Design of fuzzy PID control system for quad-rotor UAV based on particle swarm algorithm under wind disturbance conditions

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Abstract:

This project proposes an intelligent control method that employs a particle swarm algorithm to optimize the rules of a fuzzy controller. The rules of the fuzzy controller are continuously adjusted based on feedback data on the attitude changes of a quadrotor unmanned aerial vehicle and the enhanced particle swarm algorithm. This enables the controller to learn autonomously, thereby enhancing its performance under various conditions. In addition to optimizing the rules of the fuzzy controller, an analysis and modeling process is conducted for the characteristics of wind speed changes under natural conditions. The resulting model is introduced into the system as environmental noise, thereby improving the controller's performance under different conditions. Experiments are conducted in the Matlab/Simulink simulation environment to test the performance of the control algorithm. The algorithm's anti-disturbance capability and control accuracy are compared when facing complex disturbances. This research methodology offers new possibilities for precise control of quadrotor unmanned aerial vehicles and provides valuable references for future drone technology development.

Keywords:

Quad-rotor, PSO algorithm, Disturbance model of wind, Parameter tuning, Fuzzy PID control

Introduction:

Quadrotor unmanned aerial vehicles (UAVs), recognized for their low cost and strong manoeuvrability, have extensive applications in various fields, such as aerial surveying, photography, agricultural plant protection, and ground object tracking. The quadrotor flight control system, serving as the control centre of the quadrotor aircraft, is a challenging and popular research topic in the international multi-rotor flight control field. Attitude control, a crucial quadrotor flight control system component, is essential for stable flight. The investigation of control algorithms is a critical issue in quadrotor UAVs, significantly influencing the system's usability, stability, and superior performance. An excellent algorithm should enable the quadrotor UAV to meet the requirements of high control accuracy, short response time, anti-disturbance solid ability, and superior robustness, adapting to the environmental characteristics under different working conditions. PID control, simple to operate and effective in controlling quadrotor UAVs, heavily relies on parameters, making their selection critical. Numerous intelligent optimization algorithms exist for tuning PID parameters, including the chicken, genetic, and particle swarm algorithms. The particle swarm algorithm, a new heuristic global search method based on swarm intelligence, is straightforward. Since PID only requires the adjustment of three parameters, this study employs the PSO algorithm to derive optimal parameter values. These values are then applied to a PID controller for the quadrotor aircraft's attitude (flip) and altitude control.

In recent years, the traditional PID parameter tuning technology has been enhanced by many scholars globally using the particle swarm algorithm to improve its performance. A team led by Hu Wenhua introduced a particle swarm optimization algorithm with variable weight and hybridization to address the control parameter optimization problem. This method dynamically adjusts the inertia weight based on the distance between particles in the swarm and the globally optimal particle during the selection process. Hybrid evolution is incorporated to enhance particle diversity and prevent convergence to local optima. The results indicate that this optimization algorithm effectively tunes parameters, ensuring and enhancing the control quality of quadrotor aircraft and improving design efficiency. RAZA and others verified the effectiveness and stability of the PSO algorithm for PID control of upper limb rehabilitation robots. Hu Dandan and others iteratively optimized the controller parameters as particles in the particle swarm. Simultaneously, based on the traditional PSO algorithm, cross-optimization was performed on particles with poor fitness function values, referring to the genetic algorithm. The simulation results show that the optimized controller has a minor overshoot and shorter adjustment time. Roni and his team utilized both the Genetic Algorithm (GA) and the Particle Swarm Optimization (PSO) algorithm to optimize the PID controller of a three-phase MG system. Li and his colleagues introduced a sliding mode variable structure PID control strategy based on PSO optimization to enhance the performance of ship-tracking autopilots.[4]

