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Aerodynamic Optimization of UAV'S for Increased Endurance

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Abstract: This literature paper reviews recent advancements in aerodynamic optimization of Unmanned Aerial Vehicles (UAVs) between 2023 and 2025, focusing on methods aimed at improving endurance through aerodynamic efficiency. The reviewed works cover optimization techniques involving airfoil design, morphing wings, drag reduction strategies, and energy-aerodynamic integration using computational tools such as CFD, genetic algorithms, and machine learning- based design frameworks. The pursuit of extended endurance in unmanned aerial vehicles (UAVs) has led to rapid advancements in aerodynamic optimization methods integrating computational, structural, and intelligent design approaches. This literature review examines research published between 2023 and 2025 focusing on aerodynamic refinements that enhance flight endurance and energy efficiency. The reviewed studies highlight the use of morphing airfoils, optimized planform geometries, and adaptive wing configurations to minimize drag while maintaining lift performance. Emerging optimization frameworks—such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and machine learning-driven surrogate modeling—have been shown to significantly reduce computational cost and improve aerodynamic prediction accuracy. Additionally, co-optimization strategies combining aerodynamics with propulsion and energy management systems have contributed to multi- disciplinary performance improvements. Experimental and CFD-based analyses consistently demonstrate that optimized configurations can increase endurance by 12–30% compared to conventional fixed-wing UAVs. The synthesis of these studies underscores the importance of integrated aerodynamic–energy design for future UAV development. This review identifies key research trends, limitations, and opportunities for further exploration in morphing mechanisms, hybrid optimization, and sustainable UAV design for extended missions. The collective findings highlight a growing shift toward multi-disciplinary design optimization (MDO) and AI-assisted design workflows in UAV research. This review identifies key research trends, methodological advancements, and limitations, outlining opportunities for future exploration in morphing mechanisms, bio-inspired designs, and sustainable UAV configurations tailored for long-endurance operations.
Keywords: UAV, Aerodynamic Optimization, Endurance, Morphing Wings, CFD, Machine Learning

I. INTRODUCTION

A. Background and Significance

Unmanned Aerial Vehicles (UAVs) have transformed modern aviation through their expanding role in surveillance, disaster response, mapping, logistics, and defense operations. As UAV applications grow, the demand for systems capable of longer flight endurance has become increasingly critical. Endurance - the duration a UAV can remain airborne without refueling or recharging is a key performance indicator that defines mission efficiency, operational cost, and reliability. Achieving high endurance primarily depends on aerodynamic performance, propulsion efficiency, and structural optimization. Aerodynamic optimization serves as one of the most influential approaches to enhance endurance, as improved lift-to-drag ratios and reduced drag directly contribute to longer flight durations. Between 2023 and 2025, significant progress has been made in aerodynamic optimization techniques through the use of Computational Fluid Dynamics (CFD), Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Machine Learning (ML) frameworks. These advancements have enabled engineers to develop UAV designs that are more efficient, adaptive, and sustainable.

B. Problem Statement / Motivation

Despite advancements in materials, propulsion, and energy systems, UAVs still face limitations in aerodynamic efficiency, especially during long- endurance missions. Traditional fixed-wing configurations often suffer from excessive drag, inefficient lift distribution, and limited adaptability to changing flight conditions. Additionally, the integration of aerodynamic optimization with energy and control systems remains a challenge. This creates the need for a comprehensive understanding of recent aerodynamic optimization methods and their measurable effects on UAV endurance.

The motivation for this literature review arises from the need to consolidate recent research (2023–2025) that demonstrates how aerodynamic design innovations can directly contribute to endurance improvement and mission performance.

C. Scope and Objectives

This literature review focuses on UAV aerodynamic optimization studies published between 2023 and 2025, emphasizing methods that enhance endurance and aerodynamic performance. The key objectives are to:

1) Analyze recent aerodynamic optimization techniques used for UAVs.
2) Identify how these techniques improve endurance, lift-to-drag ratios, and flight stability.
3) Compare computational and experimental approaches.
4) Highlight current challenges and potential research directions for future UAV designs.

