Design of UAV yaw Angle controller based on variable domain fuzzy PID

Wang Ning, Li Zhe, Liang Xiaolong, Zhang Jiaqiang
Air Force Engineering University, College of Air Traffic Control and Navigation, Xi’an, Shaanxi 710051 China
*Corresponding author’s e-mail: 104753191123@henu.edu.cn; wnlearning@163.com

Abstract: Four-rotor UAV is widely used in reconnaissance missions, UAV usually needs to adjust the yaw angle before reconnaissance aerial photography. To improve the speed of the four-rotor uav at the adjustment of yaw angle, this paper presents a variable-domain fuzzy PID controller. First, we established the nonlinear dynamic model of four-rotor UAV. Then, we fuzzed the corresponding variables in the governing equation, formulated fuzzy rules and introduced variable theory to adjust domain of discourse. Finally, we used simulink software to carry out experiments. The experiment result shows that variable-domain fuzzy PID controller has some undoubtedly advantages in performance evaluation compared to traditional PID controller, which including dynamic property and steady state error, and can be used to improve the quality of the adjustment of yaw angle.

1 Introduction
Quadrotor UAV is a kind of vertical lift aircraft, which is widely used in military reconnaissance. In the application of quadrotor UAV to military reconnaissance, there are the following problems: 1) the flight control of quadrotor UAV is a strong coupling, nonlinear control system, it is difficult to establish an accurate dynamic model. 2) Military missions have special requirements for the reconnaissance efficiency of UAV reconnaissance flight, and there is still room for improvement of attitude adjustment efficiency in the reconnaissance flight of image reconnaissance UAV.

At present, there are linear quadratic (LQR) controller, traditional PID controller, neural network controller, backstepping controller and sliding mode controller designed by domestic and foreign research institutions. Among them, Chen Yan min et al. proposed a decentralized PID neural network (PIDNN) attitude control method for quadrotor UAV, which improves the maneuverability and robustness of UAV attitude adjustment. However, the method relies on online learning and has complex parameter tuning, so it is difficult to be widely used in engineering practice; However, both the sliding mode controller and the active rotor controller proposed by Zhao et al. Are superior to the conventional sliding mode controller and the active rotor controller in terms of speed response.

With the combination of fuzzy control theory and traditional PID control theory, the fuzzy PID control technology can improve the adaptability of the controller by changing the static parameters of the traditional PID controller into dynamic parameters, without online learning and basically without increasing the calculation amount of the controller. It has excellent control effect for many complex control objects, the design of fuzzy rules and the setting of fuzzy universe have been the research hotspots of this kind of controller. The problem of attitude angle adjustment of quadrotor UAV, Zhang Lei et al. Proposed a fuzzy PID attitude controller. Based on the traditional PID controller,
fuzzy rules were introduced to improve the speed of UAV attitude adjustment, but there was still room for improvement. [13] et al. Of Beijing University of Aeronautics and Astronautics put forward fuzzy PID attitude angle control with self-tuning quantization factor, which improves the maneuverability of UAV attitude angle control. However, the transfer function of the system is not deduced, and the design method of quantization factor and detailed simulation data are not given.

Through the literature review, it can be seen that the control efficiency of traditional PID controller is not high, the sliding mode controller of backstepping controller has a large amount of calculation, and the parameter tuning of neural network controller is complex. The research on Fuzzy PID also has some problems such as unclear system transfer function and quantization factor, which is difficult to be directly applied in engineering practice.

In order to effectively solve the problem of low efficiency of attitude angle adjustment in UAV reconnaissance image acquisition process, based on the nonlinear dynamics model of quadrotor UAV, the dynamic equation of UAV attitude angle control is derived and the transfer function of UAV yaw angle channel is given. Then, a variable universe fuzzy PID controller is designed for UAV yaw angle control, and the design formula of quantization factor is given. Finally, the controller is simulated by Simulink software, and the simulation data are compared and analyzed.

