Application of Fuzzy Neural Network PID In Laser-guided Mortar Projectile

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Abstract. Based on the high control performance requirement of laser-guided mortar control system, the permanent magnet synchronous motor (PMSM) is adopted in this paper as the electromechanical actuator of the system, the mathematical model of the motor is analyzed, and the vector control technology is adopted to achieve precise control of position, speed and torque of the electromechanical actuator. Aiming at the characteristics of non-linearity, strong coupling and large parameter changes of the system in flight, an improved fuzzy neural network PID control method is proposed by combining the classical PID control algorithm with fuzzy control and neural network control algorithm to realize the real-time tuning and optimization of PID parameters. The mathematical model of the electromechanical actuator control system is established and simulated. The results show that the fuzzy neural network PID control has good tracking performance, small amplitude error, and strong adaptability to load changes.

1. Introduction
In recent years, the proportion of precision-guided weapons used in war has increased. Many countries have improved the precision strike capability of artillery through the development of laser-guided projectiles. Under such demand, low-cost laser terminal guided mortars with good accuracy have emerged. The electromechanical actuator control system outputs a correction signal according to the measured deviation value, controls the deflection of the actuator surface, and realizes the control of the projectile's flight attitude. Thanks to the development of rare earth materials, microelectronics and computer technology, permanent magnet synchronous motors (PMSM) have been widely used in guided weapon systems with their simple structure, high efficiency, high power density, and good controllability. PMSM vector control can decouple the current torque component and the excitation component through coordinate system transformation, thereby simulating the DC motor torque control under the rotating magnetic field. Then simple control of PMSM is achieved by controlling armature current and excitation current[1].

The mortar flight end seeker transmits the calculated actuator surface angle to the control system according to the deviation. Based on the three closed loops of the position loop, the speed loop and the current loop, the position of the actuator is precisely controlled by the PID controller. The classic PID control algorithm has a history of more than a hundred years and is widely used in various industrial productions. It is simple, reliable, and highly robust, and is suitable for stable linear systems with precise mathematical models. But artillery shells are often affected by airflow disturbances in flight, and traditional PID control is often difficult to control this nonlinear and complex system, and it cannot achieve the control effect required by the guidance accuracy. Fuzzy control can express control experience and knowledge in language rules, and has a good control effect on nonlinear control systems.
with unknown mathematical models, but it is relatively lack of self-learning ability and mainly relies on expert experience. Neural network control builds models by simulating the human brain nervous system from the structure and function. It has strong ability to approximate nonlinear functions and self-learning, but it is not good at expressing knowledge explicitly.

Based on the respective advantages and disadvantages of fuzzy control and neural network control, this paper combines fuzzy control, neural network control and classic PID, and proposes a fuzzy neural network PID control technology applied to guided mortar rudder system, combined with the use of fuzzy control Experience knowledge ability and neural network self-learning ability, so as to meet the control system's requirements for accuracy and sensitivity[2].

2. Methods and theories

2.1. Design of electromechanical actuator control system

2.1.1. Three closed loop control system

The electromechanical actuator control system receives the actuator surface angle position signal calculated from the seeker. The projectile rolls at low speed during the projectile flight, and the steering gear rotates in the opposite direction relative to the projectile to achieve zero speed relative to the inertial coordinate system, and it is in position control. The system is controlled by three closed loops. The current loop is the innermost loop of the control system. The control system provides the control torque for the electromechanical actuator through the current value collected by the current sensor and the current regulator (ACR). The speed loop is in the middle ring of the system, and the speed signal collected by the Hall sensor and the speed regulator (ASR) generate the reverse rotation speed relative to the projectile to realize that the rudder surface is stationary relative to the inertial system. The position loop is in the outermost loop of the system, and the position signal collected by the Hall sensor and the position regulator (APR) output the expected phase angle of the actuator surface relative to the geodetic coordinate system.