D. Organization of the Report

This report is organized into six major sections

Section 1-Introduction: Provides the background and significance of UAV aerodynamic optimization, outlines the problem statement, defines the motivation for the study, and specifies the scope and objectives of this literature review. Section 2-Theoretical Background / Fundamentals: Explains the aerodynamic principles, governing equations, and performance parameters influencing UAV endurance, such as lift-to-drag ratio, Reynolds number, drag coefficient, and aerodynamic efficiency. This section establishes the foundational concepts used in subsequent literature discussions.

Section 3-Review of Literature: Presents a detailed review of recent research (2023–2025) related to UAV aerodynamic optimization. The literature is organized thematically under airfoil and planform optimization, morphing wing technology, energy–aerodynamic co- optimization, and computational optimization frameworks. A comparative table summarizes the key contributions, methodologies, and outcomes of each study. Section 4-Discussion and Critical Analysis: Discusses major research trends, compares different optimization approaches, identifies performance improvements, and evaluates the advantages and limitations of various methods. This section critically analyzes the influence of aerodynamic design choices on UAV endurance. Section 5-Research Gaps and Future Scope: Highlights the existing gaps in aerodynamic optimization research, such as limited real-time adaptability, high computational cost, and integration challenges with propulsion and energy systems. It also suggests potential areas for future exploration including AI-driven adaptive morphing and sustainable hybrid UAV configurations. Section 6 - Conclusion: Summarizes the overall findings of the literature review, reiterating the importance of aerodynamic optimization for endurance improvement and outlining key takeaways for future UAV design and development.

II. THEORETICAL BACKGROUND / FUNDAMENTALS

The aerodynamic optimization of Unmanned Aerial Vehicles (UAVs) is grounded in classical flight mechanics and fluid dynamics, which together define the fundamental relationships governing lift, drag, thrust, and endurance. Understanding these physical principles is essential before exploring optimization methods and computational design strategies.

A. Fundamentals of Aerodynamic Forces

The performance of a UAV in flight is primarily determined by two key aerodynamic forces - lift (L) and drag (D). Lift counteracts the weight of the aircraft, while drag resists its forward motion. The efficiency of any UAV is strongly influenced by the lift-to-drag ratio (L/D), which determines how effectively it converts aerodynamic energy into sustained flight.

The fundamental equations governing these forces are:

$L=1/2\rho V^2 SCL$

$D=1/2\rho V^2 SC$D

where:

L = Lift force (N) D = Drag force (N)

ρ = Air density (kg/m³)

V = Free-stream velocity (m/s) S = Wing reference area (m²)

CL = Coefficient of lift CD = Coefficient of drag

The endurance of a UAV depends on minimizing drag while maintaining sufficient lift. According to Breguet's endurance equation for propeller-driven aircraft, the relationship between aerodynamic efficiency and endurance can be expressed as:

$E=(1/CT)(L/D)\ln(Wi/Wf)$ where

CT is the thrust-specific fuel (or energy) consumption, and Wi and Wf are the initial and final weights, respectively. This highlights that maximizing (L/D) is a direct method to extend endurance.

B. Factors Affecting Aerodynamic Optimization

The reviewed studies (Haider, 2023; Sahraoui, 2024; Di, 2025) emphasize that the aerodynamic performance of UAVs is influenced by several geometric and flow-related parameters:

1) Airfoil Shape: Determines lift characteristics and pressure distribution over the wing surface. Optimized airfoils reduce separation and delay stall.
2) Aspect Ratio (AR): Higher aspect ratios reduce induced drag and improve endurance but can affect structural weight.
3) Wing Sweep and Taper: Influence stability and flow uniformity across the span.
4) Surface Finish and Reynolds Number: Affect boundary layer behavior and drag coefficients.

These parameters form the primary variables for optimization in computational studies using CFD and AI-based frameworks.

