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Research on Anti-swing Control of UAV Hanging System Based on Fuzzy PID

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ABSTRACT
To address the issues of trajectory tracking and load swing suppression in quadrotor UAV suspension systems, a three-dimensional mathematical model of the quadrotor UAV hanging system is established on the basis of the quadrotor UAV model and take into account the effects of the suspension load. The pendulum Angle controller is designed, and the outputs of the controller is regarded as the control compensation of the horizontal position of the UAV, and the control expectation of the roll Angle and pitch Angle of the UAV is solved, so as to realize the decoupling control under the constraint of the underdrive, and then the whole control system is divided into three subsystems of position, attitude and swing Angle, and the eight-channel control system. Considering the limitations of PID control in parameter tuning, a fuzzy PID controller is designed to adjust PID parameters online in real-time for better control. Finally, we demonstrate the effectiveness of the fuzzy PID controller for trajectory tracking and swing-angle suppression using simulations.

KEYWORDS
Quadcopter UAV; Suspended load; Fuzzy PID control; Oscillation suppression; Track tracking

The application of quadrotor UAVs carrying loads has become one of the important research directions in quadrotor UAV applications due to characteristics such as the relatively small influence of load changes on the UAV, precise hovering and payload release, and minimal constraints on the volume and shape of the carried load. Current research on quadrotor UAV suspension systems includes literature ^[1-2]^, which employs hybrid differential flatness theory for two different states of the suspension cable to achieve control of the UAV suspension system, along with path planning and tracking. Literature ^[3]^ assumes an unknown suspended load mass and designs a nonlinear geometric PD controller to achieve desired control under nominal mass conditions. Literature ^[4]^ designs an active disturbance rejection controller based on an Extended State Observer (ESO) to estimate disturbances generated during quadrotor UAV suspended flight and suppress disturbances caused by the load. Literature ^[5-7]^ designs controllers for the suspension system based on the energy method and employs other control methods to achieve control, but these controller designs rely on two-dimensional mathematical models.

In summary, most research is based on two-dimensional models of quadrotor suspension systems, preventing the models from fully characterizing the system's characteristics. Furthermore, the designed control methods for UAV suspension systems cannot be easily extended to actual three-dimensional space. Regarding load swing angle suppression, most studies do not consider the design of a swing angle controller. When designing a controller for the load swing angle, considering the maturity of quadrotor UAV control, the swing control of the load in three-dimensional space can be decomposed onto the horizontal position of the UAV, treated as control compensation for the UAV's horizontal position. A swing angle controller can then be designed to achieve load swing suppression.

1 Quadrotor UAV Suspension System Model

1.1 Model Overview

Figure 1 shows a schematic diagram of the quadrotor UAV with suspended load model. An inertial coordinate system $\{O_1 - X_1Y_1Z_1\}$ and the UAV's body coordinate system $\{o - xyz\}$ are established. The arrowheads indicate the positive directions of each axis.

Define the coordinates of the UAV's center of mass in the inertial frame as (x,y,z), and the coordinates of the suspended load in the inertial frame as (x_1,y_1,z_1). ϕ represents the roll angle (rotation around the *x*-axis), θ represents the pitch angle (rotation around the *y*-axis), and ψ represents the yaw angle (rotation around the *z*-axis). *M* represents the mass of the UAV, *m* represents the mass of the suspended load, *l* represents the cable length, *T* represents the cable tension, *L* represents the distance from the quadrotor's center of mass to the motor axis, α represents the angle between the cable and the vertical direction in the *xoz* plane, and β represents the angle between the cable and the vertical direction in the *yoz* plane.

Based on the actual flight conditions of the UAV suspension system, the following assumptions are made:

(1) The suspension cable is attached at the UAV's center of mass, and the suspended load is considered a point mass.

(2) The load is always suspended below the UAV, the cable is always taut, its length remains constant, and its mass is negligible.

(3) The influence of air resistance on the UAV suspension system is ignored.

