Adaptive Fuzzy PID Controller of a Master-Slave Robotic Catheter System in Minimally Invasive Surgery

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Abstract. Minimally Invasive Surgery (MIS) is a good choice to treat cardiovascular disease. However, the accuracy of catheter manipulation is limited by the doctor, and the X-ray damages the health of the doctors. A master-slave Robotic Catheter System (RCS) can solve the disadvantages of the traditional catheter intervention surgery. PID controller has been widely used in the master-slave RCS. However, Traditional PID controller used in the master-slave RCS will cause large overshoot or poor stability. An adaptive fuzzy PID controller can adjust the PID parameters online, reduce the overshoot, and improve the tracking performance of input signal. In this study, the dynamic model of the axial and rotational motion is presented. An adaptive fuzzy PID controller is proposed to improve the performance of the master-slave RCS. Simulation results show that the proposed controller is more effective than the traditional PID control, and the robustness is also improved.

Introduction

Minimally Invasive Surgery is getting more and more popular in diagnosis and surgery. Compared with the traditional operation, it has so many advantages such as little trauma, less blood, fast recovery and less recurrence. However, conventional minimally invasive surgery has many disadvantages: 1) In order to insert catheters successfully, the doctors not only needed to have rich knowledge and practical experience, but also needed to be very well trained. 2) During the operation, the doctors have to work around X-ray camera, so the X-ray damages the health of the doctors; 3) the doctors’ misoperation may be hurt patients.

Robotic Catheter System is a best choice to solve these problems. Many products and researches are reported in this area, such as Sensei Robotic Catheter System. Shuxiang Guo developed a Novel Robotic Catheter Manipulating System with a traditional PID controller. Harbin Institute of Technology has developed a Catheter robot system. Shenyang institute of automation of Chinese academy of sciences and Beijing Institute of Technology have studied the transmission of navigation system and motion planning problem respectively.

The traditional PID controller has been widely used in the master-slave RCS. However PID controller used in the master-slave RCS has a large overshoot, and it can’t take into account both dynamic response and control accuracy. So the tracking performance of the slave hand is not very perfect, and sometimes it may be unsafe. Due to the flexibility of the catheter used in the MIS, vessel wall friction, the blood resistance and complicated by cardiac contractions. The accurately model of steerable catheter is difficult to achieve and maintain.

The adaptive fuzzy PID is a good choice to solve these problems, not only for its flexibility and strong adaptability, but also for the high control precision of PID. On the other hand, the fuzzy controller does not require accurate model of the steerable catheter. In this paper, the dynamic model of axial and rotational motion is presented. An adaptive fuzzy PID controller is designed to reduce the overshoot, and to improve the robustness and accuracy of tracking performance. So the proposed controller used in the master-slave RCS will improve security in MIS.
System Description

As shown in Fig. 1, the master-slave RCS consists of two parts: the master hand and the slave hand. The master hand is the controller of the system. It obtains the control information from the doctors. The slave side is the catheter driver of the system. The structure of the slave hand is similar to the structure of the master hand, and they are connected via internet. So the doctors can control the master hand outside of the operating room, and then the control signals include displacement and rotation angle are sent to the slave hand. When the slave hand receives the control signals, it will drive catheter to the planned position.

![Fig.1 The master-slave system](image1)

![Fig. 2 The structure of fuzzy PID control diagram](image2)

During minimally invasive surgery, the catheter is pushed/pulled and rotated by the doctor to pass through the blood vessels to the lesion location. So the slave hand contains two degrees of freedom (axial motion and rotational motion) to imitate a doctor’s two actions: push/pull and rotate. The axial motion is driven by a stepper motor, and a DC motor is used to drive the catheter to rotate around the axis. Each motor has an encoder to obtain the displacement of the axial movement and the angle of rotational motion. Two force measuring device are used to measure force and torque information of the two motors.

Dynamic Model of the Axial Movement. The axial movement is driven by stepper motor. According to the Newton’s second law, the equation that describes the physical relationship is as follows:

\[ f(t) = m\ddot{x}(t) + c\dot{x}(t) + kx(t) \]

(1)

Where, \( f(t) \) is the force from master part, \( x(t) \) indicates moving displacement, \( \dot{x}(t) \) indicates the velocity. The Eq. 1 describes the relationship between the input force and the displacement. It is a translation system that similar to the mass-spring-damper model.