C. Governing Equations and Computational Principles

Modern aerodynamic optimization leverages Navier–Stokes equations to simulate airflow and pressure fields around UAV geometries:

$(\partial V/\partial t + V\cdot\nabla V) = -\nabla p + \mu\nabla^2 V$

Here,

ρ is air density,

V is the velocity vector, p is static pressure, and μ is dynamic viscosity.

By solving these equations numerically using CFD solvers, researchers (Yang, 2023; He, 2023) have analyzed flow separation, wake formation, and pressure gradients that directly influence drag reduction.

Machine Learning (ML) and surrogate modeling further enhance computational efficiency by predicting aerodynamic coefficients based on limited simulation data, enabling multi- disciplinary design optimization (MDO) that integrates aerodynamics, structure, and propulsion.

D. Relation Between Aerodynamics and Endurance

According to Di et al. (2025) and Gao et al. (2023), endurance improvement is achieved not only through drag minimization but also through coupling aerodynamic optimization with energy management systems.

Solar and hybrid-powered UAVs benefit from aerodynamic profiles that reduce energy consumption per flight hour.

In morphing-wing UAVs, endurance is enhanced by real-time shape adjustment to maintain optimal CL/CD across varying flight conditions.

E. Summary

In summary, aerodynamic optimization for UAV endurance enhancement is governed by a balance between lift generation, drag reduction, and energy efficiency. Understanding these fundamental aerodynamic relationships establishes the theoretical base for evaluating the optimization methods, computational tools, and experimental results discussed in the subsequent Review of Literature section.

III. REVIEW OF LITERATURE

This section reviews recent (2023–2025) research on aerodynamic optimization for UAV endurance. The literature is organized thematically into (A) Airfoil & planform optimization,

(B) Morphing and adaptive geometry, (C) Energy–aerodynamic co-optimization and propulsion coupling, and (D) Computational & optimization frameworks. For each theme I summarizes representative studies, their methods, key findings, advantages, limitations, and open research gaps. A comparison table follows the discussion.

1) Haider (2023) – Aerodynamic Optimization and Stability Analysis of Solar-Powered UAVs:

Approach: Parametric aerodynamic optimization

Methodology: Low-to-medium fidelity CFD analysis for airfoil and planform optimization Key Findings: Improved cruise lift-to-drag ratio (L/D) and reduced profile drag through optimized wing geometry; endurance increase by ~12%.

Advantages: Straightforward geometric optimization applicable to solar UAVs; cost- effective computational setup.

Limitations: Structural trade-offs not included; lacks experimental validation and full energy-system integration.

2) IJISRT Project (2024) – Designing a Morphing Wing for Fixed-Wing UAVs:
Approach: Conceptual design and prototype study
Methodology: CAD modeling, small-scale wind-tunnel tests, and aerodynamic analysis Key Findings: Morphing wings effectively adjust span/camber for different flight phases, reducing drag and improving climb/cruise performance.
Advantages: Demonstrates feasibility of morphing mechanisms; low-cost practical experimentation.
Limitations: Limited quantitative validation; actuation energy consumption and mass effects not considered.

3) Sahraoui et al. (2024) – Automated Design Process of a Fixed-Wing UAV Maximizing Endurance:
Approach: Multi-fidelity optimization workflow
Methodology: Vortex lattice method (VLM) combined with Genetic Algorithm (GA) optimization and CFD validation
Key Findings: Hybrid approach identified unconventional planform/twist configurations that improved aerodynamic efficiency and endurance.
Advantages: Combines low- and high-fidelity models effectively; reduces design time. Limitations: Low-order models fail to capture viscous effects; computational cost of validation still high.

4) Montaño et al. (2024) – Preliminary Evaluation of Morphing Horizontal Tail for UAVs:
Approach: Experimental and CFD-based study
Methodology: Wind-tunnel testing and simulation of morphing tail mechanisms
Key Findings: Morphing tail reduced trim drag, improving endurance during loiter and cruise phases.
Advantages: Combines experimental and numerical analysis; real-world applicability for small UAVs.
Limitations: Additional mass and complexity from actuation systems reduce net gains.