![Figure 1. Steering gear control system.](image-url)

2.1.2. Vector control

There are three types of coordinate systems in vector control (FOC): The $ABC$ coordinate system formed by the three windings of the PMSM three-phase stator, the coordinate axes are separated by 120°; A static coordinate system composed of the $\alpha$-axis that coincides with the $A$-axis and the $\beta$-axis that intersects with it; A rotating coordinate system composed of a $d$-axis coincident with the rotor axis and a $q$-axis perpendicular to it.

From the PMSM magnetic torque formula:

$$T_e = p_a \left[ \psi_f i_q + (L_d - L_q) i_d i_q \right]$$

(1)

It can be seen that when $i_d = 0$, the electromagnetic torque $T_e$ is proportional to the torque current component $i_q$.

The three closed-loop current command values are obtained through PID regulators to obtain the control voltages $u_{dref}$ and $u_{qref}$ of the $d$ and $q$ axes, and then the voltage is transformed to the
\(\alpha\) and \(\beta\) axes of the static coordinate system through the inverse Park transformation, and then the vector pulse width modulation technology (SVPWM) is adopted. Control the three-phase inverter to realize the control of PMSM. The FOC control system of PMSM is as follows:

2.2. PID Controller of Fuzzy Neural Network

2.2.1. Fuzzy BP neural network PID controller

The reaction sensitivity and position accuracy of the phase angle of the actuator surface of the projectile in the terminal guidance flight stage directly determine the accuracy of the projectile[3]. Therefore, this article improves the PID controller of the position loop in the steering gear vector control system. In the fuzzy control, the self-learning ability of the neural network is integrated, and the error \(e\) of the actual feedback value of the phase angle of the steering gear and the ideal output value and the rate of change of the error \(\dot{e}\) are used as input, and the fuzzy neural network outputs \(K_p\), \(K_i\), and \(K_d\) values in real time. Set the P(proportional), I(integral) and D(differential) parameters in PID[4].

In the figure \(K_p\), \(K_i\), \(K_d\) are PID controller parameters.

The control system uses BP neural network. The algorithm learning is divided into two processes of forward propagation and backward propagation. If the input value is processed layer by layer to the output layer, the actual output and expected output error exceeds a certain threshold, then the error Backward transmission layer by layer and apportion to all units of each layer, thereby correcting the weight of each unit. Repeatedly adjust the weights of each layer until the output result reaches the expected error range. According to the above principles, this paper designs a fuzzy neural network with an input layer, a fuzzy layer, a fuzzy rule layer, a normalization layer, and a clarification layer.
2.2.2. Neural network learning algorithm

The adjustment process of the weights and other hyperparameters of each layer in the BP neural network is also the learning and training process of the neural network. The learning and training are stopped when the output error is reduced to a preset threshold or the preset number of learning times. In this paper, the direct and effective gradient method is used to find the minimum error bound, which is the negative gradient descent method used to find the optimal error function and the inertia term is introduced to accelerate the convergence [5].

The error $E$ between the network output and the expected value is defined as follows:

$$ E = \frac{1}{2} \left[ r_{in}(k) - y_{out}(k) \right]^2 $$  \hspace{1cm} (2)

Among them, $r_{in}$ is the expected input value of the system, and $y_{out}$ is the actual output value of the system. The negative gradient relationship between weight $\omega_{kp}$ and its modification $\Delta \omega_{kp}$ and error $E$ is as follows:

$$ \frac{\partial E}{\partial \omega_{kp}} = \frac{\partial E}{\partial f^{(5)}} \frac{\partial f^{(5)}}{\partial \omega_{kp}} = -\delta^{(4)} y_p $$  \hspace{1cm} (3)

The correction formula of the weighting coefficient is as follows:

$$ \omega_{kp}(k + 1) = \omega_{kp}(k) - \eta \frac{\partial E}{\partial \omega_{kp}} + \alpha (\Delta \omega_{kp}(k)) $$  \hspace{1cm} (4)