2. System analysis of control object

Reconnaissance UAV is usually divided into electronic reconnaissance UAV, image reconnaissance UAV and integrated reconnaissance UAV. Image reconnaissance UAV mainly cooperates with synthetic aperture radar, infrared camera and other equipment to complete environmental reconnaissance, damage assessment and other tasks in the target area. According to the use experience of image reconnaissance UAV, the degree of freedom is the rotation degree of freedom of Z-axis, namely yaw angle. This conclusion can be explained from the following two aspects:

1) In order to ensure the imaging quality of UAV, image reconnaissance UAV generally keeps the horizontal flight to collect images, that is, the rotation around the x-axis and y-axis will make the optical equipment lose the level. Therefore, the rotation degrees of freedom of x-axis and y-axis are usually set as fixed values during reconnaissance flight.

2) In order to meet the reconnaissance track, obstacle avoidance and other conditions in the UAV reconnaissance flight process, it is necessary to adjust the UAV heading or height. Compared with the height adjustment, the UAV obstacle avoidance based on the course adjustment is more conducive to ensure the consistency of UAV reconnaissance image accuracy and size, and facilitate subsequent processing.

The control object of this paper is a small quadrotor reconnaissance UAV, which can carry out reconnaissance flight and image acquisition according to the preset longitude and latitude coordinates within 100m altitude range. Four rotor reconnaissance UAV uses inertial measurement unit (IMU) to measure yaw angle, and four motors provide power. In the reconnaissance mission, when the UAV arrives at the predetermined waypoint to collect images, it needs to adjust the yaw angle several times, which usually takes a long time to adjust to the preset attitude angle.

The quadrotor UAV is a strong coupling system with six degrees of freedom, so it is difficult to obtain the transfer function of UAV yaw channel directly.
Fig. 1 Body coordinate system of four-rotor UAV

As shown in Figure 1, the UAV body coordinate system is established with the mass center of the quadrotor UAV as the origin $\phi$, $\theta$, $\psi$. They are roll angle, pitch angle and yaw angle of UAV.

According to Newton Euler equation\cite{16},

$$
\begin{bmatrix}
F \\
\tau
\end{bmatrix} = \begin{bmatrix}
0 & 0 & mI_{y}y, 0 \\
0 & I &
\end{bmatrix} \begin{bmatrix}
V \\
\dot{\Omega}
\end{bmatrix} + \begin{bmatrix}
\Omega + mV \\
\Omega + I\Omega
\end{bmatrix}
$$

In the above formula $F$ is the external force acting on the center of mass of UAV, $\tau$ is the torque vector of UAV, $m$ is the UAV quality, $I$ is the inertia tensor matrix, $V$ and $\Omega$ are velocity vector and angular velocity vector of UAV.

Let the angular velocity of attitude angle adjustment of UAV be $W_b = [p, q, r]^T$. In which $p$, $q$, $r$ are roll angular velocity, pitch angular velocity and yaw angular velocity in UAV body coordinate system

$$
\begin{align*}
M_x &= pI_x - rI_z + qr(I_y - I_z) - pqI_z \\
M_y &= qI_y + pr(I_z - I_x) - (p^2 - q^2)I_x \\
M_z &= rI_z - pI_y + pq(I_y - I_x) - qrI_y
\end{align*}
$$

Among them, $M_x$, $M_y$, $M_z$ is the closing external torque in the direction of three axes in the coordinate system of the engine block, $I_x$, $I_y$, $I_z$ The three axes of inertia are the coordinates of the body, $I_x$, It's the product of moment of inertia.

