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A PID-type Fuzzy Logic Controller for an Interventional Surgical Robot

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***Abstract* - Intracardiac vascular disease and Intracerebral vascular disease are the highest killers of human health. With the development of modern science and technology, the use of robotic technology to assist vascular interventional surgery has become an important means to decrease cardiovascular and cerebrovascular diseases. The cardio-cerebral vascular interventional Microrobots in Operating Room can free the doctor from the surgical site and prevent the radiation from harming the doctor's body. Aiming at the master-slave control problem of the vascular intervention robot, the traditional PID controller are analyzed, and the PID-type fuzzy controller of the vascular intervention surgical robot is designed. The experimental results of the treatment of vascular diseases with micro-robots are presented in this paper show that the PID-type fuzzy controller can effectively improve operational ability, and verify the feasibility of using the PID-type controller in the master-slave control system of cardiovascular and cerebrovascular intervention robot.**

***Index Terms* –Interventional Surgical Robot, Master-slave system, PID-type fuzzy control.**

I. INTRODUCTION

Cardiovascular and cerebrovascular intervention have obvious advantages because of the small wound surface, quick recovery and less postoperative complications [1]. However, there are many shortcomings in artificial vascular interventional surgery:

1). The intervening physician continues to be exposed to X-rays, which can easily do harm to his body.

2). During a surgical interventional procedure, the human misoperation or physiological tremor produced by the intervening physician owing to their fatigue may seriously affect the success rate of the operation.

3). Doctors must have many years of experience in vascular surgery to avoid mistakes. But surgical training takes time and is expensive.

In order to enhance the accuracy of the operation of vascular interventional surgery, reduce the risk of surgery, and provide doctors free of charge from the operation site, the introduction of robotic technology into cardiovascular and cerebrovascular interventional surgery has become a hot research topic at home and abroad [2].

Some products have been developed over the past decade. Hansen Medical has developed the Sensei robot system. The doctor manipulates the catheter with the aid of the imaging system to control the slave system. The Sensei robotic system offers four ratios of teleoperation, allowing doctors to choose different control modes depending on their operational needs [3]. The Amigo teleoperation robot developed by Catheter Robotic Inc. has achieved clinical application in more than 200 patients. Catheter Robotic Inc. has also been upgrading its products, and the latest product is the Amigo RCS robot system [4]. The Stereotaxis Inc. developed the Stereotaxis Niobe robotic system in 2002, a magnetic navigation interventional system. The Stereotaxis Inc. has long been committed to the improvement of the system and updated its products to Niobe ES MNS in 2012 [5]. Corindus Vascular Robotics has developed the Corpath 200 system, a vascular interventional robotic system. The system is an open system that allows the catheter to be selected according to the doctor's operational needs [6].

In the past research, many achievements have been taken all over the world. Professor Guo proposed a new type of interventional surgical System of Miniature Surgical Robot. The system uses a combination of active and driven modes of operation to realize remote operation [7-10]. Professor Ganji established a navigation platform for cardiac radiofrequency catheter ablation [11], and carried out corresponding catheter experiments. Professor Fu designed a master-slave intervention robot system which contains the main handle, auxiliary mechanical intervention, 3D guiding image and electromagnetic sensor for catheter positioning [10].

At the same time, many research institutes have done some work in the same field. Because of the strict requirements for the safety of interventional therapy, the position tracking errors between the main followers must be reduced during the operation.

A simple and effective PID-type fuzzy controller is proposed, which can be used in a master-slave control system. The controller can reduce tracking error and time delay.

II. INTERVENTIONAL SURGICAL ROBOT SYSTEM

The role of the vascular interventional surgery robot is to assist the doctor in controlling the push, pullback, and rotation of the catheter guide wire. According to the current low control precision of most vascular interventional robots, based on extensive research on the advantages and disadvantages of vascular interventional robots developed by various research institutions at home and abroad, a master-slave control system for vascular interventional robots is designed. Microvascular surgery robot can control the use of surgical tools very accurately. The specific operation schematic is shown in Fig.1.