Defining \( x_1(t) = x(t) \), \( x_2(t) = \dot{x}(t) \), The Eq. 1 can be written as equation Eq. 2:

\[
\begin{align*}
\dot{x}_1(t) &= AX(t) + Bu(t) \\
\dot{x}_2(t) &= CX(t)
\end{align*}
\]

(2)

Where, \( X(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} \), \( A = \begin{bmatrix} 0 & 1 \\ -k/m & -c/m \end{bmatrix} \), \( B = \begin{bmatrix} 0 \\ 1/m \end{bmatrix} \), \( C = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \).

\( m \) represents the quality of the movement part (mainly includes the mass of the motor and reduction gear; the mass of the catheter is lighter, so we don’t consider it). \( c \) and \( k \) are the viscous damping coefficient and the coefficient of elasticity, respectively.

Dynamic Model of the Rotational Movement. A DC motor with a encoder is used to drive the catheter rotating around the axis. The rotational movement is treated as a mass system that connected with flexible shaft or spring. In this paper, the rotational motion is assumed as linear model, without regarding the nonlinear effects caused by the speed dependent friction, dead time and time delay.

The rotational motion is modeled as equation (3). It describes the relationship between the input torque and the rotational angle. \( J = mr^2 \) represents the moment of inertia. In the transmission system for slave hand, the transmission mechanism and catheter belong to micro system, the speed is relatively small, and the difference in segmental moment of inertia is greater. In order to simplify the calculation of the system, the analysis of the moment of inertia is as follows:
1) The DC servo motor plays a leading role to the moment of inertia, and it occupies a large share in the whole system.

2) The transmission device and the gear mechanism are usually made of aluminum material, the value of inertia converted onto the motor axis is small. Due to their low speed and small angle range, we ignore their inertia is acceptable.

3) The catheter is an approximation of continuous body of revolution, so it’s difficult to obtain its inertia. Because of the small value of the catheter radius, the value of its inertia is also very small.

Above all, \( J \) in Eq. 3 is the value of DC servo motor’s moment of inertia.

\[
m \ddot{\theta}(t) + c \dot{\theta}(t) = u(t).
\] (3)

Where \( u(t) \) indicate input torque, the rotational angle is \( \theta(t) \), and \( \dot{\theta}(t) \) indicates the velocity of rotational angle. Define \( \dot{\theta}_1(t) = \theta(t) \), \( \dot{\theta}_2(t) = \dot{\theta}(t) \), then Eq. 3 can be written as Eq. 4:

\[
\begin{align*}
\dot{\theta}(t) &= A \psi(t) + Bu(t) \\
y(t) &= C \psi(t)
\end{align*}
\] (4)

Where, \( \psi(t) = \begin{bmatrix} \dot{\theta}_1(t) \\ \dot{\theta}_2(t) \end{bmatrix} \), \( A = \begin{bmatrix} 0 & 1 \\ 0 & -c/J \end{bmatrix}, B = \begin{bmatrix} 0 \\ 1/J \end{bmatrix}, C = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \).

According to the proposed equation of state, the transfer function of the system can be obtained. The transfer functions of axial movement and rotational movement are shown as below:

\[
y_1 = \frac{m}{ms^2 + cs + k}.
\] (5)

\[
y_2 = \frac{J}{Js^2 + cs}.
\] (6)

Eq. 1 ~ Eq. 6 describe the dynamic model of the axial movement and the rotational movement for the slave hand. However, the two models are only rough approximations. Because we ignore many nonlinear factors in the driven system, such as the friction of the system, the resistance of blood flow, dead zone, time delay, the parameters of the catheter itself, environment condition and a lot of uncertainty factors, etc. So Eq. 1 and Eq. 3 are only the fundamental models, and they are incomplete.

Traditional PID controller can’t automatically adjust the parameters of control function (the proportional gain, derivative gain and integral gain) along with the changes of environment and their own parameters to achieve the best control effect. So we choose the adaptive fuzzy PID controller with characteristics of intelligence is very necessary and appropriate.

