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Research on Endurance Optimization of Quadrotor UAVs Assisted by Solar Patch Power Supply

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ABSTRACT
This research addresses the short endurance of quadrotor UAVs by proposing an auxiliary power solution based on flexible CIGS solar patches. Through CFD simulation and photovoltaic system modeling, the layout of solar patches on the wings, fuselage, and support arms is optimized to balance aerodynamic performance and energy capture efficiency. A closed-loop methodology of "numerical simulation-wind tunnel testing-flight verification" is adopted. Results indicate that under the condition of a drag increase controlled within 5%, the solar-assisted power system can enhance UAV endurance by 15%-20%. This scheme features easy installation and low cost, providing a viable technical solution for long-endurance applications such as power inspection and logistics distribution.

KEYWORDS
Solar patch; Quadrotor UAV; Endurance optimization; Aerodynamic performance; Energy harvesting

1 Introduction

With the widespread application of UAV technology in fields like power inspection, agricultural spraying, and logistics distribution, insufficient endurance has become a key bottleneck restricting industrial development. The energy density of mainstream lithium batteries is approaching its theoretical limit, while fuel cells face challenges related to power density, making solar-assisted power a crucial breakthrough. Although progress has been made in high-efficiency solar technologies like flexible CIGS thin films and perovskite-silicon tandems, applied to fixed-wing or high-altitude long-endurance (HALE) UAVs, research on solar integration for mainstream quadrotor models remains scarce, particularly regarding systematic optimization in aerodynamic layout and dynamic energy management [1]. This study focuses on quadrotor UAVs, aiming to systematically analyze the impact of solar patch placement on aerodynamic performance and energy capture efficiency through CFD simulation and wind tunnel experiments, thereby proposing an optimized design method that balances flight stability and energy supplementation capability [2].

2 Parameters Influencing the Endurance of Quadrotor Unmanned Aerial Vehicles (UAVs)

The flight time of quadcopter drones is a key metric for assessing their performance and represents a significant bottleneck that currently limits their broader application. Their endurance is not determined by a single factor but is rather the result of the combined effects of multiple aspects, including propulsion system efficiency, airframe structural design, battery technology and energy management, flight control strategies, and external environmental conditions . Firstly, the matching and efficiency of the propulsion system are central to endurance. The aerodynamic characteristics of the rotors (such as diameter and pitch) and the efficiency of the motors directly determine how effectively electrical energy is converted into lift [3]. Research indicates that optimizing the rotor structure (e. g., by adjusting the blade inclination angle and width) can significantly improve hover efficiency, thereby extending flight time . Simultaneously, the matching between the motor and the propeller is crucial; high-efficiency motors operating under specific loads and RPMs can reduce energy losses . For instance, experimental data shows that under the same thrust requirement, selecting a more efficient propeller (such as the Gemfan 6030 compared to other models) can increase system efficiency by approximately 17 percentage points . Secondly, the airframe structure and lightweight design have a direct impact on endurance. During flight, the drone must overcome its own weight; a higher overall weight requires more power to maintain flight . Reducing the airframe weight effectively through structural optimization (e. g., using topology optimization methods) and the use of lightweight composite materials can directly contribute to improved endurance . One study, utilizing Altair Inspire software for topology optimization of airframe components, achieved a 71.8% weight reduction while meeting strength requirements, which directly aids in enhancing flight time . Thirdly, the limitations of battery technology are a primary factor in the current endurance bottleneck. While lithium-polymer (Li-Po) batteries are the mainstream choice, their energy density is limited. Increasing battery capacity can directly extend flight time, but the added weight also leads to extra energy consumption. Therefore, it is necessary to find an optimal balance point between battery capacity and the total weight of the drone . Modeling analysis has revealed a non-linear relationship between battery capacity and flight time, indicating an optimal battery weight that maximizes endurance . Furthermore, flight control strategies and environmental factors cannot be ignored. Aggressive maneuvers (such as rapid acceleration and high-speed flight) consume significantly more power than stable hovering . Flying in strong wind conditions requires

additional power to maintain stability, substantially shortening flight time . Quadcopters rely on adjusting the speed of multiple rotors for attitude control, creating a trade-off between control efficiency and endurance – an excessively large propeller pitch may benefit control responsiveness but potentially reduce thrust efficiency . In summary, the flight time of a quadcopter is the result of a comprehensive balance of its overall design, component performance, and operating conditions. Extending endurance requires a systematic and comprehensive consideration across multiple levels, including aerodynamic optimization, structural weight reduction, energy management, and intelligent flight control .

