascular Interventional Surgical Robot Based on Catheter Tip Location Tracking

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***Abstract* - The control system of vascular interventional surgical robot is a complex nonlinear system. When the catheter is inserted into human blood vessels, due to the irregular and curved shape of human blood vessels, the catheter will undergo small deformation, which will affect the displacement of the catheter. In order to reduce the displacement tracking error, a BP neural network PID controller was designed to compensate the displacement error of the autonomous vascular interventional surgical robot. Firstly, the dynamic analysis is carried out according to the axial displacement motion of the vascular interventional surgical robot, and the catheter displacement tracking controller was designed. According to the displacement error, BP neural network PID control is used to output three parameters of PID. Finally, in the experiment and PID control simulation comparison, the results show that the BP neural network PID control has a small displacement tracking error and superior tracking performance, which can meet the requirements.**

Index Terms-vascular interventional surgical robot, Dynamic analysis, Displacement tracking error, BP neural network PID

I. INTRODUCTION

Cardiovascular and cerebrovascular diseases are the number one killer of health, with a higher mortality rate than tumors and other diseases. According to the China Cardiovascular Health and Disease Report 2021[1], the incidence of cardiovascular diseases is increasing rapidly and has become the leading cause of death for Chinese residents.

Vascular intervention is a way to diagnose and treat intravascular diseases, which is a minimally invasive operation, which only requires a small hole to be opened on the patient's thigh or arm for puncture, and then the surgical interventional instrument is pushed to the lesion site through the patient's vascular channel[2], and the inner diameter of the blood vessel at the lesion site is expanded through the stent , so as to restore the smooth flow of blood . With the rapid development of medical technology, interventional surgical robots have been widely used in the medical field. Compared to the initial interventional surgery, on the one hand, the doctor can be freed from the operating room and operate the robot in a remote control way to complete the operation. On the other hand, doctors are able to get rid of the burden of heavy lead clothing and reduce radiation damage. In addition, the characteristics of high stability and accuracy of the robot improve the precision of surgical instrument intervention and improve the quality of the operation.

When doctors and specialists operate vascular interventional surgical robots for a long time, they are also prone to hand fatigue and operational errors. Therefore, combining with the rich experience of doctors, an intelligent judgment and operation mechanism is established to help doctors reduce the workload and fatigue in the operation. But in practice, the expected displacement of the conduit is always different from the actual displacement. After analysis, due to the soft characteristics of the catheter itself and the irregular and curved shape of human blood vessels[3], the distance between the catheter tip and the catheter end is not equal. In addition, during catheter propulsion, due to the interference of complex forces in the vessel, the catheter propulsion displacement may also be affected, which may affect the accuracy of the surgical process.

In 2017, Meng Cheng[4] et al. the structure of master operator and slave operator of vascular interventional surgical robot system is designed, and built a virtual environment with catheter guide wire coordination training based on Unity 3D for the training system[5] of vascular interventional surgery doctors with guide wire and catheter coordination. The system uses ampere-force to achieve haptic feedback, and not only has guidewire and catheter cooperative operation training, but also simulates collision force, blood flow resistance and viscous resistance. In 2018, Yang Shuai[6] et al. proposed a strategy to eliminate tremors specifically for the robotic system of vascular interventional surgery. Because of long-term and high-intensity surgery, nervous mood and muscle fatigue, doctors may experience hand tremor, which is fatal. In 2019, Feng Suxiang[7] et al. proposed an autonomous surgical mechanism based on the vascular interventional surgical robot, in which the catheter guide wire was autonomously inserted into the designated position in the blood vessel. After experimental verification, the autonomous surgical mechanism can meet the basic requirements. Due to the irregular and curved shape of human blood vessels, the catheter will have small deformation during actual propulsion, which will affect the displacement of the catheter.

In this paper, based on the autonomous surgical mechanism in the laboratory, the effect of minimizing the actual displacement and expected displacement error was achieved in the process of catheter autonomous intervention in the blood vessel[8]. Finally, the feasibility of this method was verified by experiments. The structure of this paper is as follows: The first part introduces the research background and laboratory research status; The second part introduces the mechanism principle of autonomous operation. The third part is the research content, mainly tracking the position of catheter tip. The fourth part analyzes the feasibility of this method through experimental simulation. The fifth part makes a summary of this paper.