When PID control is applied to complex nonlinear systems, such as quadrotor unmanned aerial vehicles (UAVs), it may not ensure high control accuracy and robust anti-disturbance capability. Current research is predominantly confined to indoor environments or those with minimal interference without introducing complex environmental disturbances. The impact of such disturbances on the performance of control algorithms is not considered. In natural conditions, significant changes in environmental disturbances, such as wind speed variations, can significantly affect the flight attitude of quadrotor UAVs. This is a critical factor that must be considered when designing control algorithms. In harsh external environments, the flight of unmanned aerial vehicles will be significantly affected. During the operation of unmanned aerial vehicles in windy weather, there are strict conditions for the take-off and landing conditions of unmanned aerial vehicles. Once the wind direction or wind speed does not meet the conditions for take-off or landing, it cannot continue. If the unmanned aerial vehicle is forced to take off or land when the wind direction is unstable and the wind speed changes significantly or at a higher level, it is easy to cause accidents.

This article focuses on the X-type variable pitch and variable speed quadrotor aircraft, enhancing the particle swarm algorithm to improve the reliability of the controller. This enhancement mitigates the randomness associated with manual parameter adjustment when applying the quadrotor PID controller. The improved particle swarm algorithm, in tandem with feedback data on the attitude changes of the quadrotor unmanned aerial vehicle, is employed to continuously adjust and optimize the rules of the fuzzy controller. This methodology facilitates autonomous learning for the controller, thereby bolstering its performance in managing diverse conditions.

Wind disturbance model analysis and modeling:

The characteristics of wind speed variation are meticulously analyzed to evaluate the quadrotor unmanned aerial vehicle's capability to sustain its intended attitude amidst intense wind disturbances during flight. This analysis culminates in the development of corresponding mathematical models, which are integrated into the quadrotor UAV simulation system as environmental noise. The output of this system provides a measure of the controller's precision and its resilience to disturbances, thereby offering a comprehensive assessment of its performance under various conditions. This methodological approach enhances the robustness of the UAV's control system, enabling it to operate effectively under a wide range of environmental conditions.

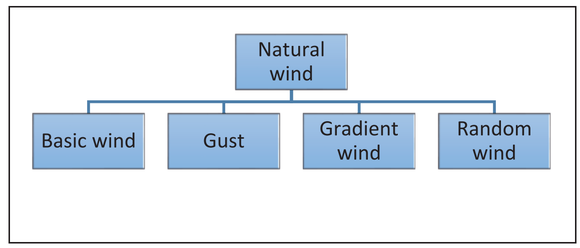


Fig.1 Wind's type classification

$V_1 = K$

$$\mathbf{V}_2 = \begin{cases} 0, & t < t_1 \\ \dfrac{V_{g\max}}{2}\left\{1-\cos\left[2\pi\left(\dfrac{t-t_1}{T_g}\right)\right]\right\}, & t_1 \leqslant t \leqslant t_1 + T_g \\ 0, & t > t_1 + t_g \end{cases}$$

$$\mathbf{V}_3 = \begin{cases} 0, & t < t_{r1} \text{ or } t > t_{r2} + t_{r3} \\ V_{r\max}\dfrac{t-t_{r1}}{t_{r2}-t_{r3}}, & t_{r1} \leqslant t \leqslant t_{r2} \\ V_{r\max}, & t_{r2} < t \leqslant t_{r2} + t_{r3} \end{cases}$$

$$\mathbf{V}_4 = \mathbf{V}_{4\max} * R_{am}(-1,1)\cos\left(\omega_n t + \varphi_n\right)$$

The analysis above leads to the derivation of mathematical models for four fundamental types of wind. By applying specific weight ratios to these four basic models, a comprehensive model for wind speed changes emerges. Here, different weights signify the impact of various fundamental winds on the overall trend of wind speed changes. Setting different weight ratios for different wind conditions allows the simulation of wind speed changes under various conditions. The formula for this model is as follows:

$V = a1*V1 + a2*V2 + a3*V3 + a4*V4$

$a1 + a\,2 + a3 + a4 = 1$

When considering the disturbance force formed by the wind on an object, according to the momentum theorem, it can be known that:

$Ft = mV$

In this context, F represents the disturbance force generated by the wind, m represents the mass of air that generates the disturbance force, and V is the wind speed. When the wind generates a disturbance to the quadrotor unmanned aerial vehicle, its force will form a force surface S on the body of the unmanned aerial vehicle. Therefore, during a specific period, the mass of air that generates disturbance can be expressed by the following formula:

$$m = \rho * S * V * t$$

Therefore, the disturbance force generated by the wind on the quadrotor unmanned aerial vehicle can be expressed as:

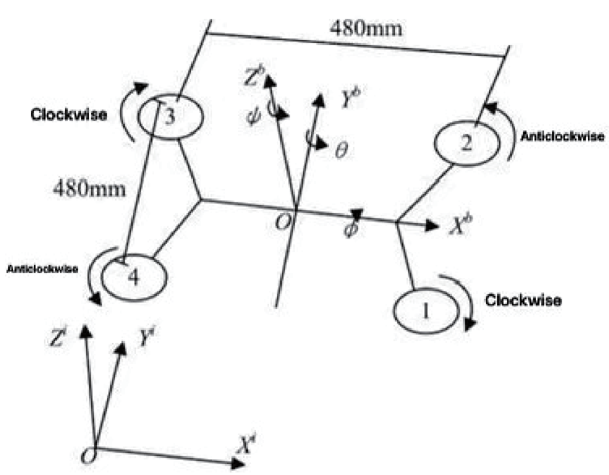
$$F = \rho * S * V^2$$

The formula suggests that the disturbance force exerted by the wind is influenced by three factors: air density, area of action, and wind speed. During task execution, quadrotor unmanned aerial vehicles typically do not traverse a large space rapidly, and the air density remains relatively constant. Consequently, the air density contributing to the disturbance force can be considered a constant. Similarly, the body structure of the quadrotor unmanned aerial vehicle does not undergo significant changes during flight, implying that the action surface 'S' of the wind disturbance force on the body can also be regarded as a constant. In summary, the magnitude of the disturbance force exerted by the wind on the quadrotor unmanned aerial vehicle is solely dependent on the magnitude of the wind speed. Therefore, the expression for the wind disturbance force can be reformulated as follows:

$$F = k * V^2$$

Quadcopter UAV kinematics modeling:

Based on the dynamic model of the quadrotor unmanned aerial vehicle, design a fuzzy PID controller to control it.



There is the following conversion relationship between the inertial coordinate system i and the body coordinate system:

$$R = \left(R_{zyx}(\psi,\theta,\varphi)\right)^{\mathrm{T}} = \begin{bmatrix} c_\theta c_\psi & s_\varphi s_\theta c_\psi - c_\varphi s_\psi & c_\varphi s_\theta c_\psi + s_\varphi s_\psi \\ c_\theta s_\psi & s_\varphi s_\theta s_\psi + c_\varphi c_\psi & c_\varphi s_\theta s_\psi - s_\varphi c_\psi \\ -s_\theta & s_\varphi c_\theta & c_\varphi c_\theta \end{bmatrix}$$

Without considering the propeller flapping characteristics, the quadrotor unmanned aerial vehicle is regarded as a uniform and symmetrical rigid body. According to Newton's second law, the translational equation of the quadrotor unmanned aerial vehicle can be obtained:

$$M\begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{pmatrix} = R\begin{pmatrix} 0 \\ 0 \\ \sum_{j=1}^{4} k\omega_j^2 \end{pmatrix} - R\left(\gamma_t\left(R^{\mathrm{T}}\vec{r^i}\right)\right) - \begin{pmatrix} 0 \\ 0 \\ Mg \end{pmatrix}$$

The total external force moment of the "X" structure quadrotor unmanned aerial vehicle can be expressed as:

$$\sum M^b = -\gamma_r \Omega^b + \begin{bmatrix} \alpha k U_1 \\ \alpha k U_2 \\ \alpha U_3 \end{bmatrix} = -\gamma_r \Omega^b + \begin{bmatrix} \alpha k\left(\omega_1^2 - \omega_2^2 - \omega_3^2 + \omega_4^2\right) \\ \alpha k\left(\omega_1^2 + \omega_2^2 - \omega_3^2 - \omega_4^2\right) \\ \alpha\left(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2\right) \end{bmatrix}$$