The attitude angle of UAV is also called Euler angle. The angular velocity and Euler angle of the body coordinate system relative to the ground coordinate system have the following relations:

$$
\begin{bmatrix}
p \\
q \\
r
\end{bmatrix} = \begin{bmatrix}
1 & 0 & -2\sin\phi \\
0 & \cos\phi & \cos\phi\sin\phi \\
0 & -\sin\phi & \cos\theta\cos\phi
\end{bmatrix}
$$

The above formula is equivalent to:
The results of (2) and (4) are as follows:

\[
\begin{bmatrix}
\dot{\varphi} \\
\dot{\theta} \\
\dot{\psi}
\end{bmatrix} = \begin{bmatrix}
 p\cos\theta + q\sin\theta\sin\theta + r\cos\theta \sin\theta / \cos\theta \\
 q\cos\theta + r\sin\theta \\
 (q\sin\theta + r\cos\theta) / \cos\theta
\end{bmatrix}
\]

\tag{4}

The results of (2) and (4) are as follows:

\[
\begin{bmatrix}
 I_x \dot{\varphi} \\
 I_y \dot{\theta} \\
 I_z \dot{\psi}
\end{bmatrix} = \begin{bmatrix}
 M_x + (I_y - I_z)qr + r\dot{I}_x + pq\dot{I}_z \\
 M_y + (I_z - I_x)pr + p\dot{I}_y - (p^2 - r^2)\dot{I}_z \\
 M_z + (I_x - I_y)pq + r\dot{I}_z + q\dot{I}_z
\end{bmatrix}
\]

\tag{5}

Suppose a quadrotor UAV airframe xoz and yoz The planes are symmetric to each other, that is, the product of rotation vectors \( I_x, I_y, I_z \) is 0.

When the flight angle of quadrotor aircraft is very small, it can be approximately considered that there is a simple integral relationship between attitude angle and angular velocity\(^{16} \dot{\psi} = r, \dot{\varphi} = p, \dot{\theta} = q \) can be obtained as follows:

\[
\begin{align*}
\ddot{\varphi} &= [M_x + \dot{\varphi}(I_y - I_z)] / I_x \\
\ddot{\theta} &= [M_y + \dot{\theta}(I_z - I_x)] / I_y \\
\ddot{\psi} &= [M_z + \dot{\psi}(I_x - I_y)] / I_z
\end{align*}
\]

\tag{6}

The final nonlinear dynamic model of UAV attitude angle control is obtained by ignoring the influence of drag

\[
\begin{align*}
\ddot{\varphi} &= [lu_1 + \dot{\varphi}(I_y - I_z)] / I_x \\
\ddot{\theta} &= [lu_2 + \dot{\theta}(I_z - I_x)] / I_y \\
\ddot{\psi} &= [lu_3 + \dot{\psi}(I_x - I_y)] / I_z
\end{align*}
\]

\tag{7}

In the above formula, \( l \) is the distance from the body center of gravity to the rotor axis, \( u_1, u_2, u_3 \). They are the control quantities of pitch, roll and yaw channels of UAV. The UAV parameters used in this experiment are shown in Table 1:

| Tab. 1 UAV hardware platform parameters | Body parameters numerical value |
|---------------------------------------|-------------------------------|
| \( l / m \)                           | 0.2                           |
| \( I_x \times 10^{-3} / (kg \cdot m) \) | 5.62                          |
| \( I_y \times 10^{-3} / (kg \cdot m) \) | 5.62                          |
| \( I_z \times 10^{-3} / (kg \cdot m) \) | 2.44                          |

Furthermore, the transfer function\(^{17-18} \) of yaw angle control of UAV can be calculated as follows:
3. Design of fuzzy PID controller

3.1 Traditional PID controller

In Figure 2, \( r(t) \) is the given value, that is, the reconnaissance heading angle during UAV reconnaissance. Error amount \( e(t) \) is the difference between the current yaw angle and the preset angle of the UAV. The input of PID controller is error signal \( e(t) \) and the output is the control quantity \( u(t) \). The mathematical model is as follows:

\[
    u(t) = k_p e(t) + k_i \int e(t) dt + k_d \frac{de(t)}{dt}
\]

