Attitude control of fixed-wing UCAV based on adaptive fuzzy PID

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Abstract. Aiming at the nonlinear and strong coupling characteristics of the fixed-wing UCAV’s rigid body six-degree-of-freedom model, an adaptive fuzzy PID attitude control method was designed based on expert experience. The nonlinear model of UCAV was linearized with the principle of small disturbance, thus the state space expressions of longitudinal and lateral channels were obtained and the decoupling of the longitudinal and lateral channels was achieved. To verify the designed adaptive fuzzy PID controller, the simulation was carried out aiming at the pitch angle and velocity of the longitudinal channel and the roll angle of the lateral channel. The result showed that the designed controller had faster responsive speed and higher stability, and it could control the UCAV to achieve the desired attitude effectively.

1. Introduction

With the rapid development of UAV technology, the traditional man-in-the-loop way for controlling will no longer be applied to the sharply changing air combat situation[1]. Due to the absence of pilots on the aircraft, the stability, robustness and control accuracy of the control system are critical to ensure UCAV’s own safety and successful completion of attack occupancy[2]. In literature[3], the root locus method in classical control theory is used to analyze and design the longitudinal control law of a fixed-wing UAV. The literature[4] introduced the LQR control method of the quadrotor UAV. Since the quadrotor UAV is usually in the disturbed state, the anti-interference ability is poor. In literature[5], a fuzzy PID controller is designed for the four-rotor aircraft’s hovering control. The controller is used to perform inner-ring’s attitude control and outer-ring’s position control on the aircraft to achieve stable hovering flight. In this paper, an adaptive fuzzy PID attitude controller is designed for a fixed-wing UAV to realize fast and stable attitude control of UCAV.

2. Six degree of freedom model of UCAV

The UCAV’s six-degree-of-freedom model describes the relationship between external forces, moments, and motion parameters of UCAV. It mainly includes dynamic models and kinematic models[6]. The UCAV dynamics model is as follows:
In the above formula, \( P \) represents the UCAV’s engine thrust and \( \theta, \phi \) are the pitch angle and roll angle of the UCAV. \( \overline{X}, \overline{Y}, \overline{Z} \) respectively represent the resistance, lateral force and lift of the aircraft. \( m \) is the body mass of the aircraft and \( u, v, w \) are the sub-speeds of the UCAV along the x, y, and z axes of the aircraft. \( p, q, r \) are the angular velocities of the UCAV around the x, y, and z axes of the aircraft. The dynamic model of UCAV’s rotation around the centroid is as follows [7]:

\[
\begin{align*}
\dot{p} &= (c_r + c_p)q + c_L + c_N \left( \overline{N} + \text{heng} \right) \\
\dot{q} &= c_p q - c_r (p^2 - r^2) + c_M \left( \overline{M} - \text{rheng} \right) \\
\dot{r} &= (c_r - c_p)q + c_L + c_N \left( \overline{N} + \text{heng} \right) \\
\end{align*}
\]

In formula (2), \( I_x, I_y, I_z \) are the rolling moment of inertia, the pitching moment of inertia, and the yaw moment of inertia, respectively. \( L, M, N, \text{heng} \) are respectively UCAV’s roll moment, pitch moment, yaw moment and engine angular momentum.

The UCAV’s kinematics model is as follows:

\[
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{z}
\end{bmatrix} =
\begin{bmatrix}
\cos \phi \cos \theta & \cos \psi \sin \theta \sin \phi - \sin \psi \cos \phi & \cos \psi \sin \theta \cos \phi + \sin \psi \sin \phi \\
\sin \psi \cos \theta & \sin \psi \sin \theta \sin \phi + \cos \psi \cos \phi & \sin \psi \sin \theta \cos \phi - \cos \psi \sin \phi \\
- \sin \theta & \cos \theta & \cos \phi
\end{bmatrix}
\begin{bmatrix}
u \\
v \\
w
\end{bmatrix}
\]

\[
\begin{align*}
\dot{\theta} &= q \cos \phi - r \sin \phi \\
\dot{\phi} &= p + \tan \theta (q \sin \phi + r \cos \phi) \\
\dot{\psi} &= \frac{q \sin \phi + r \cos \phi}{\cos \theta}
\end{align*}
\]

In the above formula, \( \dot{x}, \dot{y}, \dot{z} \) represent the velocity of the UCAV along each axis in the inertial coordinate system.