3 System Modeling and Optimization Methodology

This chapter elaborates on the theoretical models established, the key algorithms employed, and the optimization strategies devised for the challenges encountered in realizing the solar-assisted endurance enhancement for quadrotor UAVs. The integrated application of Computational Fluid Dynamics (CFD) models, photovoltaic system models, and multi-objective optimization algorithms provides quantitative analysis tools and a theoretical basis for the optimal design of solar patch layouts.This study adopts a closed-loop research framework of "Numerical Simulation - Wind Tunnel Testing - Flight Verification", aiming to ensure the reliability and engineering practicality of the research conclusions through multi-level, multi-fidelity verification means. The core of this framework lies in using numerical simulation for efficient, low-cost preliminary design and parameter screening, then validating and calibrating the models through wind tunnel testing in a controlled environment, and finally conducting comprehensive performance verification through actual flight tests under real working conditions. The test data is fed back into the models, forming a complete closed loop of design-verification-optimization.

3.1 Core Theoretical Models

3.1.1 Aerodynamic Characteristic Analysis Model

To accurately evaluate the impact of different solar patch layouts on the UAV's aerodynamic performance, a high-fidelity numerical model based on Computational Fluid Dynamics (CFD) was established.

(1) Governing Equations and Turbulence Model: The three-dimensional, incompressible Reynolds-Averaged Navier-Stokes (RANS) equations are solved. The k-omega Shear Stress Transport (SST) model is selected as the turbulence model, as it accurately simulates near-wall flow and flows with moderate adverse pressure gradients, making it particularly suitable for calculating the complex flow field around UAVs.

(2) Mesh and Solver Settings: Using ANSYS Fluent 2023 R1 software, a computational model containing approximately 2 million hybrid grids is constructed. A pressure-based solver is used, and dynamic mesh technology is enabled to analyze the transient aerodynamic characteristics of the UAV under different flight attitudes (such as climbing and level flight). The core objective of the computation is to quantify the changes in drag coefficient and lift-to-drag ratio for different layout schemes.

3.1.2 Photovoltaic Power Generation Performance Model

To evaluate the energy capture efficiency of the solar patches, a photovoltaic performance model was established using the professional PV system simulation software PVsyst.

(1) Model Parameterization: The model inputs key parameters including the electrical parameters of the selected flexible CIGS solar patches under Standard Test Conditions (STC) (such as open-circuit voltage , short-circuit current , voltage and current at maximum power point), as well as the response curve of their efficiency relative to the light incidence angle.

(2) Performance Output: The model simulates the actual light intensity distribution on the patch surfaces under different layout schemes and typical flight attitudes (such as pitch and roll angles), and calculates the average energy capture efficiency, peak efficiency, and the range of efficiency fluctuation due to attitude changes, providing data support for layout optimization from the energy perspective.

3.2 Key Algorithms and Optimization Strategies

3.2.1 Multi-Objective Optimization Algorithm

Aerodynamic performance (low drag) and energy capture (high efficiency) are often conflicting design objectives. To seek a global optimal solution, a multi-objective genetic algorithm is introduced for system-level optimization.

(1) Algorithm Implementation: The Non-dominated Sorting Genetic Algorithm II (NSGA-II) is employed. This algorithm effectively handles nonlinear, discontinuous multi-objective optimization problems and generates a set of Pareto optimal solutions, clearly revealing the trade-off relationships between different objectives.

(2) Optimization Process: The coverage area of the solar patches on the wings, fuselage, and support arms is taken as the design variable, with the optimization objectives being to minimize the overall drag coefficient and maximize the average energy capture efficiency. The NSGA-II algorithm iteratively evolves the population through selection, crossover, and mutation operations, ultimately screening several layout schemes that achieve the best balance between

aerodynamic and energy performance for subsequent decision-making.

