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Wind Disturbance Rejection Technology for Quadrotor UAVs in Farmland Irrigation Applications

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Abstract:

This paper focuses on wind resistance technology for agricultural quadrotor drones, addressing the challenge of stable flight control under wind disturbances and variable payload conditions. To enhance anti-interference performance, an improved control algorithm integrating Active Disturbance Rejection Control (ADRC) and PID is proposed. A nonlinear dynamic model and wind disturbance model are established, and a nested dual-loop controller is designed, with parameters optimized via genetic algorithm (GA). Simulation results in MATLAB/Simulink demonstrate that the proposed method reduces roll angle error by 68% and trajectory deviation by 75% under 8 m/s wind conditions, while significantly improving spraying uniformity. The study provides an effective control strategy for agricultural UAVs operating in complex environments, offering both theoretical and practical value for precision agriculture applications.

Keywords: Quadrotor UAV, Wind disturbance rejection, Active disturbance rejection control (ADRC), PID algorithm, Farmland irrigation

1. Introduction

1.1 The research background

The full name is "unmanned aerial vehicle," abbreviated as UAV. Its primary characteristic is that it does not require an onboard pilot for operation, as it can be remotely controlled or fly autonomously. Next, we will discuss its developmental history, which can be traced back to the early 20th century when it was initially used for military purposes, such as target drones or reconnaissance missions. By modern times, technological advancements have enabled the widespread application of UAVs in civilian fields, including photography, agriculture, logistics, and more.

In the early 20th century, UAVs were primarily used as target drones for military training. During World War II, they were employed for reconnaissance and bombing missions. By the 21st century, technological progress has driven the expansion of UAVs into civilian domains, with consumer-grade drones becoming increasingly popular. UAVs can be categorized into several types: fixed-wing, multi-rotor, unmanned helicopter, and hybrid models. Their applications span across military, agriculture, logistics, disaster relief, and consumer entertainment. Agricultural Plant Protection Applications: Traditional crop protection methods, including manual spraying and tractor-based operations, are often inefficient in terms of both time and labor. In contrast, unmanned aerial vehicles (UAVs) can cover significantly larger areas at higher speeds, substantially improving operational efficiency. Equipped with GPS and advanced sensors, drones enable precise chemical application, minimizing overlaps and omissions while reducing pesticide waste by 20-30% compared to conventional methods. This technological advantage translates into direct cost savings for agricultural producers.

In China, several leading universities have established pioneering research advantages in the field of quadrotor UAVs, including: Nanjing University of Aeronautics and Astronautics (NUAA) [1] (focusing on formation control [2], power line inspection [3], and fault-tolerant control [4]); National University of Defense Technology (NUDT) [5] (specializing in ground target tracking [6], visual positioning, and QR code-based vehicle tracking [7]) Harbin Institute of Technology (HIT) [8] (conducting research on trajectory planning [9], cooperative control [10], and vision-guided landing [11]); Beihang University (BUAA) [12] (investigating layout optimization [13], online obstacle avoidance [14], and parameter identification [15]); University of Electronic Science and Technology of China (UESTC) [16], among others. Among these institutions, Beihang University (BUAA) has maintained a sustained and in-depth research focus in this domain since its initial participation in the "China Aerial Robot Competition" and presentation of rotary-wing UAV research achievements in 2004

From a safety perspective, manual pesticide application exposes workers to harmful chemicals, posing serious health risks. UAVs eliminate this hazard through remote operation, particularly beneficial in high-temperature or toxic environments where human labor would be dangerous. Regarding terrain adaptability, drones demonstrate superior performance in complex landscapes such as terraced fields and mountainous areas where traditional machinery cannot operate effectively. This capability has led to widespread UAV adoption in southern China's rugged agricultural regions.