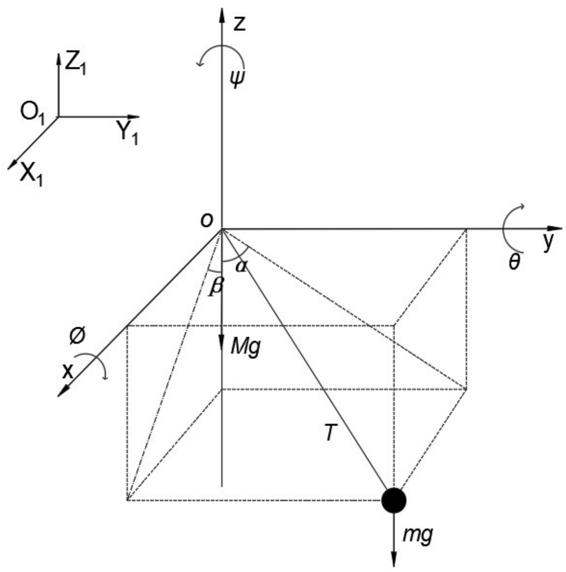


Fig.1 Sketch of a model of a quadrotor UAV suspension system

1.2 Mathematical Model of the Quadrotor UAV Suspension System

First, the Newton-Euler equations are used to establish the mathematical model of a single quadrotor UAV. Building upon the quadrotor model and adding the suspended load requires force analysis of the combined UAV-load system. The mathematical model of the UAV suspension system is further established using Hamilton's principle and the Lagrange formulation[8].

$$
\begin{cases}
\ddot{x} = \dfrac{U_x - ml(\ddot{\beta}\cos\beta - \dot{\beta}^2\sin\beta)}{(M+m)} \\
\ddot{y} = \dfrac{\begin{aligned}&U_y - ml(\ddot{\beta}\sin\beta\sin\alpha \\ &-\ddot{\alpha}\cos\beta\cos\alpha + \dot{\beta}^2\cos\beta\sin\alpha \\ &+\dot{\alpha}^2\cos\beta\sin\alpha + 2\dot{\alpha}\dot{\beta}\sin\beta\cos\alpha)\end{aligned}}{(M+m)} \\
\ddot{z} = \dfrac{\begin{aligned}&U_z - ml(\ddot{\beta}\sin\beta\cos\alpha \\ &+\ddot{\alpha}\cos\beta\sin\alpha + \dot{\beta}^2\cos\beta\cos\alpha \\ &+\dot{\alpha}^2\cos\beta\cos\alpha - 2\dot{\alpha}\dot{\beta}\sin\beta\sin\alpha)\end{aligned}}{(M+m)} - g \\
\ddot{\phi} = \dfrac{LU_2 + \dot{\theta}\dot{\psi}(I_y - I_z)}{I_x} \\
\ddot{\theta} = \dfrac{LU_3 + \dot{\phi}\dot{\psi}(I_z - I_x)}{I_y} \\
\ddot{\psi} = \dfrac{LU_4 + \dot{\phi}\dot{\theta}(I_x - I_y)}{I_z} \\
\ddot{\alpha} = \dfrac{2Ml\sin\beta\dot{\alpha}\dot{\beta} - \cos\alpha U_y - \sin\alpha U_z}{Ml\cos\beta} \\
\ddot{\beta} = \dfrac{\begin{aligned}&-Ml\sin\beta\cos\beta\dot{\alpha}^2 - \cos\beta U_x \\ &-\sin\beta\sin\alpha U_y - \sin\beta\cos\alpha U_z\end{aligned}}{Ml}
\end{cases}
$$

Where U_x、U_y、U_z represent the components of the total thrust U_1 along the x、y、z axes respectively, U_1 represents the total lift generated by the four rotors, U_2、U_3、U_4 represent the roll, pitch, and yaw moments respectively, g is the gravitational acceleration, and I_x、I_y、I_z represent the moments of inertia around the x、y、z axes respectively.

2 Controller Design

2.1 System Control Strategy

This paper, based on the quadrotor UAV, decomposes the swing control of the suspended load onto the horizontal position of the UAV. That is, the output of the swing angle controller is used as control compensation for the UAV's horizontal position controller and converted into the desired input for the attitude angle controller. As shown in Figure 2, the entire suspension control system is divided into three control subsystems: the position control subsystem, the attitude control subsystem, and the swing angle control subsystem, forming an eight-channel control system. This approach not only enables UAV trajectory tracking but also controls the swing angle of the suspended load.