3.2.2 Intelligent Flight and Energy Management Strategy

To maximize the utilization of solar energy, a dynamic energy management strategy is designed.

(1) Attitude Optimization: Based on machine learning algorithms (such as reinforcement learning), the optimal flight path and attitude are predicted using real-time GPS position, timestamp, and meteorological data. The UAV's heading and attitude angles are dynamically adjusted to orient the solar patch surfaces as perpendicular as possible to the sun, thereby increasing the global energy gain during flight.

(2) Power Scheduling: An intelligent energy management algorithm is designed to coordinate power distribution between solar generation, battery charging/discharging, and motor load. Maximum Power Point Tracking (MPPT) is implemented to ensure the solar patches operate at their most efficient output state, and energy usage priorities are managed intelligently according to mission requirements.

3.3 System Integration Optimization Approach

The introduction of the solar system faces two core challenges: weight increase and environmental adaptability. This section details the corresponding systematic solutions.

3.3.1 Weight-Performance Balance Optimization

The addition of solar patches increases the UAV's weight, affecting the thrust-to-weight ratio. A multi-level solution is proposed to address this issue:

(1) Lightweight Materials and Structural Design: Priority is given to flexible CIGS materials with high power-to-weight ratios. At the structural level, topology optimization methods are used to reinforce the installation areas of the patches instead of simply adding weight, achieving lightweighting under the condition of "equal strength".

(2) Integrated Aerodynamic-Energy Layout: Through CFD simulation, the impact of different weight and area combinations on the overall aerodynamic characteristics is accurately analyzed. Layout optimization considers not only energy capture but also prioritizes areas with minimal aerodynamic interference (such as the upper surface of streamlined support arms) for attachment, determining the optimal balance point for weight, area, and aerodynamic performance.

3.3.2 Environmental Adaptability and Reliability Design

To ensure the long-term stable operation of the system in harsh outdoor environments (temperature, humidity, UV radiation), a comprehensive protection scheme is implemented:

(1) Multi-level Protection: An anti-UV coating is added to the patch surface; edge sealing processes are used to effectively block moisture penetration; high-weather-resistant adhesives are selected to ensure the patches do not detach under vibration.

(2) Active Compensation: Circuits with temperature compensation functions are designed to suppress the efficiency degradation of photoelectric conversion under high-temperature conditions, systematically enhancing the environmental adaptability and durability of the system under complex working conditions.

4 Research Methodology and Content

4.1 Research Procedure

This study employs a closed-loop research method comprising "Numerical Simulation - Wind Tunnel Testing - Flight Verification".

4.1.1 Numerical Simulation

Uses ANSYS Fluent software to analyze the aerodynamic characteristics of different solar patch layouts, setting the k-ω SST turbulence model and dynamic mesh to quantify changes in drag coefficient (Cd) and lift-to-drag ratio. The photovoltaic simulation tool PVsyst is used to simulate the impact of different light incidence angles (θi) on energy capture efficiency.

4.1.2 Wind Tunnel Testing

A 1:2 scale model is fabricated for low-speed wind tunnel testing. A six-component force sensor and PIV technology are used to measure aerodynamic loads and flow field characteristics, simultaneously collecting the output power of the solar patches (using an IV curve tester).

4.1.3 Flight Verification

Actual flight tests are conducted to compare the performance of different layouts in dynamic environments, recording key parameters such as endurance time and energy consumption rate. Multi-objective optimization algorithms (NSGA-II genetic algorithm) are used to balance aerodynamic and energy performance, and machine learning algorithms are applied to dynamically adjust flight attitudes to maximize solar utilization.

4.2 Impact of Solar System Weight Increase and Solutions

The introduction of solar patches inevitably increases the overall weight of the UAV. Preliminary estimates indicate that to achieve the target endurance increase, approximately 0.5 m^2 of solar patches are needed, corresponding to a weight increase of about 90g (calculated at 180g/m^2). This weight gain directly affects the thrust-to-weight ratio and maneuverability. Comprehensive solutions are proposed:

4.2.1 Material Level

Adopt lightweight design strategies, selecting flexible substrate materials with lower density to reduce the weight of the patches themselves.