The traditional PID control structure includes proportion link, integral link and differential link, as shown in Fig. 2. The proportion link is used to eliminate the dynamic error of the system, the integral part is used to eliminate the steady-state error of the system, and the differential part is used to reduce the overshoot of the system and make the system response faster. The proportion coefficient, integral coefficient and differential coefficient, which are used to adjust the relative size of three kinds of error elimination items in PID controller. In the actual project, the determination of control variable method mainly depends on engineering experience debugging, and the following principles can be followed:

1. The order of parameter determination is proportional coefficient, integral coefficient and differential coefficient.
2. Adjust proportional coefficient \( k_p \). When the initial value is larger, the other two coefficients are set to zero, and then turn down to the critical value of system oscillation, taking the critical value of 60% ~ 70%.
3. The larger integral coefficient is set after the proportional coefficient is determined \( k_i \). And gradually decrease to 150% ~ 180% of the system oscillation boundary value.
4. Differential coefficient \( k_d \). Debugging is the same as \( k_i \). Generally, 30% of the oscillation boundary value is taken.

In this paper, we use the Simulink toolbox \( k_p \), \( k_i \), \( k_d \) iterative optimization was carried out, and the optimized value was preliminarily determined as follows \( k_p = 1400 \), \( k_i = 1 / -22.3 \), \( k_d = \). On this basis, the yaw angle controller is further designed.

3.2 Basic principle of fuzzy PID control

From the above section, we can see that the traditional PID controller \( k_p \), \( k_i \), \( k_d \). Once determined, it is difficult to change in practice. Generally speaking, the traditional PID control efficiency strictly depends on the accurate mathematical model of the controlled object, while the quadrotor UAV is a strong coupling and dynamic time-varying nonlinear system, and it is often difficult to establish an
accurate mathematical model. Fuzzy control can make corresponding control rules according to the experience of expert control, and the parameters of controller can be adjusted dynamically in a certain range in the control process, which has better applicability.

A complete fuzzy control process is usually composed of fuzzifying input and output variables, establishing fuzzy rule base, fuzzy reasoning and defuzzifying.

1. Fuzziness:
   Fuzzification is to convert the determined error of sensor into fuzzy vector. At present, the commonly used fuzzification methods are classified fuzzy set method, input point membership degree 1 method, single point shape fuzzy set method, membership value method. In this paper, the membership degree of input point is taken as 1. For the yaw angle of UAV, the fuzzy universe is determined as follows: negative large (NB), negative middle (nm), negative small (NS), zero (ZO), positive small (PS), median (PM), positive large (PB), and the membership function is triangle function.

2. Establish rule base:
   Fuzzy rules are usually composed of if, then, else and so on. Fuzzy decision is realized on the basis of determining fuzzy sets.

3. Fuzzy reasoning:
   At present, the commonly used fuzzy reasoning methods are Mamdani fuzzy reasoning, Larsen reasoning, Zadeh reasoning, Takagi Sugeno reasoning and so on. In this paper, Mamdani reasoning method is used, which is to calculate the Cartesian product of two fuzzy sets, that is, to obtain the system control value through the maximum and minimum value of membership function.

4. Deblurring:
   The fuzzy quantity is obtained by the above reasoning process, and the control quantity required by the system can be obtained by further resolving the fuzzy. At present, the commonly used methods are: Center of gravity method, maximum membership value method, median method. In this paper, the maximum membership value method is used, that is, the membership function values of each element are compared, and the element with the largest corresponding function value is selected as the accurate control quantity. If more than one element is the maximum value at the same time, the average value of these elements is taken to obtain the precise control quantity.