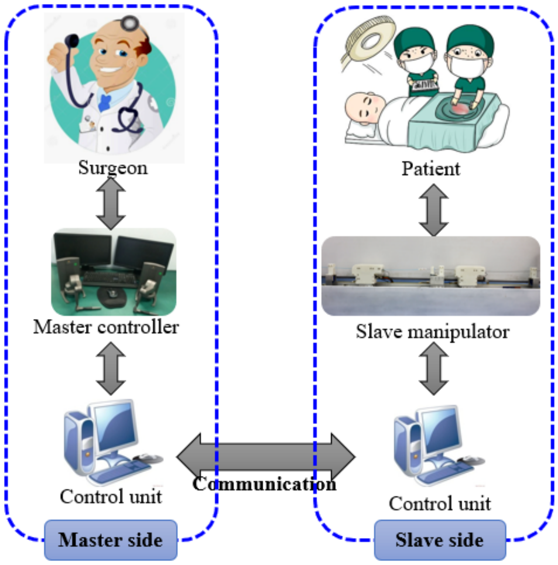


Fig.1 Schematic diagram of the system [13].

Vessel interventional surgical robot system includes master controller, slave operation and master-slave control system. Doctors manipulate the master controller to push, pull and rotate, and then send in the control information to the master-slave control system. The master-slave control system also sends information to the subordinate operator. After receiving control information from the operator, the motion of the guide wire and the catheter is controlled to follow the main controller [14].

A. *The master controller*

The purpose of the vascular interventional surgery robot is to free the doctor from the operating room. Generally, the doctor operates the master controller in a safe area without radiation.

This method is different from the traditional method of direct manipulation of the catheter in interventional vascular surgery. At present, most of the studies use motors to transmit force feedback information, and use motors to reach inertia of force feedback, so as to achieve the transmission of force information. Feedback of force transfer information from the direct detection of the guide wire of the catheter. Therefore, the main controller has the following requirements:

1). The structure of the master controller should be designed in accordance with operating habits of the doctor.

2). The master controller should be able to accurately collect the doctor's operation information in real time, including push, pull back and rotate.

3). The way of force feedback should be based on feedback without inertia to truly feedback force information.

Taking into account the above requirements, two Geomagic Touch X (Phantom Desktop) were selected as the master controller to control the catheter and the guide wire respectively [15], and they are used as a force feedback device. The master controller is shown in Fig.2.

Fig.2 Master controller [13].

B. *The slave operator*

The guide wire and the guide wire are operated directly by the slave machine, so it is very important to control the stability and accuracy of the guide wire. In order to insert the guide wire successfully, it must be in a position to push and rotate the guide wire backwards. According to the actual need of interventional surgery, an assistant operator was designed to complete the control of catheter guide wire. Its main functions include the control of the catheter drive controller and the guide wire drive controller to realize the rotation of the guide wire and the guide wire [16]. The structure of the slave operator is shown in Fig.3.

The catheter pushing controller and the guide wire pushing controller are fixed on the sliding rail by the moving block, and the coaxial control of the catheter and the guide wire is realized, and a pushing auxiliary mechanism is arranged between the catheter pushing controller and the guide wire pushing

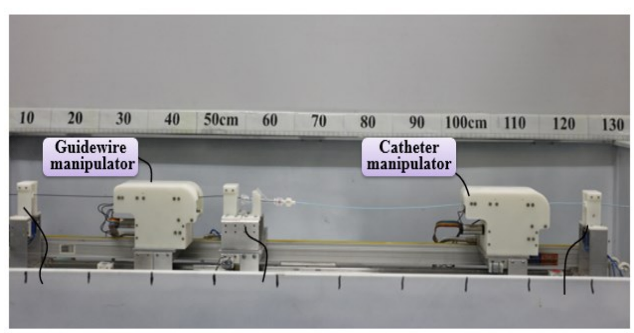


Fig.3 Slave operator [13].

controller, and It is placed at the end of the catheter to assist in supporting the end of the catheter and to collect and efflux blood from the end of the catheter. For the driving of the moving block on the slide rail, the rope driving method is adopted, and the rope driving is used to complete the control of the axial movement, which has the advantages of small inertia, simple structure, easy disassembly and the like.