3. Stability analysis of UCAV’s model

3.1. Linearization of UCAV’s model

The above model is a nonlinear function of the UCAV’s motion parameters. There are many parameters and the coupling is serious. Therefore, it is very difficult to find the analytical solution [9]. But it can be linearized with a small perturbation equation. And since the change of aerodynamic force and moment acting on UCAV is basically a linear function of motion parameters, the linear differential equations obtained by small perturbation equations can be used to analyze the stability of UCAV [10].

The UCAV model is trimmed at a height of 6000m and a flight speed of 158m/s to find the angle of attack required to balance the gravity of the model and the elevator yaw angle required to balance the pitch moment of the aircraft.
3.2. Stability analysis of UCAV’s model

The motion mode of the UCAV can be analyzed based on the state space expression of the UCAV and the inherent characteristics of UCAV’s small perturbation motion can be analyzed by the distribution of eigen roots of UCAV’s linear motion equation.

3.2.1. Longitudinal motion mode analysis of UCAV

In the equilibrium state, the distribution of longitudinal characteristic root of UCAV is as shown in the figure below. It can be seen that the longitudinal eigenvalue contains a pair of pure virtual roots, a pair of conjugate complex roots with negative real parts and a pair of unequal negative real roots, and it has no eigen roots with positive real parts. Therefore, the system is stable and controllable.

![Figure 1. Distribution of longitudinal characteristic roots of UCAV.](image-url)
3.2.2. Longitudinal frequency domain characteristics analysis of UCAV
When the elevator yaw angle is input, the amplitude-frequency characteristics and phase-frequency characteristics of the impulse response of the longitudinal state quantities such as the height, pitch angle, angle of attack, and pitch rate corresponding to the UCAV are as shown in the following figure.

![Impulse response with elevator as input.](image)

It can be seen from the above figure that when the elevator is a pulse input, the transient process of the impulse response of the longitudinal state quantities such as UCAV’s height, pitch angle, angle of attack and pitch rate is similar to the steady state process. Therefore, a typical trimming point can be selected to design the UCAV’s longitudinal control law.

3.2.3. Lateral motion mode analysis of UCAV
In the equilibrium state, the distribution of lateral characteristic root of UCAV is as shown in the figure below. It can be seen that the lateral characteristic root contains a pair of approximately pure virtual roots and two pairs of unequal negative solid roots, and it has no characteristic roots with positive real parts. Therefore, the system tends to be stable and controllable.

![Distribution of lateral characteristic roots of UCAV.](image)
3.2.4. Lateral frequency domain characteristics analysis of UCAV

The UCAV’s lateral control inputs primarily have ailerons and rudders. When the aileron declination is used as the input, the amplitude-frequency characteristics and phase-frequency characteristics of the impulse response of the lateral state quantities such as the roll angle, yaw angle, side slip angle, roll angular rate, and yaw rate corresponding to the UCAV are as shown in the following figure:

![Impulse response with aileron as input](image1)

When the rudder declination is used as the input, the amplitude-frequency characteristics and phase-frequency characteristics of the impulse response of the lateral state quantities such as the roll angle, yaw angle, side slip angle, roll angular rate and yaw rate corresponding to the UCAV are as shown in the following figure:

![Impulse response with rudder as input](image2)

**Figure 4.** Impulse response with aileron as input.

**Figure 5.** Impulse response with rudder as input.
It can be seen from the above figure that when the aileron or rudder is a pulse input, the transient process of the impulse response of the lateral state quantities such as UCAV’s roll angle, yaw angle, side slip angle, roll angular rate and yaw rate is similar to the steady state process. Therefore, a typical trimming point can be selected to design the UCAV’s lateral control law.