3.3 design of fuzzy PID controller
The fuzzy PID control principle diagram of UAV yaw angle is shown in Fig. 3. Firstly, the proportional coefficient is obtained according to the debugging principle of traditional PID controller $k_p$, Integral coefficient $k_i$, And differential coefficient $k_d$. Then, according to the error value in the adjustment process, the fuzzy controller outputs the dynamic correction values corresponding to the above three coefficients $\Delta k_p$, $\Delta k_i$, $\Delta k_d$. Finally, the proportion coefficient of the fuzzy PID controller is obtained $k_p$, Integral coefficient $k_i$, And differential coefficient $k_d$:
\[
\begin{align*}
    k_p &= k'_p + \Delta k'_p \\
    k_i &= k'_i + \Delta k'_i \\
    k_d &= k'_d + \Delta k'_d 
\end{align*}
\]  

When the yaw angle of UAV reconnaissance is fuzzy controlled, the input value is the relative azimuth angle between the current position of UAV and the target waypoint and the relative azimuth change rate, in which the calculation formula of azimuth error is given:\[19\]Is:

\[
E = \arctan(\frac{B_j - A_j}{B_w - A_w}) \times \cos(B_w)
\]

(11) Where \((B_j, B_w)\) Is the longitude and latitude of the current position of the UAV \((A_j, A_w)\) Is the longitude and latitude of the preset reconnaissance waypoint, \(E\) The yaw angle should be adjusted for UAV. The purpose of this paper is to optimize the adjustment process of yaw angle error \(E\), \(\Delta\theta\) Where, \(e\) It is the yaw angle required for UAV reconnaissance aerial photography, \(\theta\) Is the current yaw angle of UAV. According to the traditional PID control knowledge, the introduction of high-order variables in the control process can effectively improve the control accuracy and shorten the adjustment time. Therefore, the change rate of yaw angle error is defined as:

\[
EC = \frac{d}{dt}(\theta - \theta_c)
\]

(12) Where, \(\theta_c\) It is the yaw angle required for UAV reconnaissance aerial photography, \(\theta\) Is the current yaw angle of UAV. According to the traditional PID control knowledge, the introduction of high-order variables in the control process can effectively improve the control accuracy and shorten the adjustment time. Therefore, the change rate of yaw angle error is defined as:

\[
EC = \frac{d}{dt}(\theta - \theta_c)
\]

(13) According to the experience of experts, the yaw angle error is selected in this paper \(E\) And error change rate \(EC\) The basic domains on fuzzy sets are \([-1,1]\), \([-400,400]\), and the corresponding fuzzy language subsets are \{NB, NM, NS, ZO, PS, PM, PB\}. Output of fuzzy system \(\Delta k'_p, \Delta k'_i, \Delta k'_d\) The basic universe of fuzzy language is set as \([-0.45,0.45]\), \([-0.1,0.1]\), \([-0.1,0.1]\), and the corresponding fuzzy language subsets are \{NB, NM, NS, ZO, PS, PM, PB\}. The triangular function is used for membership function, and the maximum membership value method is used to solve the fuzzy problem. In MATLAB, the fuzzy logic designer module is used to set the above rules, and finally the fuzzy control rules table is shown in Table 2.

3.4 domain adjustment mechanism design

Compared with the traditional PID control, fuzzy PID has the advantages of restraining overshoot and improving response speed, but the determination of its universe is strictly dependent on expert experience, and once set, it can not be modified online, so its adaptive ability is limited. Variable universe theory adds quantization factor to fuzzy controller \(k_p, k_i, k_d\) And scale factor \(k_p, k_i, k_d\) In this paper, the domain of fuzzy control is compressed or expanded to further increase the adaptability of the system. The better performance can be obtained by giving the approximate range of the universe. The adjustment rules can be understood as: the amplification and reduction of quantitative factors are equivalent to the expansion and contraction of input universe, and the amplification and reduction of scale factor are equivalent to the expansion and contraction of output universe.