II. Overview of Robotic Platform for the Vascular Interventional Surgery

Our team's robot platform for vascular interventional surgery is divided into primary end and secondary end. Fig.1 shows the conceptual diagram of the vascular interventional surgery robot. The main end includes the main operator, the main controller and the display screen; The slave side includes the slave operator, the slave controller and the IP camera. The whole system is suitable for short-range surgery and adopts wired connection mode. Its working flow is that the operator controls the main operator with both hands and controls the catheter guide wire propulsion respectively. The master operator can collect the operator's action information, including axial displacement information and radial rotation distance[9]. It is then sent to the slave controller via CAN communication. The slave controller controls the slave operator based on the information received. The auxiliary operator can control both the catheter and the guide wire individually or simultaneously. During operation, the resistance information of conduit and guide wire can be collected from the slave operator and processed by the slave controller, transmit the signal from the controller to the master end. The master controller will feed back the received signal to the master operator after force signal conversion to provide tactile feedback to the doctor[10]. During the operation, A high-definition camera is placed at the secondary end to view the catheter intervention in real time[11]. According to the existing conditions of the laboratory, the visual feedback part adopts the remote surgery interactive system TE40, whose camera and display screen are connected through the Internet, independent of the CAN communication with the master and slave terminals.

However, due to the long duration of interventional surgery, doctors concentrate on the operation of vascular interventional surgery robot for a long time, especially easy to cause the doctor fatigue state[12]. Therefore, our team established a surgical method judgment mechanism independent of doctors, to help doctors perform surgeries, and proposed a vascular interventional autonomous surgical operation method based on deep learning, which can reduce the workload of doctors and achieve the purpose of assisting doctors.

Training data are obtained in the operation process of autonomous operation mechanism of vascular interventional surgical robot. In this paper, imitation medical image data and primary operation data are collected at the same time, and the corresponding relationship between them is established in advance. After data acquisition, it needs to be pre-processed, and then the pre-processed training data is divided into training set and test set according to the proportion of 70% and 30% and input into the network. According to the training network model, a set of continuous medical images are input to replace the doctor for judgment. The training model outputs the continuous operation judgment signal corresponding to the medical image, and injects the operation judgment signal into the slave controller to achieve the purpose of autonomous operation.

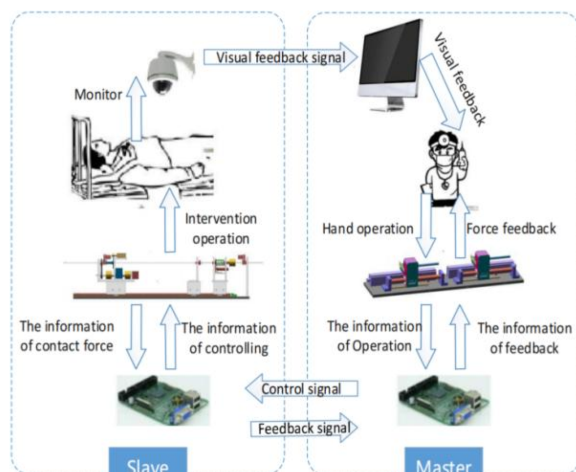

Fig.1 Conceptual diagram of vascular interventional surgical robot

III. Study on Position Tracking Control of Catheter Tip

A. *Dynamic Model of Catheter Intervention*

The vascular interventional surgical robot uses a stepper motor to carry out axial movement from the end, and pushes the catheter into the blood vessel from the end[13]. The dynamic analysis of the axial displacement movement of the catheter involved in the blood vessel is carried out to simplify the external interference factors. The dynamic model of catheter was established according to the motor drive of interventional surgical robot[14]:

$$f(t) = m\ddot{x}(t) + c\dot{x}(t) + kx(t) \quad (1)$$

Where, is the force that drives the motor to rotate, $x(t)$ is the displacement, $\dot{x}(t)$ is the velocity and $\ddot{x}(t)$ is the acceleration.