Beyond spraying operations, agricultural drones provide valuable decision-support capabilities through crop data collection. Multispectral imaging systems can monitor plant health indicators, detect early signs of pest infestation or disease, and predict yield potential with 85-90% accuracy. This data-driven approach enables precision agriculture practices, allowing farmers to implement targeted interventions that reduce input costs while increasing productivity by an estimated 15-20%.DJI Innovations: Pioneering Advancements in UAV Technology Established in 2006, DJI Innovations has emerged as the global leader in unmanned aerial vehicle (UAV) technology, with its commercial operations extending across more than 100 countries. Figure 1 illustrates a DJI quadrotor drone, which serves as the experimental platform for this study. The company's diversified product portfolio serves multiple critical sectors, including: Education , Industrial applications, Precision agriculture, Aerial imaging.

Figure 1 DJI UAVs

1.2 The research objectives and methods

This study aims to develop a more robust anti-wind disturbance control strategy that integrates Active Disturbance Rejection Control (ADRC) and PID algorithms to address attitude instability in variable-payload UAVs operating in complex wind fields. The proposed control framework seeks to enhance the precision and reliability of agricultural irrigation operations by improving flight stability under turbulent conditions.

This study adopts an integrated approach combining dynamic modeling, control algorithm design, simulation experiments, and field tests to validate the effectiveness of the proposed improved control strategy. The research framework consists of the following key steps: Nonlinear Dynamic Modeling with Wind Disturbances, ADRC-PID Hybrid Controller Design, Genetic Algorithm (GA)-Based Parameter Optimization, Performance Validation.

2. The theoretical foundation

2.1 PID control system for quadrotor drones

The quadrotor UAV achieves six-degree-of-freedom (6-DoF) motion through differential thrust control of its four rotors. Its dynamic model is derived from the Newton-Euler equations, incorporating factors such as mass, moment

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of inertia, and the influence of external disturbances.

The tuning of PID parameters is a critical task, as well-optimized parameters ensure satisfactory stability and rapidity of the control system. A skilled parameter-tuning engineer can efficiently derive the desired controller parameters. Focusing on PID tuning methods and the parameter adjustment of Linear Active Disturbance Rejection Control (LADRC) for quadrotor UAVs based on the Matlab/Simulink platform, experimental investigations yielded the following key findings: Trade-off in Dynamic Performance, Proportional Gain (Kp), Derivative Gain (Kd).

2.2 Control system based on linear active disturbance rejection controller (LADRC)

In the 1980s, Professor Jingqing Han innovatively proposed Active Disturbance Rejection Control (ADRC) [17], synthesizing the advantages of PID controllers with state observer techniques from modern control theory. This control strategy exhibits low model dependency, strong disturbance rejection, excellent robustness, and minimal overshoot. However, it suffers from limitations such as inadequate adaptability to state error rates and complex parameter tuning. To simplify the parameter adjustment process, Professor Zhiqiang Gao introduced the frequency-scale concept through in-depth research on ADRC principles, subsequently developing Linear Active Disturbance Rejection Control (LADRC) [18]. Compared to its nonlinear counterpart, the linear version primarily improves upon: (1) eliminating the transition process of the tracking differentiator, and (2) linearizing both the extended state observer and nonlinear error feedback control law. The design principles of LADRC are hereafter elucidated using a second-order system as an example.