At present, the commonly used quantitative factor and scale factor are respectively

\[
\alpha(x) = 1 - x e^{-k_2 x^2}
\]

(14)

\[
\beta(t) = K_i \sum_{i=1}^{n} p_i \int_0^t e^{-k(x + \beta(0))} d\tau + \beta(0)
\]

(15)
Tab. 2 Fuzzy rule control table

| E      | NB   | NM   | NS   | ZO   | PS   | PM   | PB   |
|--------|------|------|------|------|------|------|------|
| NB     | PB/NB/PS | PB/NB/NS | PM/NM/NB | PM/NM/NB | PS/NS/NB | ZO/ZO/NM | ZO/ZO/PS |
| NM     | PB/NB/PS | PB/NB/NS | PM/NM/NB | PM/NM/NB | PS/NS/NB | ZO/ZO/NM | ZO/ZO/PS |
| NS     | PM/NM/ZO | PM/NM/NS | PM/NS/NS | PM/NS/NS | ZO/ZO/NS | NS/PM/NS | NS/PM/ZO |
| ZO     | PM/NM/ZO | PM/NM/NS | PM/NS/NS | PM/NS/NS | ZO/ZO/NS | NS/PM/NS | NM/PM/NS |
| PS     | PS/NM/ZO | PS/NS/NS | ZO/ZO/ZO | ZO/ZO/ZO | NS/PS/ZO | NM/PM/ZO | NM/PB/ZO |
| PM     | PS/ZO/PM | ZO/ZO/PM | NS/PS/PM | NM/PS/PM | NM/PM/PS | NM/PM/PB | NB/PB/PB |
| PB     | ZO/ZO/PB | ZO/ZO/PM | NM/PS/PB | NM/PM/PB | NM/PM/PB | NB/PB/PB | NB/PB/PB |

Fig. 4 Variable domain fuzzy PID simulation model

In this paper, the input quantization factor is selected as \( \alpha(e) = 1 - 0.25 \exp(-0.5e^2) \), \( \alpha(e) = 1 - 0.25 \exp(-0.5e^2) \). The scale factor is \( \beta_e = 2|e|, \beta_i = 1/(|e| + 0.5), \beta_d = 2|e| \). Finally, the variable universe fuzzy PID controller is obtained, as shown in Fig. 4.

4. Simulink simulation and result analysis

4.1 Simulink simulation establishment
Matlab software is used to simulate the traditional PID control and the fuzzy PID controller designed in this paper, mainly using the fuzzy logic toolbox in MATLAB built-in Simulink library. In order to compare the performance improvement of UAV yaw angle adjustment by introducing fuzzy control, a simulation model of yaw angle control based on traditional PID is designed, and the parameters are adjusted by using signal constraints toolbox. Then, keeping the parameters unchanged, fuzzy control is added to the simulation model to form the fuzzy PID control system. Then, by introducing the idea of variable universe, the universe adjusting mechanism is designed on the basis of fuzzy PID controller. Finally, the step signal is used as the input signal to test and analyze the dynamic performance index and steady-state error of the control system, such as adjustment time, overshoot, etc.

The variable universe fuzzy PID simulation model is shown in Figure 4.

4.2 Simulation results and analysis
According to the above model, the yaw angle control of UAV is simulated. In control theory, it is
generally considered that the step input is a more severe working state for the system. If the dynamic performance of the system under the action of step function is better than that of a certain system, then the dynamic performance of the system under the action of other forms of input is also better than that of a certain system. Therefore, this paper uses step signal as input to simulate the designed variable universe fuzzy PID controller. The simulation results are shown in Fig. 5. It can be seen that the dynamic performance of variable universe fuzzy PID controller is better than that of traditional PID controller and fuzzy PID controller for yaw angle control of UAV.