Let $x_1(t) = x(t)$,$x_2(t) = \dot{x}(t)$, have

$$\begin{cases} \dot{X}(t) = AX(t) + Bu(t) \\ y(t) = CX(t) \end{cases} \quad (2)$$

In formula,

$$\dot{X}(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} \quad (3)$$

$$A = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{c}{m} \end{bmatrix} \quad (4)$$

$$B = \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix} \quad (5)$$

$$C = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \quad (6)$$

Where m is the mass of the secondary device when the catheter is pushed, c is the damping coefficient between various devices in the push process, and k is the elastic coefficient of the slave device when pushing the catheter. According to Formula (1), the transfer function of the catheter in the blood vessel be written:

$$H(s) = \frac{1}{ms^2 + cs + k} \quad (7)$$

B. BP Neural Network PID Principle

PID controller has more reliable and stable excellent performance, and has been widely used in the industrial field, In robot design, PID is effective in trajectory tracking control and other aspects. PID stands for proportional, integral and differential control. Its principle is to process the error signal and achieve the overall tracking effect of the system.

The time-domain equation of the traditional PID controller is:

$$u(t) = k_p[e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de(t)}{dt}] \quad (8)$$

Where, k_p is the proportional coefficient, T_i is the integration time, k_p/T_i is the integration coefficient k_i , T_d is the differential time, k_pT_d is the differential coefficient k_d , $e(t)$ is the error signal, $u(t)$ is the output signal of the system.

BP neural network mainly includes input layer, hidden layer and output layer, and each layer includes multiple neurons[15], as shown in Fig.2. The information processing method of BP neural network has the following characteristics:

(1) High fault tolerance of information. Information (i.e., the weight of connections between neurons at each layer) is distributed and stored in the whole neural network.

(2) Parallel processing of information. Each neuron can process the received signal independently and output it after calculation, without interfering with each other. The whole network has good real-time performance and synchronization.

(3) Have the ability of self-learning. The network can keep learning as the system runs,and update the specific parameters in the network (neuron threshold and connection weight).

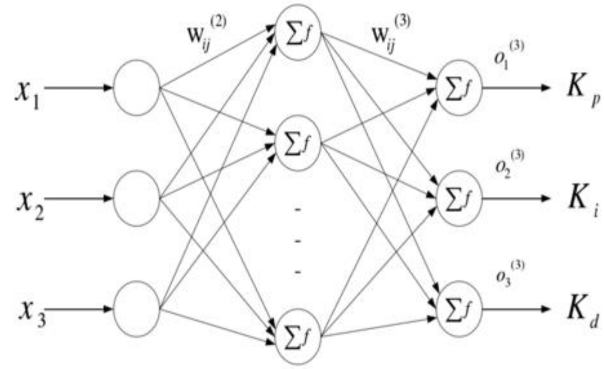

Fig.2 BP network structure diagram

The BP neural network algorithm mainly includes the forward propagation of signal and the back propagation of error. Forward propagation is mainly the output signal generated by the input layer to reach the output layer through the intermediate layer. When the actual output is different from the expected output, the error will be propagated back, and the weight of neurons will be updated according to the error and propagated backward until the expected value is obtained.

C. Catheter Tip Position Control Method

In the process of autonomous surgery, the operating displacement signal output of the training network model is transmitted to the slave end, and the stepper motor is controlled to push the conduit forward. After several tests, it was found that the actual displacement of the catheter tip in the blood vessel was not consistent with the expected displacement of the surgery[16].

After analysis and research, the main reasons are as follows:

(1)Due to system delay, system nonlinearity, external interference and other factors, the control performance deteriorates.

(2) When the catheter is pushed in the blood vessel, due to the irregular and curved shape of human blood vessels, the catheter will undergo slight deformation, thus affecting the displacement of the catheter.

In order to improve the accuracy of autonomous operation, improve the intelligence level of autonomous operation. In this paper, displacement compensation is carried out for the deviation between actual displacement and expected displacement. By combining BP neural network with PID, the position of catheter tip can be tracked and controlled, which can make the control effect better[17]. The principle diagram of BP neural network PID controller is shown in Fig 3.