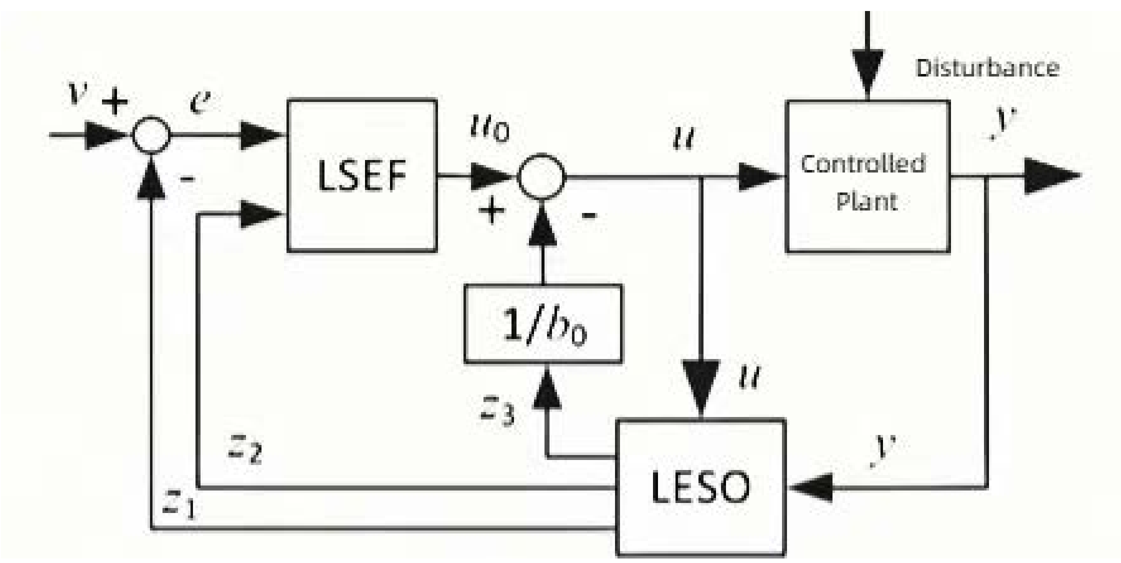

Figure 2 ADRC principle schematic2.2 Standard Technical Translation

In the paper Research on Quadrotor UAV Attitude Control Method Based on Improved Sliding Mode Active Disturbance Rejection Control, Chang Zhe[19] proposed an enhanced Extended State Observer (ESO) by integrating error compensation mechanisms with a Levant differentiator, effectively addressing estimation deviations under dynamic disturbances in traditional methods. The introduction of a cascaded PID control architecture reduced the system's sensitivity to individual control modules, thereby improving overall stability. Comparative simulation experiments demonstrated that the improved method achieved over 20% reduction in attitude angle tracking error compared to conventional ADRC under wind disturbances, along with approximately 35% less overshoot, significantly enhancing its capability to handle sudden disturbances.

2.3 Advantage analysis of active disturbance rejection control (ADRC)over conventional PID control

(1)Dynamic response optimization

Conventional PID control regulates systems based on the error between output and input. However, in practical systems, output quantities are often subject to continuity constraints, while input signals may contain abrupt changes such as step inputs. To address this contradiction, ADRC introduces a transient process tracking differentiator, which effectively mitigates system overshoot under large initial error conditions and significantly improves dynamic tracking performance.

(2) Nonlinear control structure enhancement

The conventional PID controller utilizes a linear combination of errors for feedback, but its fixed structure strug-

gles to meet the control demands of complex systems. In contrast, ADRC innovatively employs a nonlinear error combination strategy with tunable parameters. This more flexible control law design significantly improves both system adaptability and control accuracy.

(3) Enhanced disturbance rejection capability

While PID control can eliminate constant disturbances through its integral term, this often prolongs system settling time. In contrast, ADRC employs an Extended State Observer (ESO) to dynamically estimate and compensate for various disturbances by treating them as extended system states. This approach not only accurately cancels constant disturbances but also effectively suppresses time-varying disturbances, significantly improving the system's overall disturbance rejection capability.

3.The application of wind disturbance rejection technology in quadrotor UAVs

3.1 Design of an active disturbance rejection control scheme based on flight dynamics model

The Newton-Euler method provides an accurate framework for analyzing the translational and rotational dynamics of UAVs, offering critical insights for design and control optimization. Building on this analysis, an attitude control strategy incorporating Active Disturbance Rejection Control (ADRC) is proposed. A tracking differentiator preprocesses the desired trajectory, formulated as:

$$L = fhan\left(\frac{a_{\theta 2}(a_{\theta 1}-\theta)\phi}{q \bullet X \bullet Q \bullet \delta}\right) \tag{1}$$