![Fig. 5 Step signal response](image)

Table 3 is the simulation data of the step signal dynamic performance of the controller designed in this paper. Here, the dynamic performance index and steady-state error are defined in reference [27] and will not be repeated. Among them, the adjustment time is the main optimization index in this paper, which reflects the time spent by UAV to adjust yaw angle in reconnaissance mission. For step signal, the adjusting time of traditional PID controller is 0.089s, that of fuzzy PID controller is 0.069s, and that of variable universe fuzzy PID is 0.057s after adding universe adjustment mechanism. At the same time, we also pay attention to the overshoot and steady-state error of the control system. Excessive overshoot will cause system oscillation, and excessive steady-state error will affect the accuracy of UAV yaw angle adjustment. It can be seen from the data in Table 3 that the variable universe fuzzy PID controller has better dynamic and steady-state performance than fuzzy PID and traditional PID in the three key indicators of regulation time, overshoot and steady-state error.

| Index                        | Traditional PID | Fuzzy PID | Variable universe |
|------------------------------|-----------------|----------|-------------------|
| Adjustment time / S          | 0.089           | 0.069    | 0.057             |
| Overshoot σ %                | 4.1             | 0.5      | 0.4               |
| Steady state error / %       | 8.4             | 5.68     | 3.75              |

Table 3: Step signal response dynamic performance and steady state error index

The above advantages are mainly due to the variable universe fuzzy mechanism can dynamically adjust the three parameters of PID controller according to the output error. As can be seen from Fig. 5, in the early stage of system response to step signal, the variable universe fuzzy mechanism can adjust to obtain a larger scale coefficient, so as to maximize the output slope of the PID controller, so as to quickly respond to the yaw angle adjustment signal. In the later stage, the variable universe fuzzy mechanism can reduce the scale coefficient, increase the differential coefficient and integral coefficient, thus reducing the overshoot and steady-state error. Although fuzzy PID has some adaptive
ability, its adaptive ability is not as good as variable universe fuzzy PID because its universe is not variable, so its response to step signal is inferior to variable universe fuzzy PID.

5. Conclusion
The simulation results show that compared with the traditional PID control, the variable universe fuzzy PID control has better dynamic performance and steady-state error index. In the case of slow adjustment speed in the course of UAV yaw angle control, variable universe fuzzy PID control has certain advantages in adjusting time, overshoot and steady-state error, that is, it can make yaw angle adjustment faster, more stable and accurate. Compared with the traditional PID control, the yaw angle adjustment time can be reduced to 64.0% by using variable universe fuzzy PID control, which can effectively shorten the yaw angle adjustment time in UAV reconnaissance mission, and has a good application prospect in UAV reconnaissance mission.

Acknowledgments
Our work is supported by the National Natural Science Foundation (No.: 61703427), we can't have finished this paper without this support.