The relationship between the central value $c_{ij}$ and the width $\sigma_{ij}$ of the membership function and the negative gradient of the error $E$ is as follows:

$$ \frac{\partial E}{\partial c_{ij}} = \frac{\partial E}{\partial f^{(3)}} \frac{\partial f^{(3)}}{\partial c_{ij}} = -\delta^{(2)} \frac{2(x_i - c_{ij})}{\sigma^2_{ij}} $$  \hspace{1cm} (5)

$$ \frac{\partial E}{\partial \sigma_{ij}} = \frac{\partial E}{\partial f^{(3)}} \frac{\partial f^{(3)}}{\partial \sigma_{ij}} = -\delta^{(2)} \frac{2(x_i - c_{ij})^2}{\sigma^3_{ij}} $$  \hspace{1cm} (6)

The correction formula for the central value and width of the membership function is as follows:

$$ c_{ij}(k + 1) = c_{ij}(k) - \eta \frac{\partial E}{\partial c_{ij}} + \alpha (\Delta c_{ij}(k)) $$  \hspace{1cm} (7)

$$ \sigma_{ij}(k + 1) = \sigma_{ij}(k) - \eta \frac{\partial E}{\partial \sigma_{ij}} + \alpha (\Delta \sigma_{ij}(k)) $$  \hspace{1cm} (8)
Among them \( \eta_1, \eta_2, \eta_3 \) represent the learning rate; \( k \) represents the iterative step, and \( \alpha \) is the inertia factor.

2.3. System Simulation
In order to verify the control effect of the fuzzy neural network PID in the mortar servo system through simulation, Simulink is used in Matlab to establish the permanent magnet synchronous motor vector control model based on the traditional PID controller and the fuzzy neural network PID controller. Because the fuzzy neural network PID is difficult to build directly from the toolbox in Simulink, the S-function program is written to express the fuzzy neural network (FNN) sub-module.

![Figure 5. Fuzzy neural network PID simulation model.](image)

The permanent magnet synchronous motor selected for this system has a rated voltage of 24V, a rated power of 64W, a rated speed of 3000 r/min, a rated armature current of 3.13A, a rated torque of 0.2NM, a torque coefficient of 0.057NM/A, and a back-EMF coefficient of 4.13V/RPM. The number of magnetic poles is 8, the phase resistance is 0.89Ω, and the phase inductance is 0.62mH. The moment of inertia of the rudder blade converted to the motor rotor is 001g.cm².

The initial value of the learning rate of the fuzzy neural network PID algorithm is set as \( \eta_1 = \eta_2 = \eta_3 = 0.15 \), The inertia factor is set to \( \alpha = 0.04 \).

3. Results & discussion

3.1. Step signal performance simulation
A step signal with a actuator surface angle of 1° is input into the control system, and the simulation results of Fig. 6 and Fig. 7 are obtained.

![Figure 6. Traditional PID step characteristic curve.](image) ![Figure 7. PID step characteristic curve of fuzzy neural network.](image)
It can be seen that the traditional PID has an overshoot of about 10%, and the system stabilization time takes about 0.4s. The fuzzy neural network PID has only about 1% overshoot, and the signal stabilization time is about 0.1 seconds. Compared with the traditional PID, the control performance of the step signal is much better.

3.2. Follow signal performance simulation
Input a sine signal with an amplitude of 2 and a period of 50rad/s in the steering gear control system, and the simulation results of Fig. 8 and Fig. 9 are obtained.

![Figure 8. Classic PID followability curve.](image1)

![Figure 9. PID following characteristic curve of fuzzy neural network.](image2)

It can be seen that the traditional PID has signal distortion. The fuzzy neural network PID does not have the distortion problem. Compared with the traditional PID, the follow-up control performance of the continuous signal is better.

4. Conclusions
This paper studies the control system of terminal guided mortar rudder, selects permanent magnet synchronous motor and establishes three closed-loop control system, analyzes the characteristics of PMSM, selects vector control method with better control performance, and applies fuzzy neural network control to the position of vector control algorithm to improve the performance of actuator control. The steering gear control system model is established, and the position loop is controlled by traditional PID and fuzzy neural network PID respectively. Through the comparison of simulation results, the following conclusions can be drawn: Compared with traditional PID, fuzzy neural network PID has a small overshoot and system response time Short, better follow-up for continuous signals.

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