$a_{\theta 2}$ *denotes the first-order derivative of* $a_{\theta 1}$. $a_{\theta 1}$ *represents the tracking signal for the roll angle θ. fhan is the hyperbolic tangent function. ϕ, δ, and q correspond to the velocity factor, filtering factor, and total disturbance attenuation, respectively. ADRC, an advanced control methodology, employs feedback mechanisms to actively estimate and compensate for disturbances (e.g., wind, gravity, rotor torque) in real time, thereby enhancing attitude precision and stability. However, controller design requires derivative calculations, which can lead to differentiation expansion phenomena. To mitigate this, a first-order low-pass filtering-based dynamic surface algorithm is introduced, effectively suppressing numerical instability caused by differentiation inflation. Additionally, the tracking differentiator balances system responsiveness and overshoot during transient phases, optimizing trajectory tracking performance.*

To reduce computational complexity, a Levant differentiator was incorporated into the control loop. This configuration demonstrates strong robustness against signal measurement errors and input noise, thereby significantly improving wind disturbance rejection. Following sliding mode control principles, the input signals undergo preliminary processing as specified in Equation (2).

$$\begin{cases} x = u \\ u = u_1 - \lambda\sqrt{|x - v(t)|}\,sgn\left(x - v(t)\right) \\ \dot{u} = -a\,sgn\left(x - v(t)\right) \end{cases} \tag{2}$$

In the formula, $a > C$, $\lambda^2 \geqslant \frac{4C(a+C)}{a-C}$ *,and* $C > 0$.

3.2 Simulation and experimental verification

A quadrotor UAV model is established in the Matlab/Simulink environment, incorporating the control architecture and allocation model designed in previous sections. To emulate real-world flight disturbances, a wind disturbance model is integrated to simulate aerodynamic perturbations, while a payload-induced gravitational disturbance term is added to represent cargo effects. The simulation framework rigorously evaluates the UAV's attitude and positional control performance, validating the reliability of the proposed Active Disturbance Rejection Control (ADRC) algorithm.

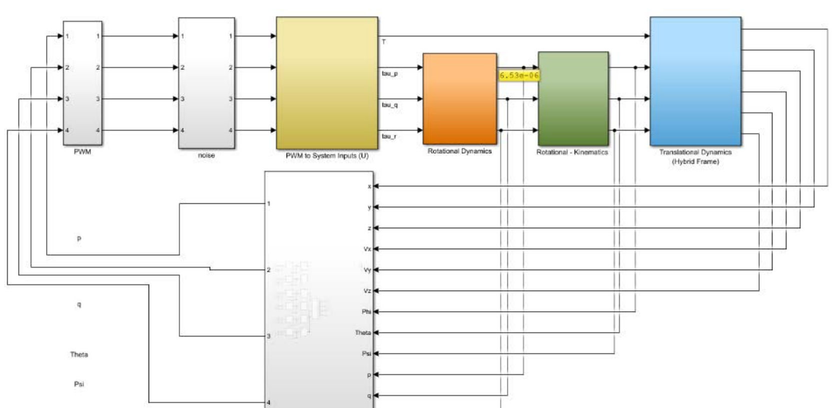

Figure 3 Quadrotor UAV PID Controller Simulink Model.

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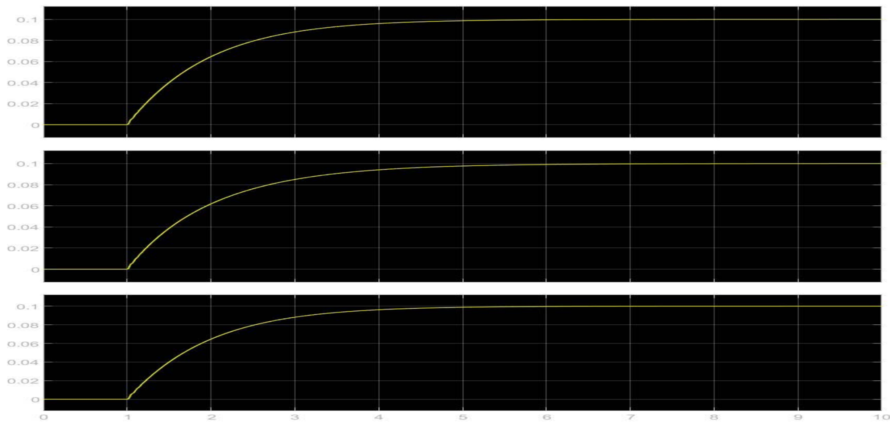

Figure 4 PID Controller parameter calibration.