There is the following relationship between the Euler angle and the body angular velocity:

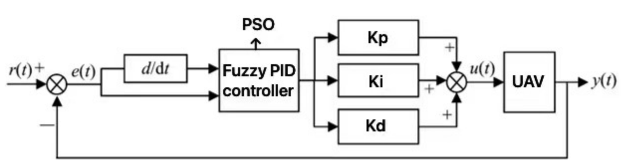
$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} \dot{\varphi} - \dot{\psi}\sin\theta \\ \dot{\theta}\cos\varphi + \dot{\psi}\sin\varphi\cos\theta \\ -\dot{\theta}\sin\varphi + \dot{\psi}\cos\varphi\cos\theta \end{bmatrix}$$

Summarizing the above formula, we can get:

$$
\begin{cases}
\ddot{x} = \left(C_\varphi C_\theta C_\psi + S_\varphi S_\psi\right)\dfrac{1}{M}\displaystyle\sum_{j=1}^{4} k\omega^2 - \dfrac{R}{M}\left(\gamma_t\left(R^{\mathrm{T}}\vec{v}^i\right)\right) \\
\ddot{y} = \left(C_\varphi C_\theta C_\psi - C_\psi S_\varphi\right)\dfrac{1}{M}\displaystyle\sum_{j=1}^{4} k\omega^2 - \dfrac{R}{M}\left(\gamma_t\left(R^{\mathrm{T}}\vec{v}^i\right)\right) \\
\ddot{z} = \dfrac{C_\varphi C_\theta}{M}\displaystyle\sum_{j=1}^{4} k\omega^2 - \dfrac{R}{M}\left(\gamma_t\left(R^{\mathrm{T}}\vec{v}^i\right)\right) - g \\
p = \dot{\varphi} - \dot{\psi}\sin\theta \\
q = \dot{\theta}\cos\varphi + \dot{\psi}\sin\varphi\cos\theta \\
r = -\dot{\theta}\sin\varphi + \dot{\psi}\cos\varphi\cos\theta \\
\dot{p} = qr\left(\dfrac{I_y - I_z}{I_x}\right) + \dfrac{l}{I_x}U_1 - \dfrac{R\gamma_t R^{\mathrm{T}}}{I_x}p + \dfrac{J_r}{I_x}qU_3 \\
\dot{q} = pr\left(\dfrac{I_z - I_x}{I_y}\right) + \dfrac{l}{I_y}U_2 - \dfrac{R\gamma_t R^{\mathrm{T}}}{I_y}q + \dfrac{J_r}{I_y}pU_3 \\
\dot{r} = pq\left(\dfrac{I_x - I_y}{I_z}\right) + \dfrac{1}{I_z}U_3 - \dfrac{R\gamma_t R^{\mathrm{T}}}{I_z}r
\end{cases}
$$

Design of fuzzy PID controller:

In order to make the fuzzy PID controller have more substantial applicability and better control performance when dealing with different complex systems and noise, an improved particle swarm algorithm is designed to optimize continuously and re-adjust the fuzzy rules during the operation of the system so that the control system can "learn" and "evolve".



The process of the improved particle swarm algorithm is as follows:

1) The particle swarm is initialized, generating the position and velocity of all particles and determining the inertia weight of the particles.