**Fuzzy PID controller**

The principle of adaptive fuzzy PID controller. The basic principle of the adaptive fuzzy PID controller is to use the fuzzy control rules to adjust the parameters of PID controller online. The current-feedback error \( e \) and derivative \( ec \) are used as the inputs of the fuzzy controller, and the outputs are the value of \( k_p \), \( k_i \) and \( k_d \). The structure of adaptive fuzzy PID controller is shown in Fig.2. Fuzzy controller is mainly composed of fuzzification, fuzzy inference, the membership functions, rule base and defuzzification.
Membership Functions. The membership functions for controller inputs (error $e$ and derivative $ec$) and the output $p_k$ are defined on the common interval (-1,1), which are shown in Fig.3. The value of language variable are {NB, NM, NS, ZO, PS, PM, PB}, the fuzzy language variables are defined as: negative big (NB), negative middle (NM), negative small (NS), zero (ZO), positive small (PS), positive middle (PM), positive big (PB). The membership functions for controller outputs $i_k$ and $d_k$ are defined on (0,1) and (0,2) respectively, which are shown in Fig.4 and Fig.5. As shown in Fig.3 to Fig.5, trimfs are selected as membership functions of two inputs and three outputs.

Fuzzy Control Rules. The design of fuzzy rules is the core of the fuzzy controller. Fuzzy control rules have nothing to do with mathematical model of controlled objects. The fuzzy control rules are built by expert knowledge and the experience of manipulators.

The equivalent expression of traditional PID controller is given as Eq. 7:

$$u(t) = k_p e(t) + k_i \int_0^t e(t) dt + k_d \frac{de(t)}{dt}.$$ (7)

Where $k_p$, $k_i$, and $k_d$, are the proportional, integral, and derivative gains respectively, $u(t)$ is the output of the PID controller. The error $e(t) = r(t) - y(t)$, where $r(t)$ is the input signal, and $y(t)$ is the value of output.

According to the different value of error $e$ and the derivative $ec$, the self-tuning rules of $k_p$, $k_i$, and $k_d$, during the control process as shown below.

1) When $e$ is big value: to improve the speed of response, choosing a big $k_p$; A small $k_i$ and a small $k_d$ are also need to avoid large overshoot and integral saturation.

2) When $e$ is middle value: The value of $k_p$ should be decreased; A moderate $k_i$ and a moderate $k_d$ should be adopted to keep reducing the error and avoid large overshoot.

3) When $e$ is small value: We should increase $k_p$ and $k_i$ for better steady performance; In order to avoid oscillating around the corresponding static value, a middle $k_d$ should be selected.

According to the experience of the experts, we use the fuzzy control rules as shown in table 1. We build 49 control rules in this paper, and the rules for the present problem are structured as follows:

1) If( $e$ is NB) and( $ec$ is NB) then($k_p$ is PB)($k_i$ is NB) ($k_d$ is PS)

2) If( $e$ is NB) and( $ec$ is NM) then($k_p$ is PB)($k_i$ is NB) ($k_d$ is NS)

......

49) If( $e$ is PB) and( $ec$ is PB) then($k_p$ is NB)($k_i$ is PB) ($k_d$ is PB)
Defuzzification. Defuzzification is the procedure that produces a real value from the result of the inference. The centre of gravity method is one of the most widely used methods, because of its computational efficiency. So choose it for defuzzification.

The Adaptive Fuzzy PID Controller of the Master-slave RCS.

The structure of the master-slave RCS’s adaptive fuzzy PID controller is shown in Fig.6. The input signal from the master part is position command. Then compared with the actual value, we will obtain the values of $e$ and $ce$. Control rules of the controller are established based on experience. According to the values of $e$ and $ce, k_p, k_i$ and $k_d$ will be changed by fuzzy controller, then they will be sent to PID controller as proportion coefficient, integral coefficient and differentiation coefficient.