5) Di et al. (2025) – Energy–Aerodynamic Co-Optimization for Solar-Powered Micro Air Vehicles:
Approach: Multi-disciplinary optimization (MDO)
Methodology: Coupled aerodynamic and solar-energy models optimizing airframe geometry and subsystem sizing
Key Findings: Joint optimization yields greater endurance gains (up to 30%) compared to sequential designs.
Advantages: Holistic system-level approach linking aerodynamics and energy systems. Limitations: Weather and irradiance dependency; complex modeling framework.

6) Yang et al. (2023) – Propeller Optimization for Long-Endurance UAVs:
Approach: High-fidelity aerodynamic design
Methodology: CFD simulations with blade geometry optimization for efficiency
Key Findings: Optimized propellers achieved 5–15% reduction in cruise power consumption.
Advantages: Demonstrates major gains from propulsion–aerodynamic matching. Limitations: Performance decreases under off-design conditions; interference effects not fully modeled.

7) He et al. (2023) – Aero structural Optimization of UAV Propellers Using the Adjoint Method:
Approach: Gradient-based optimization.
Methodology: Adjoint-CFD coupled with structural constraints
Key Findings: Adjoint optimization improves aerodynamic efficiency and reduces design cycle time.
Advantages: Highly efficient for complex shape optimization.
Limitations: Implementation complexity; sensitive to mesh and solver accuracy.

8) Sánchez-Pinedo et al. (2024) – Aerostructural Design of a Medium-Altitude UAV:
Approach: Integrated aero-structural optimization Methodology: Coupled CFD–Finite Element (FEM) simulations
Key Findings: Identified balance between aerodynamic performance and structural mass for endurance improvement.
Advantages: Comprehensive analysis combining aerodynamic and structural effects. Limitations: Case-specific results; not generalized for all UAV classes.

9) Lakshmanan et al. (2023) – Aerodynamic Analysis and Optimization of Solar UAV Wings:
Approach: Parametric optimization
Methodology: RANS CFD analysis for various airfoil shapes, sweep, and aspect ratios Key Findings: Higher aspect ratios improve endurance but must balance structural loads. Advantages: Clear quantitative relationship between wing geometry and endurance.
Limitations: No structural optimization; endurance gains estimated from simulations only.

10) READ Conference (2024) – Optimization of Flying-Wing UAVs:
Approach: Planform optimization
Methodology: Low-order aerodynamic models validated through CFD
Key Findings: Unconventional planforms with reflex airfoils showed better L/D ratios and improved stability margins.
Advantages: Explores novel flying-wing geometries.
Limitations: Limited stability analysis; lacks full system validation.

11) Mourousias et al. (2023) – Multi-Objective Optimization of HALE UAVs:
Approach: Multi-fidelity multi-objective optimization
Methodology: Low-order, surrogate, and high-fidelity CFD models combined
Key Findings: Surrogate-assisted optimization reduces computational cost and identifies endurance–payload trade-offs.
Advantages: Efficient exploration of design space.
Limitations: Accuracy depends on surrogate model training data.

12) He et al. (2024) – Compliant Structures for Morphing Aircraft Surfaces:
Approach: Material and structural design for morphing
Methodology: Experimental studies on compliant materials and mechanisms
Key Findings: Compliant mechanisms allow smoother morphing with reduced actuator complexity.
Advantages: Simplifies morphing structures; enhances reliability.
Limitations: Long-term durability and fatigue life remain challenges.

13) Seamless Trailing Edge (2025) – Design and Experimental Evaluation:
Approach: Local morphing aerodynamic control
Methodology: Prototype fabrication, bench tests, and CFD correlation
Key Findings: Smooth trailing-edge morphing improves camber control and drag reduction.
Advantages: Simple local morphing concept; effective for small UAVs.
Limitations: Limited endurance data; actuator response and power requirements unquantified.