4. Design of adaptive fuzzy PID attitude controller

The traditional PID controller cannot meet different expected output values because of the fixed parameters, and the parameter adjustment is also time consuming, so it can not meet the design requirements of the UCAV’s attitude controller[11]. In order to truly reflect the pilot's operational characteristics, the pilot's operating experience can be learned from the design of the UCAV’s attitude controller. Considering that the pilot's operating experience in controlling the attitude of the aircraft is ambiguous, the fuzzy control method can be used to construct the controller[12]. The specific attitude control process is shown in the figure below:

![Figure 6. Flow diagram of attitude control of UCAV.](image)

The input variable of the fuzzy PID attitude controller is the error of the expected state and the actual state \( e \) and the change rate of error \( \frac{de}{dt} \). Inside the controller, the output of the fuzzy controller is the amount of change of \( K_p, K_i, K_d \), which is used to adjust the three parameters of the PID controller. The output of the PID controller is the joystick offset \( \Delta \text{joystick} \). The domain of discourse of input and output of the fuzzy controller is as follows:

\[
\begin{align*}
& e \in [-\pi, \pi] \\
& \dot{e} \in [-2\pi, 2\pi] \\
& \Delta \text{joystick} \in [-0.1, 0.1]
\end{align*}
\]

The domain of discourse of input and output is divided into 7 linguistic variables, respectively \( \text{NB} \), \( \text{NM} \), \( \text{NS} \), \( \text{ZO} \), \( \text{PS} \), \( \text{PM} \), \( \text{PB} \), and they correspond to 7 fuzzy subsets: negative big, negative medium, negative small, zero, positive small, positive medium and positive big. The membership function is a Gaussian membership function with the following expression:

\[
U(x) = \exp\left(-\frac{(x-\bar{x})^2}{\sigma}\right)
\]

The key to fuzzy control design is to summarize the experience of experts, construct appropriate fuzzy rules, and obtain fuzzy rule tables for adjusting \( K_p, K_i, K_d \), as follows:
Table 1. Fuzzy rule list of $\Delta K_p$, $\Delta K_i$ and $\Delta K_d$.

| $\Delta K_d$ | $\Delta K_p$ | $\Delta K_i$ | $\frac{de}{dt}$ |
|------------|-------------|-------------|-----------------|
| $\text{NB}$ | $\text{PM}$ | $\text{PM}$ | $\text{PS}$ |
| $\text{NB}$ | $\text{PM}$ | $\text{PM}$ | $\text{PS}$ |
| $\text{ZO}$ | $\text{ZO}$ | $\text{ZO}$ | $\text{ZO}$ |
| $\text{PS}$ | $\text{PS}$ | $\text{PS}$ | $\text{PS}$ |
| $\text{PS}$ | $\text{PS}$ | $\text{PS}$ | $\text{PS}$ |
| $\text{PS}$ | $\text{PS}$ | $\text{PS}$ | $\text{PS}$ |
| $\text{PM}$ | $\text{PM}$ | $\text{PM}$ | $\text{PM}$ |
| $\text{PM}$ | $\text{PM}$ | $\text{PM}$ | $\text{PM}$ |
| $\text{PM}$ | $\text{PM}$ | $\text{PM}$ | $\text{PM}$ |
| $\text{PM}$ | $\text{PM}$ | $\text{PM}$ | $\text{PM}$ |

5. Simulation results and analysis

The constructed UCAV’s nonlinear motion model is shown in the figure above. The trimming point is selected at a height of 6000 m and a flight speed of 158 m/s. The pitch angle and velocity are selected to simulate the longitudinal control law and the roll angle is selected to simulate the lateral control law. The simulation results are compared with those of the traditional PID controller and they are shown in the figure below:
It can be seen that compared with the traditional PID controller, the adaptive fuzzy PID controller designed in this paper has faster response speed, higher steady-state accuracy, and the overshoot is almost zero, that is, when approaching the desired state, the oscillation is smaller. In the 10th second of the simulation, step signal interference is added, and compared with the traditional PID controller, it can be seen that the adaptive fuzzy PID controller can track the step signal more quickly and accurately than the traditional PID controller. It also verifies that the adaptive fuzzy PID controller has better anti-interference ability.

6. Conclusion
In this paper, an adaptive fuzzy PID attitude controller is designed for UCAV’s nonlinear motion model combined with expert experience. Using the small perturbation principle to linearize the UCAV’s nonlinear motion model, the longitudinal and lateral state space expressions of the UCAV’s model are obtained, and the decoupling control of the longitudinal and lateral channels is realized. The SIMULINK platform is used to build the UCAV’s nonlinear motion model for simulation verification. The simulation results show that the designed adaptive fuzzy PID attitude controller can effectively control the UCAV to achieve the desired attitude and remain stable. The tracking performance can be maintained after the introduction of step signal interference, which verifies the effectiveness of the adaptive fuzzy PID attitude controller.
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