III. THE CONTROLLING METHOD OF THE MASTER-SLAVE SYSTEM

A. The conventional PID control algorithm

Proportional integro-differential controller is a feedback mechanism of control loop widely used in industrial control system. The PID controller continuously calculates the error value. The error value is used as the difference between the expected setting point and the measurement process variables, and is corrected by using the proportionate, integral and differential terms (p, I and d, respectively).

The block diagram of conventional PID controller is shown in the Fig.4.

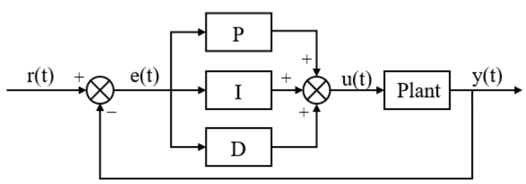


Fig.4 Conventional PID Controller.

In P I d control, the input is R (T), the output is Y (T), the error between input and output is E (T), and the control signal is the sum of three terms: P (proportional to error), I (proportional to error integral) and D (proportional to error derivative).

In this model, the P atom is proportional to the current value of the error. If the error is large and positive, the output will be broad and positive. I semester use the wrong value of the past and integrate it over time to generate my semester. If there are residual errors after the application of proportionate control, the residual errors can be eliminated by increasing the control effect of historical cumulative errors. Item D is an estimation of future error trend based on its current change rate. It can reduce the influence of errors by controlling the rate of change.

The conventional PID control algorithm is described by:

$$u(t) = K(e(t) + 1\big/T_I \int_0^t e(t)\,\mathrm{d}\,t + T_D\,\mathrm{d}\,e(t)/\mathrm{d}t) \qquad (1)$$

The parameters of the controller are proportional gain K, integral time T_I and differential time T_D. The traditional PID control algorithm can also be written in the following form:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)\,\mathrm{d}\,t + k_d\,\mathrm{d}\,e(t)/\mathrm{d}t \qquad (2)$$

Where k_p is the proportional gain, k_i is the integral gain, k_d is the differential gain.

B. The PID-Type Fuzzy Logic Control algorithm

The conventional fuzzy controller can be generally divided into two-dimensional and three-dimensional fuzzy controllers. Two-dimensional fuzzy controllers generally uses output error and the rate of change of the error to determine the control. The three-dimensional fuzzy controller uses the output error, the integral of the error and the derivative of the error to determine the control. This is similar to the PID controller. Therefore, the three-dimensional fuzzy controller is also called the PID-type fuzzy controller. There are two cases for a two-dimensional fuzzy controller [17].

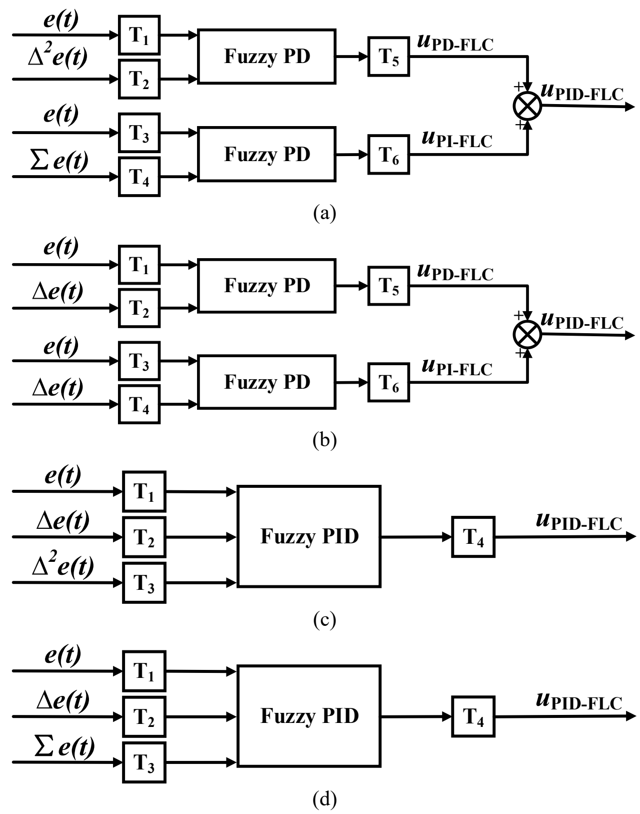


Fig. 5 Common PID-type fuzzy logic controllers [18].