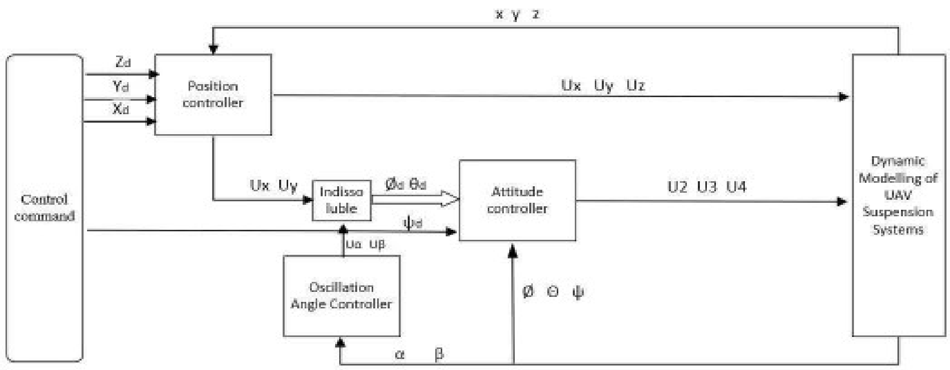


Fig.2 Control channel planning for quadcopter UAV hoisting systems

2.2 Design of Anti-swing Controller Based on Fuzzy PID

Although the PID controller is simple in design, reliable in performance, and has good stability, its parameters are fixed. For nonlinear systems with complex and variable parameters in practical control, achieving more satisfactory control performance requires continuous optimization and tuning of the PID parameters. Therefore, this paper incorporates a fuzzy control algorithm based on PID control to design a fuzzy PID-based anti-swing controller. The fuzzy control algorithm is used to adjust the PID parameters online in real-time for adaptive correction, enabling the controller to adapt to dynamic and static parameters. This controller retains the advantages of PID control while enhancing the flexibility and control precision of the system.

As shown in Figure 3, the fuzzy PID controller uses sensors to obtain inputs, which are then fuzzified. Through fuzzy inference and defuzzification, the required output quantities are obtained. These outputs optimize the PID controller parameters, enabling adaptation to various changing system parameters. The key design aspects lie in determining the fuzzy relationship between the error e, the error change rate e_c, and the PID control parameters, as well as establishing the fuzzy control rules to improve the system's adaptive capability. By processing e and e_c , new PID control parameters can be derived.

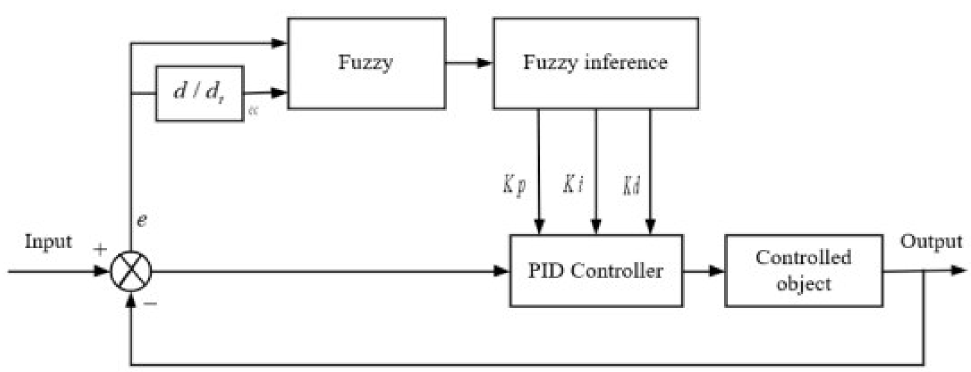


Fig.3 Block diagram of the fuzzy PID control structure

2.2.1 Input and Output Fuzzification

In fuzzy control, the shape of the membership function significantly impacts the control effect. To balance control precision and computational efficiency, appropriate types of membership functions need to be selected based on the required control precision and real-time requirements, using different resolutions at different positions. Generally, using low-resolution membership functions where the system error is small can improve the robustness of the control system, while using high-resolution membership functions where the system error is large yields better control performance.

The fuzzy controller for the UAV suspension system has 2 input variables and 3 output variables. The inputs are the system control error e and its change rate e_c. The outputs are the PID parameter adjustments ΔK_p、ΔK_i、ΔK_d.

Following the above principles, the fuzzy universe for the input error e and error change rate e_c is set to $[-3,3]$, with a quantized universe of $\{-3,-2,-1,0,1,2,3\}$. The corresponding fuzzy subsets are {NB,NM,NS,ZO,PS,PM,PB}. Triangular membership functions, which are computationally simple, are chosen for the middle fuzzy subsets, while Gaussian membership functions, which offer strong adaptability, are chosen for the subsets at both ends.

The fuzzy universes for the output PID parameter adjustments ΔK_p、ΔK_i、ΔK_d are $[-3,3]$、$[-0.5,0.5]$、$[-5,5]$ respectively. The fuzzy subsets are {NB,NM,NS,ZO,PS,PM,PB}. Triangular membership functions are chosen for the middle subsets, and Gaussian membership functions are chosen for the subsets at both ends.