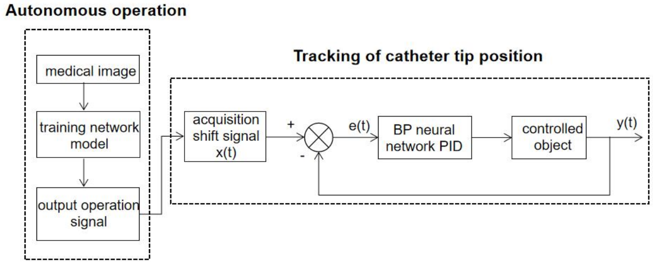

Fig.3 BP-PID control principle structure diagram

The function of BP neural network is to adjust the weight of each neuron through self-learning ability, which is realized as the weighted summation operation of the signal input layer, and activated by activation function as the input of the output layer, to obtain the output signal, and compared with the expected value. Finally, the gradient descent method is used to reverse propagation error to modify the weight of neurons, after repeated many times, Realtime adjustment of three parameters of traditional PID makes the control effect reach the best.

The BP neural network structure in this paper is composed of 3 input nodes, 5 implicit nodes and 3 output nodes. The input signal is the system state quantity, and the output signal is the three parameters in the PID controller. The BP network structure diagram is shown in Fig 4.

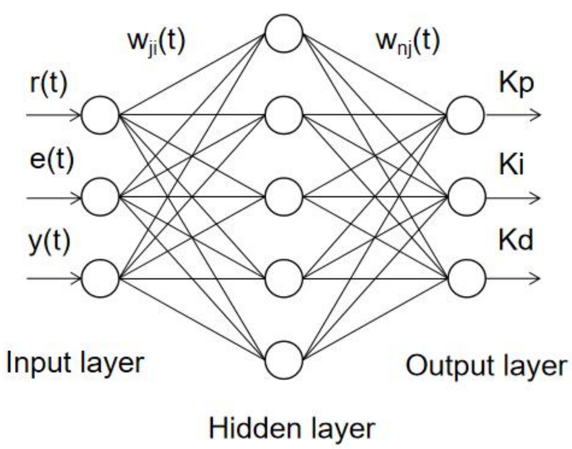

Fig.4 BP network structure diagram

In Fig.4, the input is three neurons, representing the expected input value $r(t)$, the actual output value $y(t)$ and the error value $e(t)$. The number of hidden layers is determined as 5 neurons after experiments and simulation results. The number of output neurons is 3, respectively representing the three parameters of PID k_p, k_i and k_d. $w_{ji}(t)$ is the weight from the input layer to the hidden layer; $w_{nj}(t)$ is the weight from the hidden layer to the output layer.

The operation steps of BP neural network PID control are as follows:

(1) First, the number and initial value of the nodes of the input layer and the hidden layer of the BP network $w_{ji}(0)$ and $w_{nj}(0)$ of synaptic weights of each layer are set; And set the learning rate η and momentum factor α, then t=1;

(2) At time t, sample $r(t)$ and $y(t)$, and calculate the error $e(t) = r(t) - y(t)$;

(3) Then, according to the known parameters, Calculate the input and output of neurons in each layer of the network;

(4) Calculate the output of the controller $u(t)$;

(5) Automatically adjust $w_{ji}(t)$ and $w_{nj}(t)$ through the self-learning process of neural network;

(6) Let t=t+1, then return to step (2), repeat many times until the requirements are met.

In the actual PID controller, k_p, k_i and k_d cannot be set to a negative number, so the activation function of the output layer of the network is:

$$g(x) = \frac{1}{2}(1+\tanh(x)) = \frac{e^x}{e^x + e^{-x}} \tag{9}$$

Expression of network output layer:

$$net_n^{(3)}(k) = \sum_{n=1}^{5} w_{nj}^{(3)} O_j^{(2)} \tag{10}$$

$$K_p = O_1^{(3)}(k) = g(net_1^{(3)}(k)) \tag{11}$$

$$K_i = O_2^{(3)}(k) = g(net_2^{(3)}(k)) \tag{12}$$

$$K_d = O_3^{(3)}(k) = g(net_3^{(3)}(k)) \tag{13}$$

Incremental PID control algorithm is selected in this paper. The expression is:

$$\begin{aligned}\Delta u(k) &= K_p[e(k)-e(k-1)] + \\ &K_i e(k) + K_d[e(k) - 2e(k-1) + e(k-2)]\end{aligned} \tag{14}$$

BP neural network PID algorithm aims to adjust three PID parameters online through network training, constantly update the weight threshold to reduce the error, and finally reach the expected value.