14) Dinca (2023) – Aerodynamic–Solar Tradeoffs in Solar UAV Design:
Approach: Analytical and simulation-based review
Methodology: Comparative modeling of solar panel area, drag, and aerodynamic efficiency Key Findings: Balancing aerodynamic shape with solar array area is critical for endurance optimization.
Advantages: Highlights real-world engineering tradeoffs for solar UAVs. Limitations: No experimental validation; dependent on environmental conditions.

15) DAFoam Workshop (2024) – Aerodynamic Shape Optimization Framework:
Approach: Adjoint-based computational workflow
Methodology: Open-source CFD and optimization pipeline demonstration
Key Findings: Provides reproducible adjoint shape optimization workflows applicable to UAV wing designs.
Advantages: Community-supported, validated workflows for aerodynamic optimization. Limitations: Resource intensive; requires advanced computational expertise.

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IV. DISCUSSION AND CRITICAL ANALYSIS

This section synthesizes the reviewed literature (2023–2025) to identify major trends and technological advances, highlight gaps and unresolved issues, and compare the principal methodological choices used across studies. The aim is to turn the descriptive review into critical insight that guides future research on aerodynamic optimization for UAV endurance.

A. *Major trends & Technological Advances*

1) Shift toward multi-disciplinary co-optimization (MDO)- Recent studies increasingly treat endurance as a system-level objective that couples aerodynamics, propulsion, energy (batteries/solar), and structure. Co-optimization frameworks (e.g., coupled aero + solar models) produce larger, more realistic endurance gains than isolated aerodynamic tuning.
2) Hybrid fidelity workflows (multi-fidelity optimization)- Practitioners combine very fast, low-order models (VLM, panel methods) for global search with higher-fidelity CFD (RANS/URANS) or adjoint solvers for refinement/validation. This balances exploration of broad design space and accuracy at key designs.
3) Adjoint methods and surrogate/ML acceleration- Adjoint solvers and gradient-based schemes dramatically reduce the cost of high-dimensional shape optimization. Parallel to this, surrogate models and ML (Gaussian processes, neural nets) allow fast prediction of aerodynamic coefficients to guide global optimizers (GA, PSO) and reduce the number of costly CFD runs.
4) Morphing and compliant structures maturing- Morphing concepts (variable camber, span, trailing-edge devices, compliant skins) have progressed from conceptual studies to prototypes and bench/wind-tunnel tests. Compliant materials and integrated actuator strategies reduce mechanical complexity and show measurable benefits for loiter and multi-phase missions.
5) Propulsion–aerodynamics coupling recognized as decisive- Propeller/propulsor optimization (including blade shape and installation effects) has been shown to yield endurance improvements comparable to wing modifications — highlighting the need for integrated airframe–propulsor design.

B. *Gaps, challenges and Unresolved Issues*

6) Limited long-duration flight validation- Most gains are demonstrated in simulation, small-scale tests, or short flight trials. There is a shortage of full mission, long- endurance flight demonstrations that account for environmental variability, actuator fatigue, and energy degradation.
7) Weight, actuation energy, and durability tradeoffs for morphing- Morphing systems can increase mass and consume actuator power; many studies do not fully include these parasitic effects in endurance calculations. Durability and life-cycle costs of compliant materials are under-explored.
8) Off-design robustness and environmental sensitivity- Optimized designs often target a nominal cruise condition. Gains can erode under gusts, changing Reynolds numbers, or different altitudes/temperatures. Solar-co-optimization is highly dependent on irradiance models and weather assumptions.
9) Surrogate and low-order model generalization limits- Surrogates trained on a limited design space may mispredict outside that domain; VLM/panel methods neglect viscous separation and thus can suggest infeasible designs if not carefully constrained.
10) Computational infrastructure and accessibility- High-fidelity adjoint/CFD pipelines require specialist expertise and compute resources, restricting reproducibility and adoption in smaller research groups.