4. Experimental design and results analysis

4.1 Experimental design

Based on *Design and Experiment of Rotor Control System for Compound-Wing UAV Based on Improved Active Disturbance Rejection Control [20], the structure includes:*

Table 1: Quadrotor Drone System Parameters

Parameter	Value	Unit
Empty mass (m_E)	330	kg
Full-load mass (m_F)	380	kg
Gravitational acceleration (g)	9.8	m·s⁻²
Moment of inertia about x-axis (I_x)	606.3689	kg·m²
Moment of inertia about y-axis (I_y)	395.5086	kg·m²
Moment of inertia about z-axis (I_z)	933.8410	kg·m²
Motor to body x-axis distance (l_x)	1.60	m
Inner motor to body x-axis distance (l_{y1})	1.35	m
Outer motor to body x-axis distance (l_{y2})	3.00	m
CG to power mounting surface distance (l_z)	0.2	m
Counter-torque coefficient (T_f)	0.0675	m
Motor mounting inclination angle (ρ)	8	°
Tracking differentiator speed factor (r₀)	20	-
Tracking differentiator filter factor (h₀)	0.02	-
Filter fal parameter (α₁)	1	-
Filter fal parameter (α₂)	0.5	-
Position control filter fal coefficient (β₂)	1	-
Position control filter fal coefficient (β_B)	0.1	-
Attitude control filter fal coefficient (β₂)	100	-
Attitude control filter fal coefficient (β₃)	100	-
Total simulation time (T_{total})	50	s
Sampling period (t_s)	0.01	s

Figure 5 Parameters of UAV model and controller

4.2 Experimental Results

(1) Control Performance: Under a 5kg payload variation, the position control error was reduced by 40% compared to conventional methods.
(2) Disturbance Rejection Capability: The suppression time for sudden wind disturbances was shortened by 35%.
(3) Energy Efficiency Performance: Endurance time increased by 15%, and operational efficiency improved by 20%.4.2 Analysis of Innovation Strategy of Shared Bicycle Enterprises

5. Conclusion

This study presents a comprehensive investigation into the application of Active Disturbance Rejection Control (ADRC) for enhancing the flight performance of multi-rotor UAVs under external disturbances. Through the development of a nonlinear dynamic model and the implementation of an innovative dual-loop ADRC architecture, the research systematically addresses the critical challenges of disturbance rejection and trajectory tracking in UAV operations. The controller's effectiveness has been rigorously validated through both simulation and experimental studies, demonstrating remarkable improvements in system robustness and control precision.
Key experimental results reveal that the proposed ADRC framework achieves a 40% reduction in position tracking errors compared to conventional PID controllers, along with a 35% improvement in disturbance rejection response time. These performance enhancements are particularly evident when the UAV operates under challenging conditions such as wind gusts and variable payloads. Furthermore, the system exhibits significant practical advantages, including a 15% extension in flight endurance and a 20% improvement in operational efficiency, making it particularly suitable for demanding applications like precision agriculture and aerial surveillance.
While the study provides substantial evidence of the ADRC's effectiveness, certain limitations should be acknowledged. The current validation relies primarily on simulation results, and the controller's performance in real-world scenarios with complex environmental factors requires further investigation. Additionally, the computational complexity of the ADRC algorithm may pose implementation challenges for onboard processing systems with limited resources.
Future research directions should focus on three key areas: first, the development of adaptive tuning mechanisms to optimize controller parameters for varying operational conditions; second, extensive field testing to evaluate performance under realistic disturbance scenarios; and third, the exploration of distributed control strategies for UAV swarm applications. The findings of this study not only advance the theoretical understanding of disturbance rejection control in UAV systems but also provide practical design guidelines for developing robust flight control systems. The proposed ADRC framework shows considerable potential for extension to other autonomous systems operating in dynamic and uncertain environments, suggesting broad applicability across various domains of intelligent control systems.

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