IV. EXPERIMENTS AND RESULTS

According to the design scheme in this paper, firstly, real-time medical images need to be input into the training network model of autonomous surgery, and the output to the operational displacement signal obtained from the secondary controller, namely, the expected displacement. Then, based on DSA imaging, information about the location of the catheter in the blood vessel is obtained, which is transmitted to the control system, and the displacement of the actual movement of the catheter tip is calculated, namely the actual displacement. Finally, BP-PID control algorithm is used to compensate the error between the actual displacement and the expected displacement.

For medical images of catheters in blood vessels, edge extraction is firstly carried out to make the image edge of the catheter tip more clear and distinct from the image background. The image after edge extraction is already a binary image [19]. From the point of view of pixel point, the gray value of binary image is only 0 and 255, that is, the whole image is only presented as black and white. After importing the binary image into MATLAB, we use find function to pick out the pixel coordinates of black points and fit them. Through the above processing methods, we obtained the image coordinate data of the catheter tip, as shown in Fig.5.

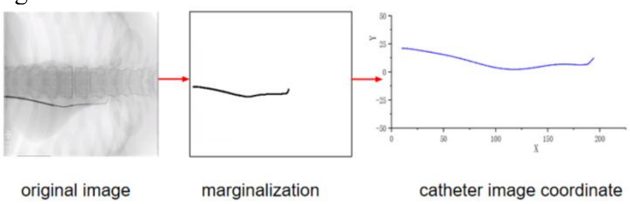

Fig.5 Obtaining the image coordinates of the catheter tip

After the coordinates of the medical image are obtained continuously, the distance of the catheter tip in a certain period of time can be calculated according to the distance formula between the two points, and the deviation of the displacement can be calculated, which is converted into an input signal and transmitted to the control end, so as to control the motor rotation and achieve the effect of displacement compensation.

In order to verify the effect of the newly designed controller in displacement tracking, The applicability of BP-PID algorithm in the displacement tracking system of interventional surgical robot is simulated by MATLAB. Simulink tool is used to simulate and compare the PID and BP -PID, and the Simulink models built are shown in Fig.6 and Fig.7 respectively.

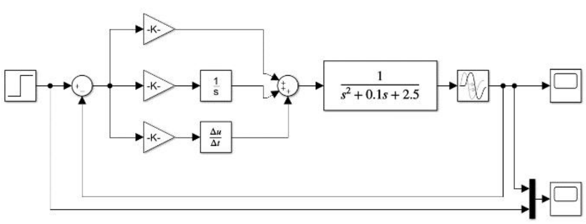

Fig.6 Simulink simulation of traditional PID

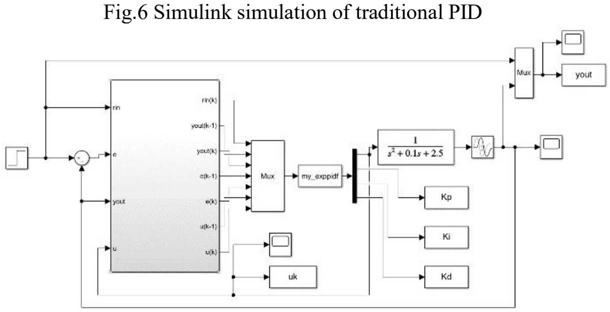

Fig.7 Simulink simulation based on BP neural network PID

In the autonomous operation of the vascular interventional surgical robot, AlexNet trained output model is used to replace the doctor for operation judgment, that is, a set of continuous medical images are input, the training model outputs the continuous operation judgment signal corresponding to the medical image, and the judgment signal is input to the slave controller to control the autonomous operation of the catheter. The displacement of the judgment signal is collected as the expected displacement. In the simulation design, the step signal is taken as the input signal to replace the expected displacement of a certain sampling time.