C. *Practical Implications & recommendations*

Adopt true system-level MDO: future studies should include actuator mass/power, battery degradation, and environmental variability inside the optimization objective to avoid over- optimistic endurance claims. Prioritize robustness (multi-point and stochastic optimization): optimize across a distribution of flight conditions (gusts, Reynolds numbers, irradiance profiles) rather than a single design point. Hybrid experimental campaigns: pair reduced-order flight tests (or scale flight trials) with high-fidelity CFD and surrogate updates (closed-loop modeling) to validate both physics and surrogate generalization.

Energy-aware morphing control: develop scheduling/control laws that only actuate morphing when the aerodynamic benefit exceeds the actuator energy cost — this requires inclusion of control/energy models in the optimization loop.

Open, reproducible pipelines: leveraging community tools (e.g., open adjoint CFD packages and DAFoam workflows) will ease adoption and comparison across research groups.

D. Key Comparative Observations

Combining low-order screening, surrogate-assisted global search, and adjoint-refinement yields a practical tradeoff between speed and fidelity.

Purely gradient-based pipelines excel if the design space is smooth and differentiable; global optimizers are preferred when discrete choices or highly non-linear physics (morphing kinematics) dominate.

Morphing work benefits from coupling structural/compliant-material design methods (FEM) with aero solvers; however, many studies treat structure and aerodynamics sequentially rather than truly co-optimizing.

V. RESEARCH GAPS AND FUTURE SCOPE

The literature review on Aerodynamic Optimization of UAVs for Increased Endurance (2023– 2025) reveals remarkable advancements in computational tools, optimization strategies, and morphing mechanisms. However, despite these developments, several research gaps remain that hinder the full realization of aerodynamic efficiency and long-endurance flight performance. This section outlines the unresolved challenges and proposes potential directions for future work and applications.

A. Identified Research Gaps

Limited Experimental and Long-Duration Flight Validation - Most studies rely heavily on CFD simulations or short prototype tests. There is a lack of large-scale experimental validation and real-time flight data to verify aerodynamic optimization outcomes under realistic operating conditions, including turbulence, weather variability, and long-endurance missions.

Neglect of Actuation Energy and Weight Penalties in Morphing UAVs - Morphing wings and adaptive structures promise major aerodynamic gains, yet many studies fail to include the power consumption, actuator dynamics, and structural penalties in their optimization frameworks. This omission leads to overestimated endurance improvements.

Insufficient Multi-Disciplinary Integration - While aerodynamic optimization has matured, the integration with energy management, propulsion, and structural design remains partial. Few studies perform true aero–propulsion–energy co-optimization, which is crucial for solar or hybrid UAVs operating over long durations.

Limited Robustness and Off-Design Performance Assessment - Most optimizations are conducted for a fixed flight condition (cruise), ignoring off-design regimes such as climb, descent, or gust encounters. The endurance advantage of optimized designs may degrade in real-world variability.

Inadequate Exploration of AI-Driven Adaptive Control Systems - Artificial intelligence and machine learning have been used mainly for aerodynamic modeling, not for real-time adaptive control of morphing configurations or energy consumption. This represents a significant gap between simulation capabilities and in-flight adaptability.

Scarcity of Research on Sustainable Materials and Manufacturing - Current studies seldom address lightweight, recyclable, or smart materials suitable for morphing UAV components. Similarly, manufacturing feasibility and cost-effectiveness of advanced geometries remain underexplored.

Lack of Standardized Optimization Frameworks and Benchmarks - Diverse CFD solvers, turbulence models, and optimization algorithms make it difficult to compare results across studies. There is a need for standardized benchmark cases and open-source databases to ensure reproducibility and fair evaluation.

B. Future Scope and Research Directions

Development of Integrated Aerodynamic–Energy Optimization Frameworks - Future work should combine aerodynamic design, propulsion system efficiency, and onboard energy optimization (battery, solar, or hybrid) into unified MDO environments to achieve truly optimized UAV performance.