Generally speaking, two-input and three-input fuzzy controllers are the most common structures. Some of the most common structures are illustrated in figure 5. It should be pointed out that the input and output variables of the controller are standardized within this range. Therefore, the first two structures need the appropriate values of six scale factors (see Fig. 5 (a), (b). The last two structures need four scale factors (see Fig. 5 (c), (d)).

E (T) is an error between input and output, while Cupid FLC is a control signal. As can be observed in Figure 6, parameters (t1, 2, 3, 4) are scaling factors that convert input and output variables into ranges [-1, 1].

The underlying fuzzy rules are given in figure 7. The input variables E (T) and _E (T) and output variables U (T) of the fuzzy controller are converted into five linguistic variables: Nb (negative large), NS (negative small), Z (zero), PS (positive small) and Pb (large). It takes 25 rules to complete the fuzzy rule base. According to the expected response of the system to the specific input of the interventional surgical robot system, the rule base table was designed. The rule base of the ambiguity section is given in table 1. The membership functions of input variables are presented in Figures 7 (a) and (b). The member function of the output variable is shown in Figure 7 (c).

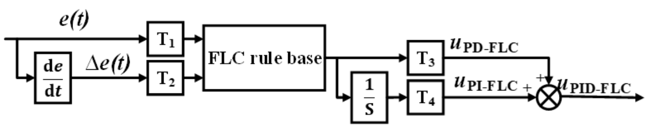


Fig.6 Alternative PID-type fuzzy logic controller.

TABLE I
FUZZY RULE-BASE FOR THE OUTPUT VARIABLE

e(t)	Δe(t)				
	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	Ns	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

IV. EXPERIMENTAL RESULTS AND ANALYSIS

MATLAB Simulink environment is used to simulate the control effect of the proposed controller. According to the dynamic model of the slave operator of the vascular interventional surgery robot, a linear plant of second order is considered to be used in this simulation.

$$G(s) = \frac{1}{1.2S^2 + 1} \tag{3}$$

The simulation block diagram is shown in Fig. 8.

The response of the plant is observed by using two controllers: conventional PID controller and the controller proposed in this paper. The parameters are described in Table II.

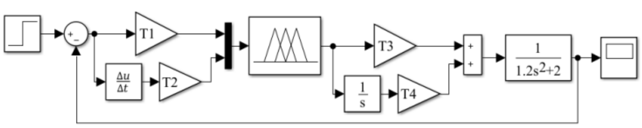
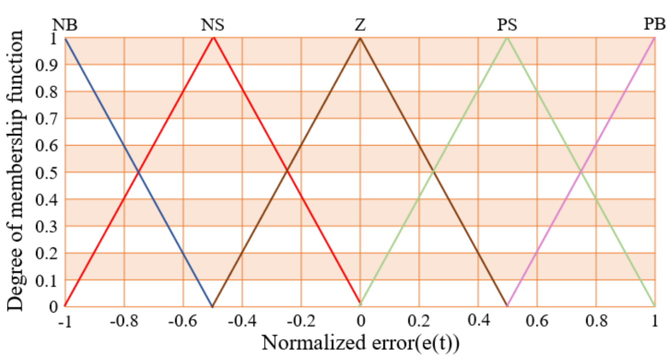


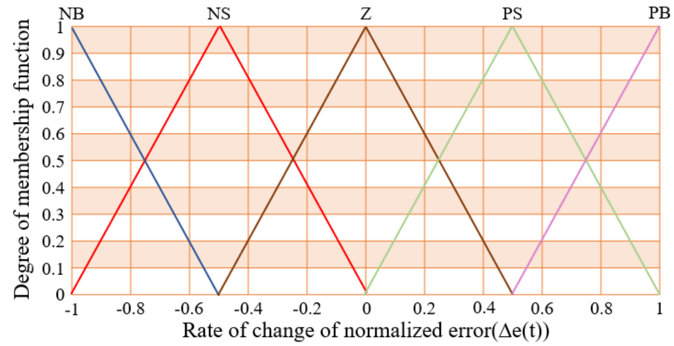
Fig.8. Block diagram of the PID-type fuzzy logic controller.