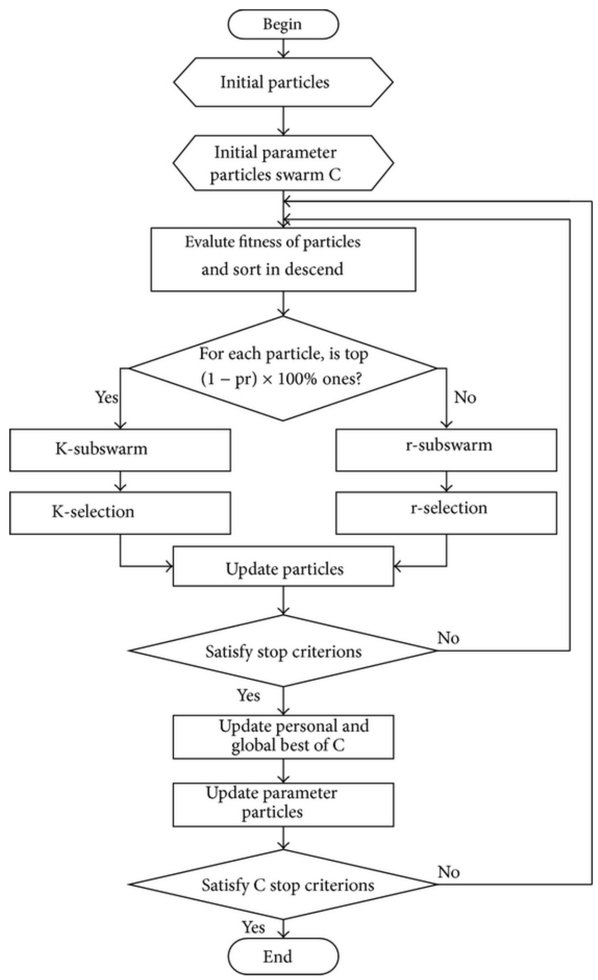
2) The velocity and position of the particles are updated according to the velocity and position formulas of the particle swarm.

3) Each particle is substituted into the simulation model, and the corresponding ITAE value is calculated.

4) The arithmetic mean of all particle ITAE values is calculated. An even number of particles with ITAE values less than average are taken directly into the next iteration. The remaining particles undergo crossover and selection to generate the same number of offspring sorted together with their parents. Half of the smaller ITAE values are taken into the next iteration.

5) Each particle's fitness value is compared with the fitness value of the best position experienced by that particle. If it is better, that particle is used as a new one. Each particle's fitness value is compared with the fitness value of the best position experienced by the particle swarm. If it is better, that particle is used as a new one.

6) If the final condition is not met (the fitness value is less than the preset threshold or exceeds the maximum number of iterations), the process returns to step 2). Otherwise, the algorithm is exited, and the optimization process curve and optimal solution are output.[5]



Using the improved chaotic particle swarm algorithm to adjust the three parameters of PID, the adjusted PID controller controls the quadrotor aircraft and obtains the difference between the actual output value and the input step signal value by calculating ITAE (i.e., the fitness value of the function) to determine whether it meets the stopping condition of the algorithm. If it is satisfied, the calculation process ends. If it is not satisfied, the operation is repeated until a value that meets the set conditions or reaches the maximum number of iterations is obtained.

Conclusion:

This paper presents a novel fuzzy PID control methodology for quadrotor unmanned aerial vehicles, utilizing a particle swarm algorithm to optimize the rules of the fuzzy controller. Simultaneously, a wind disturbance model is developed to evaluate the controller's robustness in complex environments. The simulation model, as proposed in this study, can serve as a valuable tool for future validation efforts.

Provided the feasibility, this methodology could be implemented in the real-world control of quadrotor unmanned aerial vehicles, with ongoing enhancements to the rule optimization process facilitated by the particle swarm algorithm. The algorithm's rapid convergence speed, the ergodicity, randomness, and sensitivity to initial values of the chaotic sequence, coupled with the adaptive inertia weight method, balance the global and local search capabilities of the particle swarm algorithm. This balance expedites the convergence speed towards the optimal rule during the optimization process, thereby reducing computational overhead.

In conclusion, this research contributes to the field by offering a comprehensive and efficient approach to quadrotor UAV control, paving the way for future advancements in this domain. Future work will focus on further refining the rule optimization process and exploring the practical application of this method in real-world scenarios. The ultimate goal is to enhance the reliability and efficiency of quadrotor UAVs, making them more adaptable and effective in varying environmental conditions.

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