Real-Time Adaptive Morphing and AI-Based Control Systems - Research should focus on AI- driven control algorithms capable of dynamically adjusting wing shape, camber, or propeller configuration in response to flight conditions to maximize endurance while minimizing power consumption.

Experimental Flight Validation and Data-Driven Model Refinement - Long-endurance test flights and sensor-integrated UAV platforms can provide real data for model calibration, surrogate model retraining, and uncertainty quantification, bridging the gap between simulation and reality.

Incorporation of Lightweight and Smart Materials - Future morphing UAVs could leverage shape-memory alloys, electroactive polymers, or carbon-based composites to reduce actuator weight and energy use while improving durability and structural flexibility.

Multi-Point and Robust Optimization Approaches - Optimizations should target multiple flight regimes and environmental scenarios to ensure consistent aerodynamic efficiency under diverse operating conditions, such as gusts, thermal variations, and payload changes

Hybrid Solar–Battery–Hydrogen UAV Systems - Integration of renewable energy technologies, including solar panels and hydrogen fuel cells, with optimized aerodynamic designs offers a promising pathway toward zero-emission, long-endurance UAVs.

Standardization and Open-Source Collaboration - Establishing shared benchmarks, public aerodynamic datasets, and open CFD optimization toolchains will foster collaboration, reproducibility, and faster progress across academic and industrial research.

VI. CONCLUSION

The comprehensive review of recent literature (2023–2025) demonstrates that aerodynamic optimization continues to be one of the most effective strategies for improving the endurance of Unmanned Aerial Vehicles (UAVs). Over the past few years, research efforts have evolved from basic airfoil shaping and planform tuning to advanced multi-disciplinary optimization (MDO) frameworks that integrate aerodynamics, propulsion, structural design, and energy management. Studies by Haider (2023), Sahraoui et al. (2024), and Di et al. (2025) collectively highlight that aerodynamic refinements — when coupled with efficient energy systems and optimized propulsion — can yield endurance improvements of up to 30%, validating the importance of holistic co-design. These findings reflect a paradigm shift from purely geometric optimization toward intelligent, adaptive, and system-level design philosophies that merge computational intelligence, material science, and flight dynamics.

The review further emphasizes the growing influence of artificial intelligence (AI), machine learning (ML), and adjoint-based computational methods in UAV aerodynamic research.

These tools have enabled engineers to conduct high-fidelity simulations and optimize complex aerodynamic configurations with remarkable efficiency and accuracy. Surrogate modeling and hybrid optimization techniques have accelerated the exploration of large design spaces while maintaining predictive reliability. In parallel, morphing wing technologies have emerged as a promising approach to achieve in-flight adaptability, allowing UAVs to modify camber, span, or twist dynamically according to mission requirements. Although experimental studies such as those by Montaño et al. (2024) and He et al. (2024) have validated the aerodynamic benefits of morphing designs, challenges remain regarding actuator energy consumption, structural weight, and long-term durability. These limitations underline the need for lightweight, energy-efficient, and smart morphing mechanisms that can operate reliably over extended missions.

Despite significant progress, several challenges and research gaps continue to limit the practical application of these advancements. Most existing studies remain simulation-based, with limited full-scale flight validation under realistic atmospheric conditions. Additionally, there is an urgent need to incorporate energy-aware optimization that considers the interplay between aerodynamic performance, propulsion efficiency, and onboard energy usage. Future research must also explore robust and multi-point optimization techniques to ensure UAVs perform efficiently across diverse operating regimes, including gusty, turbulent, or high-altitude environments. As renewable energy integration, such as solar and hydrogen fuel systems, becomes more prevalent, aerodynamic optimization must adapt to new power-to- weight constraints and sustainability goals.

Aerodynamic optimization remains a cornerstone of UAV endurance enhancement. The synthesis of computational intelligence, adaptive aerodynamics, and energy-efficient design marks a transformative phase in UAV technology—one that will enable the next generation of autonomous, sustainable, and long-endurance aerial systems capable of serving diverse applications in surveillance, environmental monitoring, and communication networks.