TABLE II
THE PARAMETERS OF THE SIMULATION

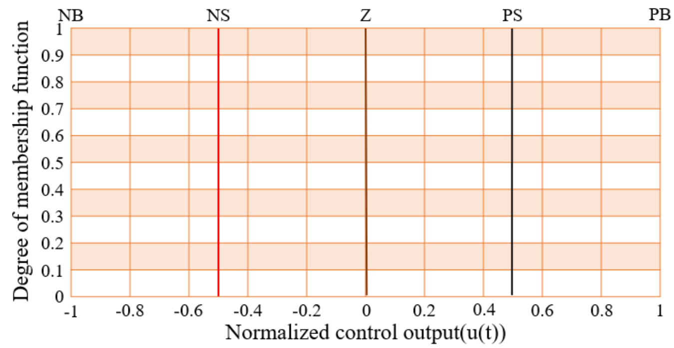
	T_1	T_2	T_3	T_4	k_P	k_I	k_D
Value	6.4	0.355	300	50	20	50	20



(a) Membership function for input e(t)



(b) Membership function for input Δe(t)



(c) Membership function for output variable

Fig.7 Membership functions for input and output variables.

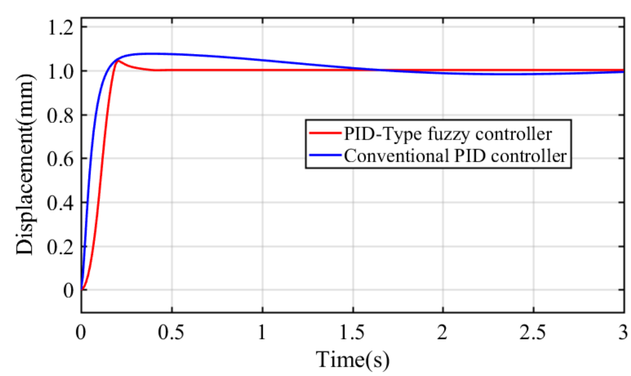


Fig.9 Step response position tracking comparison.

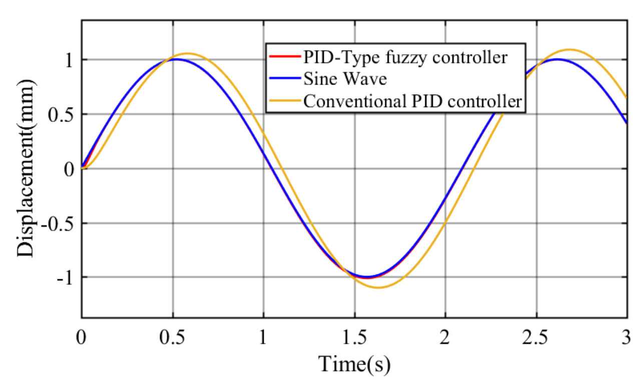


Fig.10 Sinusoidal response position tracking comparison.

It can be seen from Fig. 9 and Fig. 10 that the unsteady state fuzzy controller can greatly reduce the oscillation of the system, shorten the stability time of the system, and has high tracking performance.

V. Conclusion

A kind of unsteady-state fuzzy controller with good real-time and accuracy in master-slave control system of vascular intervention robot is proposed. However, the research done at this stage still has many shortcomings and needs further improvement. First, the mathematical model of the interventional surgical robot is not very accurate. This paper just briefly analyzes that the system is a second-order system, and does not give an accurate system model of this system. Second, in the simulation experiments of this paper, the selected parameters are only given by author, and are not optimized by algorithms such as optimization algorithms.

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