References:
[1] Su Jingya; fan Penghui; CAI Kaiyuan; nonlinear PID attitude control of quadrotor aircraft [J]. Journal of Beijing University of Aeronautics and Astronautics, 2011, v.37; No.223 (09): 1054-1058
[2] Liu Yunping; Huang Xijie; Li Xianying; Chen Cheng; sliding mode PID trajectory tracking control of quadrotor aircraft [J]. Mechanical science and technology, 2017, v.36; no.274 (12): 1859-1865
[3] Li Yawen; Zhai Jinling; Peng Xiaobang; design and implementation of a four rotor aircraft with position PID control [J]. Automation and instrumentation, 2016, NO.201 (07): 96-97
[4] Zhou M D, Guo Y J, Gao F Q, etal. Self-tuning PID controller design for quad rotor aircraft. Computer Simulation.2017.34 (11):34-42.
[5] Lou ganfei, fan louying, Shen Weihua. Autonomous flight control algorithm for quadrotor UAV Based on LQR [J]. Journal of Lishui University, 2019,41 (05): 7-9
[6] Chen Hongliang, Zhang Xiangwen. UAV attitude control based on LQR controller [J]. Automation applications, 2019, (10): 1-4
[7] Ha di razmi. Sliding mode altitude control of four rotor UAV Based on adaptive neural network [J]. Journal of Central South University, 2018,25 (11): 2654-2663
[8] Chen Yanmin, he Yongling, Kong Lingbo, Zhou Minfeng. Decentralized PID neural network control for quadrotor aircraft [J]. Chinese Journal of inertial technology, 2014,22 (02): 185-190
[9] Zhao Hongchao, Zhou Hongqing, Wang Shuhu. Sliding mode control of quadrotor UAV Based on extended state observer [J / OL]. Command control and simulation, 2020, (06): 1-7
[10] He Yuanyuan, Li Guowen, Wang Haokun. Design of adaptive backstepping sliding mode attitude controller for quadrotor UAV [J]. Journal of Hangzhou University of Electronic Science and Technology (self SCIENCE EDITION), 2019,39 (02): 57-63
[11] [MANN G I, HU B G, GOSINE R G.Analysis of direct action fuzzy PID controller structures[J].IEEE Transactions on Systems Man&Cybernetics, Part B Cybernetics, A Publication of the IEEE Systems Man&Cybernetics Society, 1999, 29 (3) :371-388.
[12] Zhang Lei, Li Hao. Fuzzy PID attitude control of quadrotor aircraft [J]. Computer simulation, 2014,31 (08): 73-77
[13] Ge Lin, Wang Hua. Fuzzy PID control of four rotor aircraft with self-tuning quantization factor [J]. Electro optic and control, 2017,24 (07): 90-94
[14] Hu Baogang, Ying Hao. Review of research and development of fuzzy PID control technology and some important problems it faces [J]. Acta automatica Sinica, 2001, (04): 567-584
[15] Du Wei, Chen Fei. Key technologies for cooperative use of reconnaissance UAVs [J]. Electronic information countermeasure technology, 2018, 33 (01): 12-17
[16] Gong Juan. Research on attitude control of quadrotor aircraft based on Fuzzy Adaptive PID [D]. Chongqing University of Posts and telecommunications, 2018
[17] Han Zhifeng, Li Rongbing, Liu Jianye, hang Yijun. Dynamic model optimization of small quadrotor aircraft [J]. Control engineering, 2013, 20 (S1): 158-162
[18] Bouabdallah S, Becker M, Siegwart R. Autonomous Miniature Flying Robots: COMING SOON [J]. IEEE Robotics Automation Magazine, 2007: 88-99.
[19] Zhang Xiaolong, Zhu Pingan, Hu Chunsheng. A simple algorithm for missile target distance and azimuth based on latitude and longitude [J]. Ordnance automation, 2019, 38 (10): 7-9
[20] Zhang R, Tao J, Gao F. A new approach of Takagi -Sugeno fuzzy modeling using improved GA optimization for oxygen content in a coke furnace [J]. Ind Eng Chem Res, 2016, 55 (22): 64-74.
[21] Feng Huafeng, Pan Haipeng, Chen Weili. Design of online self-tuning fuzzy PID temperature control system [J]. Industrial control computer, 2019, 32 (8): 95-97
[22] Dong S, Jiang F, etc. Fuzzy-PID based heating control system [C]. Institute of Electrical and Electronics Engineers Inc, 2016.
[23] Zhang Haidi. Blackbody temperature control with adaptive dual output based on PID self-tuning function [J / OL]. Acta automatica Sinica: https://doi.org/10.16383/j.aas.c190277
[24] Mao Jun, Liu Siyang. Arc length adjustment control of welding machine based on Variable Universe Fuzzy PID [J]. Control engineering, 2019, 26 (12): 2188-2192
[25] Cui Jiashan. Design of cruise missile control system based on Adaptive Fuzzy PID [D]. Harbin: Harbin Institute of technology, 2012
[26] Wang Bo, Chen Wanqiang, Li Xiangyang. Simulation Research on steering gear system based on Fuzzy Adaptive PID control [J]. Journal of Chongqing University of Technology (NATURAL SCIENCE EDITION), 2015, 29 (10): 52-56
[27] Lu Jingchao. Automatic control principle [M]. Xi'an: Northwest Polytechnic University Press, 2009: 52-53