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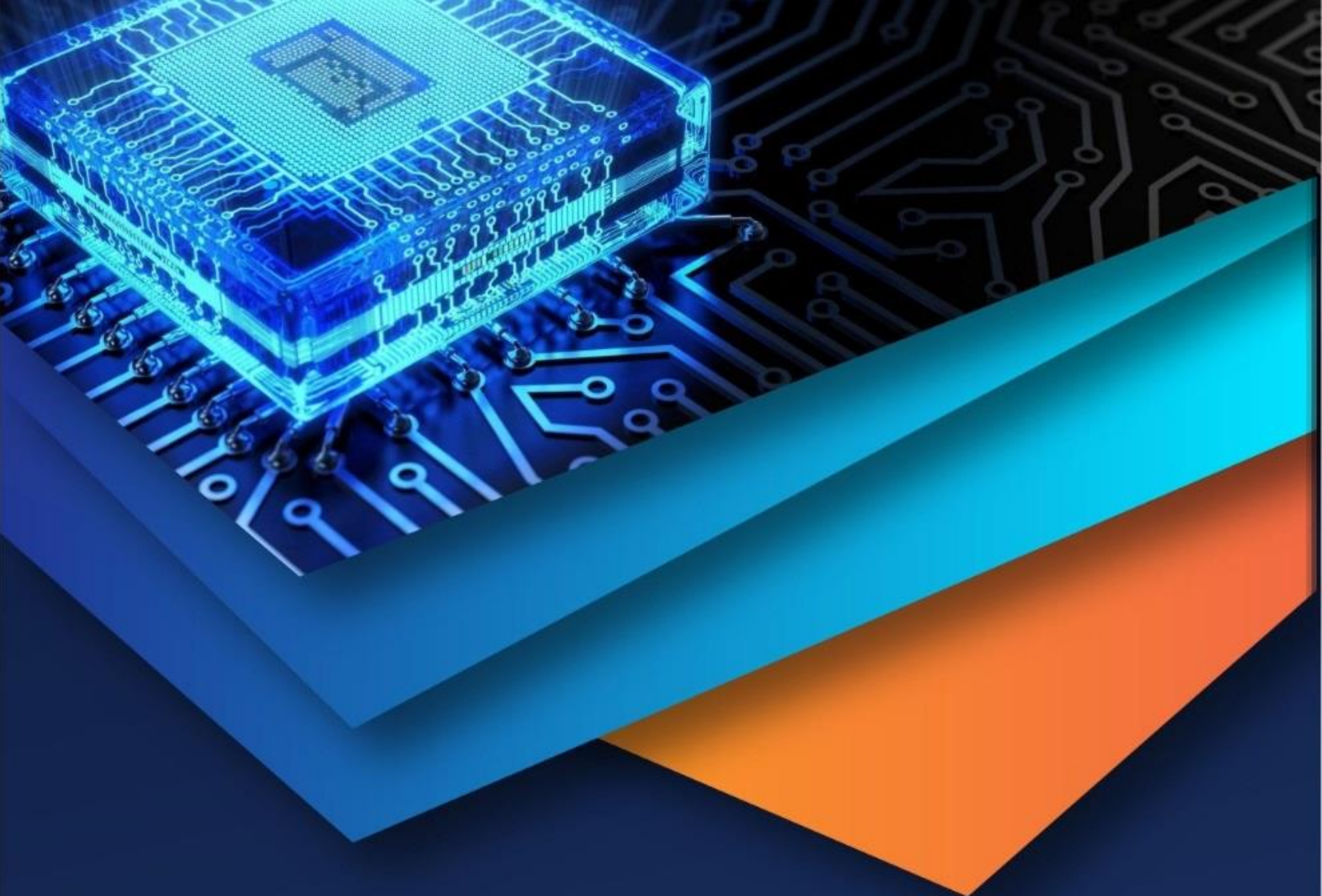

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