MATLAB Simulation

To test the tracking performance of the controller, change the rule base of the fuzzy controller, and adjust the parameter $k_p, k_i$ and $k_d$. A simulation model of adaptive fuzzy PID controller is constructed in Matlab/Simulink. The parameters of the dynamic model are shown as following: $m = 1kg$, $c = 0.04N/(m/s)$, $k = 2N/m$, $J = 1kg\cdot m^2$. So transfer functions of the axial motion and rotational motion can be obtained according to Eq. 5 and Eq. 6, which are shown as Eq. 8 and Eq. 9.

$$y_1 = \frac{1}{s^2 + 0.04s + 2}.$$  \hspace{1cm} (8)

$$y_2 = \frac{1}{s^2 + 0.04s}.$$  \hspace{1cm} (9)

Table 1  Fuzzy Control Rules for $k_p$, $k_i$ and $k_d$

| E\EC | NB     | NM     | NS     | ZO     | PS     | PM     | PB     |
|-------|--------|--------|--------|--------|--------|--------|--------|
| NB    | PB/NB/NS | PM/NM/NS | PM/NM/NS | PS/NS/NS | ZO/ZO/NS | ZO/ZO/NS | PB/NB/NS |
| NM    | PB/NB/NS | PM/NM/NS | PS/NS/NS | ZO/ZO/NS | NS/ZO/NS | PB/NB/NS |
| NS    | PM/NB/ZO | PM/NS/NS | ZO/ZO/NS | NS/ZO/NS | NM/PM/NS | NM/PM/NS | PB/NS/ZO |
| ZO    | PM/NM/ZO | PM/NS/NS | ZO/ZO/NS | NS/ZO/NS | NM/PM/NS | NM/PM/NS | ZO/NS/ZO |
| PS    | PS/NM/ZO | ZO/ZO/NS | NS/PS/NS | NM/PS/NS | NM/PM/NS | NM/PM/NS | ZO/NS/ZO |
| PM    | PS/ZO/PB | ZO/ZO/NS | NS/PS/PB | NM/PS/PB | PS/NS/PB | NS/PS/PB | PB/NS/PB |
| PB    | ZO/ZO/PB | ZO/ZO/NS | NM/PS/PB | NM/PS/PB | PS/NS/PB | NS/PS/PB | PB/NS/PB |
The step response of axial movement and rotational movement are shown in Fig.7 and Fig.10. Fig.8 and Fig.11 shows tracking error of the axial movement and the rotational movement. Partial enlarged view of the axial movement and the rotational movement are shown in Fig.9 and Fig.12.

In the axial movement, the input signal is displacement command comes from the master hand. According to Fig.7 and Fig.8, the PID controller used in the axial movement has a large overshoot. While the overshoot of the proposed adaptive fuzzy PID is smaller compared with PID controller. The response of the adaptive fuzzy controller is quicker than the PID controller, the rising time and settling time is shorter. The proposed controller has reduced hysteresis, so it prevents the oscillation curve of the slave hand. The tracking performance of adaptive fuzzy PID controller in axial motion is also improved. In 3 seconds, a step disturbance signal (the value is 0.1mm) is added to the system. Fig.9 shows that the anti-interference capability of adaptive fuzzy PID is stronger than PID controller’s anti-interference capability.

In the rotational movement, the input signal is angle command comes from the master hand. According to Fig.10 and Fig.11, the tracking performance of adaptive fuzzy PID controller used in the rotational movement is also better than PID controller, less time to reach the desired angle shows successful performance of adaptive fuzzy PID controller. Fig.10 shows that the adaptive fuzzy PID controllers have good performance in reducing the maximum overshoot. In 3 seconds, a step disturbance signal (the value is 0.1deg) is added to the system. According to Fig.12, the anti-interference capability of adaptive fuzzy PID controller is also perfect than the PID controller.

Conclusion

Due to the disadvantages of the traditional PID controller in the master-slave RCS, the dynamic model of the axial and rotational motion is presented, an adaptive fuzzy-PID controller is proposed to improve the tracking performance. MATLAB/simulation results show that the designed adaptive fuzzy-PID controller has better performance in tracking the master’s signal compared with traditional
PID controller. So the proposed controller is a better choice to be used in a master-slave RCS, not only for its high accuracy, the perfect tracking performance and robustness, but also for its security in MIS.

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