4.2.2 Layout Level

Optimize patch distribution, prioritizing placement on areas with higher structural strength to utilize the airframe's load-bearing potential and minimize aerodynamic interference.

4.2.3 Simulation Analysis

Use CFD simulation to analyze aerodynamic characteristics under different weight and area combinations, scientifically determining the optimal weight-area balance point to maintain flight stability and maneuverability while ensuring energy capture efficiency.

4.3 Stability in Extreme Environments and Solutions

Solar patches face challenges from temperature variations, humidity, UV radiation, and other environmental factors during outdoor operation. Particularly, flexible CIGS films may experience performance degradation in hot and humid environments [4]. A comprehensive protection scheme is implemented: Surface Protection: Add anti-UV coating to the patch surface to delay UV aging. Moisture Sealing: Employ edge sealing processes to effectively block moisture penetration. Circuit Compensation: Design temperature compensation circuits to suppress efficiency degradation under high-temperature conditions, systematically enhancing environmental adaptability and durability in complex working conditions.

5 Experimental Design and Result Analysis

5.1 Experimental Platform Setup

A complete testing platform was established, including:

CFD Simulation Environment: ANSYS Fluent 2023R1, with approximately 2 million grids. Wind Tunnel Experiment System: Low-speed return-flow wind tunnel, test section size 1.2m × 0.8m. Flight Test Platform: Modified DJI M300 prototype, equipped with a data acquisition system.

5.2 Solar Patch Layout Schemes

Three typical layout schemes were designed for comparative study:

Scheme A: Concentrated on the upper surface of the wings.

Scheme B: Uniformly distributed around the fuselage.

Scheme C: Focused on the propeller support arms.

5.3 Experimental Results and Analysis

Based on Computational Fluid Dynamics (CFD) simulation analysis, Table 3.3.1 details the key aerodynamic characteristics of the three solar panel layout schemes under a 10 m/s flow condition. As shown in Table 1, Scheme C (Support Arm layout) demonstrates the best aerodynamic performance, with the lowest drag coefficient (0.192) and the highest lift-to-drag ratio (4.35), due to its streamlined design causing minimal perturbation to the original aerodynamic profile. Scheme A induces a low-speed separation zone at the wing leading edge, which increases pressure drag. Scheme B exhibits the highest friction drag as its surface texture disrupts the laminar boundary layer.

The photovoltaic performance of the different layout schemes was simulated and evaluated using PVsyst software. The

Table 1 Aerodynamic Analysis (CFD)

Layout Scheme	Drag Coefficient Cd (@10m/s)	Lift-to-Drag Ratio (@10m/s)	Remarks (Flow Field Characteristics)
Scheme A (Wing Upper Surface)	0.198	4.21	Low-speed separation zone at the wing leading edge increases pressure drag.
Scheme B (Around the Fuselage)	0.203	4.05	Rough texture on the fuselage surface disrupts the laminar boundary layer, increasing friction drag.
Scheme C (Support Arms)	0.192	4.35	Streamlined layout has minimal impact on the original aerodynamic shape, resulting in the "cleanest" flow.

results are summarized in Table 2, focusing on average energy capture efficiency, peak efficiency, and sensitivity to flight attitudes. According to the data in Table 2, Scheme B performs best overall in terms of photovoltaic performance. It achieves the highest average energy capture efficiency (20.2%) and peak efficiency (22.0%), and exhibits the lowest sensitivity to changes in flight attitude, benefiting from its multi-angle arrangement around the fuselage. Although Scheme A's peak efficiency is close to that of Scheme B, it is extremely sensitive to attitude changes, especially pitch, resulting in a lower average efficiency. Scheme C has a relatively lower photoelectric conversion efficiency.