The adjustment principles for the three parameters of the fuzzy adaptive PID controller are as follows:

(1) When $|e|$ is large, to achieve fast tracking, a larger ΔK_p is selected. To prevent the error change rate $|e_c|$ from becoming excessively large and suppress rapid increases, a smaller ΔK_d is chosen. To prevent integral windup and excessive overshoot, a smaller ΔK_i is generally chosen.

(2) When $|e|$ and $|e_c|$ are of medium size, to avoid excessive overshoot, a smaller ΔK_p or a smaller ΔK_p can be selected. To ensure a fast system response, an appropriate ΔK_d is chosen.

(3) When $|e|$ is small, to achieve good steady-state control performance, larger ΔK_p and ΔK_i are selected. To avoid system oscillation and improve disturbance rejection, a larger ΔK_d is chosen when $|e_c|$ is small, while a smaller ΔK_d is chosen when $|e_c|$ is large.

Based on the above principles, the adjusted parameters are substituted into the following formulas:

$$\begin{cases} K_p = K_{p0} + \Delta K_p \\ K_i = K_{i0} + \Delta K_i \\ K_d = K_{d0} + \Delta K_d \end{cases}$$

Where K_{p0}、K_{i0}、K_{d0} are the initial PID parameter values.

2.2.2 Fuzzy Inference and Defuzzification

For the fuzzy control rules, the fuzzy relation can be expressed as:

$$R = E \times E_c \times \Delta K$$

Where E is the fuzzy quantity of error, E_c is the fuzzy quantity of error change rate.

The combined fuzzy relation for ΔK_p、ΔK_i、ΔK_d across all 49 rules can be represented as:

$$\begin{cases} R_{\mathrm{p}} = \bigcup_{i=1}^{49} R_{pi} = E \times E_c \times \Delta K_p \\ R_{\mathrm{i}} = \bigcup_{i=1}^{49} R_{ii} = E \times E_c \times \Delta K_i \\ R_{\mathrm{d}} = \bigcup_{i=1}^{49} R_{di} = E \times E_c \times \Delta K_d \end{cases}$$

The fuzzy control output is obtained from the fuzzy relation:

$$U = (E \times E_c) \circ R$$

Where $\times$ denotes the fuzzy Cartesian product operator, and $\circ$ denotes the fuzzy composition operator.

The fuzzy quantities obtained after fuzzy inference need to be defuzzified. This paper employs the widely used Center of Gravity (COG) method for defuzzification to obtain the final actual output values for the control system.

The COG method takes the centroid of the area enclosed by the membership function curve and the horizontal axis as the final output value of the fuzzy inference:

$$z_0 = \frac{\int z\mu_A(z)dz}{\int \mu_A(z)dz}$$

Where A is the fuzzy set, and $\mu_A(z)$ represents the degree to which z belongs to the fuzzy set A.

3 Simulation Analysis

Simulation analysis of the quadrotor UAV suspension system is conducted in MATLAB to verify the effectiveness of the fuzzy PID controller for desired trajectory tracking and suspended load swing angle suppression.

The parameters of the UAV suspension system are shown in Table 1:

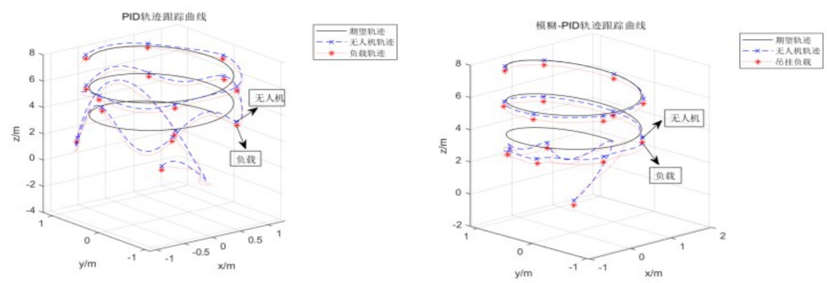
Table 1 System model parameters

Parameters	value
M	1.8 kg
l	0.3 m
m	0.2 kg
L	0.2 m
I_x	$0.03\ kg \cdot m^2$
I_y	$0.03\ kg \cdot m^2$
I_z	$0.04\ kg \cdot m^2$
g	9.81 N/kg

The desired trajectories for the various control quantities of the suspension system are as follows:

$$\begin{cases} x_d = \cos(0.3t) \\ y_d = \sin(0.3t) \\ z_d = 0.4t + 3 \\ \psi_d = \cos(t) \end{cases} \tag{20}$$