In Formula (7), each parameter value m=1kg, c=0.1N/(m/s), k=2.5N/m .In order to verify that the BP neural network PID displacement tracking control effect is better than the PID control, the experiment is designed in two parts, including the expected displacement remains unchanged and the expected displacement changes, the simulation input signal with step signal and step signal to replace the expected displacement.

If the expected speed is unchanged, step signal is used as input. The comparison effect of the two control algorithms is shown in Fig.8.

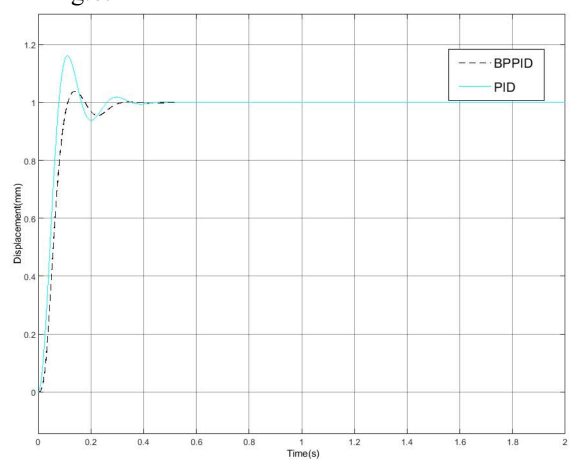

Fig.8 Comparison of PID and BP-PID simulation effect

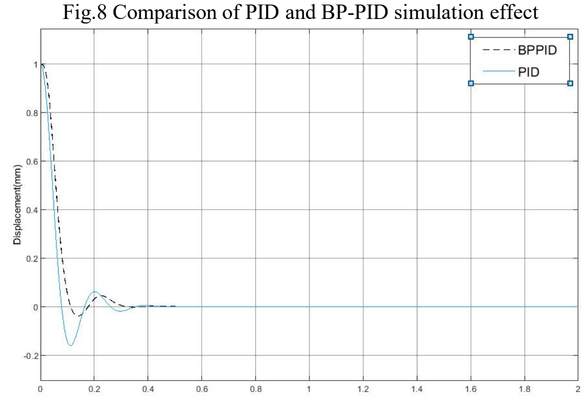

Fig.9 Comparison of PID and BP-PID error

The black solid line in Fig.8 is the response output curve of the BP-PID control algorithm, and the blue solid line is the response output curve of the traditional PID control algorithm. Through analysis, the system dynamic performance indicators are obtained as shown in Table 4.1.

TABLE I

DYNAMIC PERFORMANCE INDICATORS

Control strategy	Rise time t/ms	Adjust time t/ms	Overshoot δ /%
PID	6	40	8%
BP-PID	4	28	4%

The expression of overshoot is shown in the following formula, namely:

$$\delta = \frac{y(t) - y(\infty)}{y(\infty)} \tag{15}$$

Where, $y(t)$ is the maximum value of system output, and $y(\infty)$ is the stable value of the system. As can be seen from Table 4.1, compared with the traditional PID, the BP -PID used for position tracking control has little change in the system's rise time, the adjustment time is slightly reduced, and the overshoot decreases from 16% of the traditional PID to 4% of the latest control algorithm. Therefore, compared with PID algorithm, BP neural network PID algorithm in the system will be more practical, can ensure that the control system speed and stability to achieve the best control effect, and then improve the efficiency of surgery, enhance the safety of operation.

Ⅴ. CONCLUSIONS

Vascular interventional surgery robot, as an auxiliary system used in surgery, needs to have good control precision to ensure the safety of the doctor's operation. In this paper, BP-PID control method was used to track the position of catheter tip autonomous intervention of the vascular interventional surgical robot, so that the actual displacement can reach the expected speed, and the displacement difference can be compensated.This indicates that the proposed control strategy has good control quality, can make the system have good robustness, can improve the accuracy of autonomous surgery, improve the intelligence level of autonomous surgery. In future work, this research method will be incorporated into the mechanism of autonomous surgery to complete the final experiment of the paper and improve the accuracy of autonomous surgery.

ACKNOWLEDGMENT

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