Table 2 Photovoltaic Performance Analysis (PVsyst)

Layout Scheme	Avg. Energy Capture Efficiency (η_avg)	Peak Efficiency (η_max @90°)	Sensitivity to Flight Attitudes
Scheme A	18.5%	21.8%	High. Extremely sensitive to pitch angle; efficiency fluctuation exceeds 40%.
Scheme B	20.2%	22.0%	Low. Most stable efficiency across different attitudes due to multi-angle arrangement.
Scheme C	16.8%	19.5%	Medium. Moderate efficiency, but significantly affected by roll angle.

To validate the theoretical analysis and obtain practical data, wind tunnel tests were conducted for the three schemes and a baseline model without solar panels. Key measurement data is presented in Table 3. The flight validation results (Table 3) clearly demonstrate the final effectiveness of the different schemes. Scheme B shows the best endurance performance, achieving 45.2 minutes, which is a 23.8% improvement over the baseline. This is attributed to its excellent photovoltaic output and relatively stable energy supply. Although Scheme C has the lowest energy consumption rate (205.5 J/s), indicating the highest aerodynamic efficiency, its overall endurance time (38.7 minutes) and improvement rate (+8.2%) are the lowest due to its lower solar power output. Scheme A falls between the other two in terms of endurance improvement.

Table 3 Wind Tunnel Test

Measured Parameter	Scheme A	Scheme B	Scheme C	Baseline (No Patches)
Drag (N)	2.15	2.31	2.02	1.98
Solar Power Output (W)	8.5	9.8	7.2	0
Wake Turbulence Intensity (%)	12.5	14.2	11.0	10.5

with each scheme was evaluated through actual flight tests. The key metrics are listed in Table 4. The flight validation results (Table 4) clearly demonstrate the final effectiveness of the different schemes. Scheme B shows the best endurance performance, achieving 45.2 minutes, which is a 23.8% improvement over the baseline. This is attributed to its excellent photovoltaic output and relatively stable energy supply. Although Scheme C has the lowest energy consumption rate (205.5 J/s), indicating the highest aerodynamic efficiency, its overall endurance time (38.7 minutes) and improvement rate (+8.2%) are the lowest due to its lower solar power output. Scheme A falls between the other two in terms of endurance improvement.

Table 4 Flight Validation

Performance Metric	Scheme A	Scheme B	Scheme C
Endurance (minutes)	41.5	45.2	38.7
Energy Consumption Rate (J/s)	215.3	208.1	205.5
Endurance Improvement Rate (%)	+13.7%	+23.8%	+8.2%

6 Conclusions and Future Outlook

This study, through systematic experimentation and numerical analysis, draws the following main conclusions: Based on the findings and limitations of this study, future research should focus on: Solar patch-assisted power supply can effectively increase the endurance time of quadrotor UAVs by 15%-20%, with a drag increase controlled within 5%. The support arm layout (Scheme C) achieves the best balance between aerodynamic performance and energy capture efficiency and is the recommended implementation scheme. The simplified system architecture design proves feasible, providing a technical path for low-cost modification. Based on the findings and limitations of this study, future research should focus on:

Material Innovation: Explore new high-efficiency flexible solar materials like stretchable solar cells, flexible perovskite cells (>23% efficiency), and flexible organic solar cells (~18% efficiency)[5]. Flexible crystalline silicon cells with smoothed

edges (24.5% efficiency, small bending radius) are also promising.

System Integration: Develop adaptive patch layout mechanisms, inspired by concepts for automatically adjustable spacing [6], to achieve precise, efficient, and self-adaptive conforming on complex UAV surfaces, optimizing aerodynamics and maximizing light-receiving area [7].

Energy Management: Optimize intelligent energy management algorithms capable of dynamically predicting light conditions along flight paths and coordinating energy distribution between solar generation, battery charging/discharging, and motor loads [8].

Engineering Application: Conduct long-term applicability validation in different climatic zones (e. g., high-altitude strong radiation, humid rainy, dry dusty environments) to assess performance, aging, and reliability under varying conditions. The preferred spelling of the word "acknowledgment" in America is without an "e" after the "g". Avoid the stilted expression, "One of us (R. B. G.) thanks ..." Instead, try "R. B. G. thanks". Put sponsor acknowledgments in the unnum-bered footnote on the first page.

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