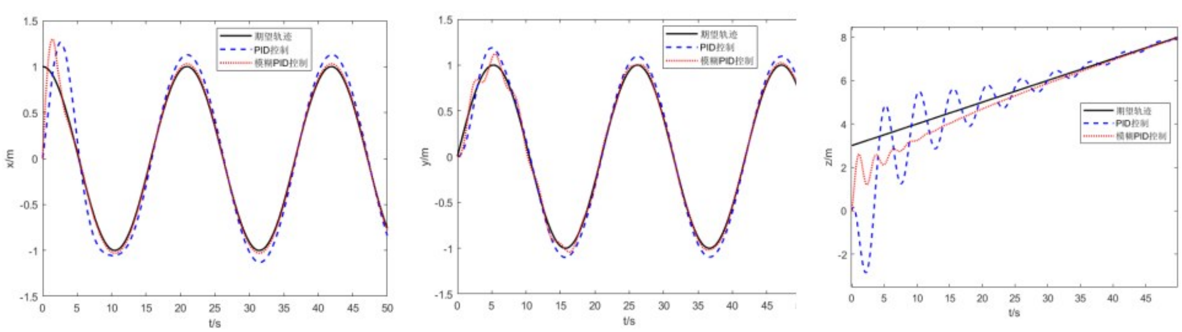
The simulation results are shown in the figures below:



(a) PID control trajectory tracking curve (b) Fuzzy PID control trajectory tracking curve

Fig.4 Spatial trajectory tracking curve

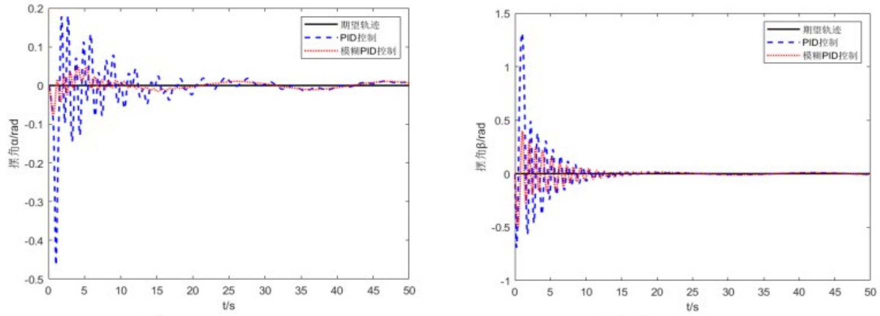
Figure 4 shows the trajectory of the UAV suspension system in three-dimensional space. The black curve represents the desired trajectory, the blue curve represents the UAV trajectory, and the red curve represents the suspended load trajectory. It can be observed that the designed fuzzy PID controller effectively controls the UAV to follow the desired trajectory, with faster response speed, smaller overshoot, and smaller error compared to the PID controller.



(a) x response curve (b) y response curve (c) z response curve

Fig.5 Drone position response curve

Figure 5 shows the UAV position response curves. The black curve represents the desired curve, the blue curve represents the response result under PID control, and the red curve represents the response result under fuzzy PID control. As seen in Fig. 5, for the controller designed based on the PID control method, the response times for the x-axis, y-axis, and z-axis are 5s, 7.4s, and 35s, respectively. For the controller designed based on the fuzzy PID control method, the response times are 3.5s, 6.5s, and 20s, respectively, representing improvements of 30%, 12%, and 42% in settling time compared to PID control. Furthermore, the overshoot of fuzzy PID control is significantly lower than that of PID control, and the curve tracking effect is better. This demonstrates that the fuzzy PID controller achieves superior control performance compared to the PID controller for the nonlinear system with complex and varying parameters.



（a） α response curve （b） β response curve

Fig.6 Comparison of suspension swing angle response curves

Figure 6 shows the response curves of the suspension swing angles. From the simulation curves, under the controller designed based on PID control, the errors for swing angles α and β are 1.7° and 5.7°, with response times of 20s and 13s, respectively. Under the controller designed based on fuzzy PID control, the errors are 1.2° and 4.6°, with response times of 10s and 11s, respectively. The comparison shows that fuzzy PID control provides more significant suppression of swing angles during flight, with faster response times.

4 Conclusion

This paper investigates the current research status of load swing suppression in quadrotor UAV suspension systems and designs a fuzzy PID controller to continuously tune the PID parameters for improved control performance. Comparative simulations finally validate that the fuzzy PID controller exhibits faster trajectory tracking response, superior tracking performance, and enhanced swing angle suppression for the UAV suspension system compared to conventional PID control. It demonstrates better control effectiveness for nonlinear control systems with complex and varying parameters. Furthermore, the control strategy presented in this paper can provide a research foundation for future studies on UAV suspension systems.

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