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3	
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An integrated framework for multidisciplinary design optimization of unmanned aerial vehicles

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Abstract:

The growing demand for high-performance Unmanned Aerial Vehicles (UAVs) in civil, commercial, and defense applications has increased the need for advanced engineering methodologies capable of addressing complex and often conflicting design requirements. Conventional sequential design approaches generally optimize individual subsystems independently, frequently overlooking the interactions between aerodynamics, structures, propulsion, flight dynamics, control systems, and mission performance. These limitations may result in increased development costs, longer design cycles, and reduced overall system efficiency. This paper proposes an integrated framework for Multidisciplinary Design Optimization (MDO) of UAVs that combines mission analysis, conceptual aircraft design, aerodynamic optimization, structural analysis, propulsion system integration, flight performance evaluation, and system-level optimization within a unified engineering process. The proposed framework facilitates continuous information exchange among engineering disciplines, enabling designers to identify globally optimal solutions while satisfying operational, structural, and aerodynamic constraints. The framework incorporates modern computational tools, including Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), numerical optimization algorithms, and simulation-based performance evaluation techniques. Furthermore, the study discusses the potential integration of artificial intelligence and machine learning algorithms to accelerate design optimization and improve engineering decision-making during the early stages of UAV development. The proposed integrated framework provides a systematic methodology for improving aircraft efficiency, reducing structural weight, minimizing energy consumption, shortening product development time, and enhancing mission effectiveness. The presented approach establishes a foundation for future research on intelligent multidisciplinary optimization of next-generation unmanned aerial systems.

Keywords:

Unmanned Aerial Vehicle (UAV), Multidisciplinary Design Optimization, Integrated Design Framework, Aircraft Design, Aerodynamic Optimization, Structural Optimization, Flight Performance, Systems Engineering, Artificial Intelligence

1. Introduction

Unmanned Aerial Vehicles (UAVs) have become one of the most rapidly evolving technologies in modern aerospace engineering. Owing to continuous advances in lightweight materials, electric propulsion, autonomous navigation, artificial intelligence, and communication systems, UAVs are now capable of performing increasingly complex missions in both civilian and military sectors. Their applications include precision agriculture, environmental monitoring, infrastructure inspection, disaster management, border surveillance, logistics, aerial mapping, scientific research, and defense operations. As these applications continue to expand, UAV designers are required to develop aircraft that simultaneously satisfy demanding requirements for endurance, payload capacity, flight efficiency, reliability, maneuverability, and operational safety. The design of a UAV is inherently a multidisciplinary engineering problem involving strong interactions among aerodynamics, structural mechanics, propulsion systems, flight dynamics, control engineering, avionics, and mission analysis. Decisions made in one discipline inevitably influence the performance of other subsystems. For example, reducing structural weight may improve flight endurance but could

compromise structural strength. Similarly, increasing wing span may improve aerodynamic efficiency while introducing additional structural and manufacturing challenges. These multidisciplinary interactions make UAV design significantly more complex than optimizing individual components independently. Conventional aircraft design methodologies generally follow a sequential design philosophy in which each engineering discipline is analyzed separately. Although this approach has been successfully applied in many aerospace projects, it often fails to account for the complex coupling effects between different engineering domains. Consequently, repeated design iterations become necessary, increasing development time, computational cost, and engineering uncertainty. These limitations have encouraged the aerospace community to adopt integrated engineering approaches capable of simultaneously considering multiple design disciplines. Multidisciplinary Design Optimization (MDO) has emerged as one of the most effective methodologies for addressing these challenges. MDO integrates aerodynamic analysis, structural optimization, propulsion system design, flight dynamics, control analysis, and mission performance evaluation within a unified optimization framework. Rather than optimizing each subsystem independently, MDO

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searches for a globally optimal solution that satisfies multiple design objectives and engineering constraints simultaneously. This integrated strategy improves aircraft performance, reduces structural weight, enhances energy efficiency, and shortens product development cycles. Recent developments in Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), surrogate modeling, high-performance computing, artificial intelligence, and machine learning have significantly expanded the capabilities of multidisciplinary optimization. These technologies enable engineers to evaluate thousands of design alternatives within a relatively short period while improving prediction accuracy and reducing prototype development costs. Digital engineering environments further facilitate collaboration among multidisciplinary design teams, enabling efficient data exchange throughout the aircraft development process. Despite these advances, many existing UAV design methodologies remain fragmented, with limited integration between conceptual design, aerodynamic optimization, structural analysis, propulsion selection, and mission performance evaluation. As a result, there is still a need for a comprehensive framework that combines these engineering disciplines into a systematic and unified design methodology. Therefore, this paper proposes an Integrated Multidisciplinary Design Optimization Framework for UAV development. The proposed framework combines mission analysis, conceptual aircraft design, weight estimation, constraint analysis, aerodynamic optimization, structural evaluation, propulsion system integration, flight performance assessment, and system-level optimization into a continuous engineering workflow. The objective is to provide a comprehensive methodology that improves design efficiency, enhances aircraft performance, and supports the development of next-generation unmanned aerial vehicles capable of meeting increasingly complex operational requirements [1,2,3,4,5,6,7].

Literature Review

Multidisciplinary Design Optimization has been extensively investigated in aerospace engineering as an effective approach for improving aircraft performance through the simultaneous optimization of multiple interacting disciplines. Early MDO studies primarily focused on integrating aerodynamic and structural analyses, while more recent research has expanded to include propulsion, flight dynamics, control systems, mission planning, and lifecycle considerations. Raymer emphasized the importance of conceptual design in determining the overall performance and cost of an aircraft, highlighting that early design decisions have the greatest influence on the final system. Roskam presented a structured aircraft design methodology that remains a foundation for preliminary aircraft design. Gudmundsson further developed conceptual design procedures for general aviation aircraft, many of which have been adapted for fixed-wing UAV development. In the field of UAVs, Austin described comprehensive design principles covering mission definition, sizing, propulsion selection, and system integration. Beard and McLain focused on small UAV flight dynamics and control, while Valavanis and Vachtsevanos presented multidisciplinary perspectives on UAV technologies and applications. The concept of MDO was formalized by Martins and Lambe, who surveyed optimization architectures and demonstrated the advantages of integrating multiple engineering disciplines into a unified optimization framework. Their work has influenced numerous studies

involving aerodynamic shape optimization, structural weight reduction, and mission-based aircraft optimization. More recently, advances in Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), surrogate modeling, artificial intelligence, and machine learning have enabled more efficient MDO implementations. These technologies reduce computational cost while allowing engineers to evaluate larger design spaces and more complex engineering constraints. Despite these developments, many published studies address only selected aspects of UAV design, and comprehensive integration of conceptual design, aerodynamics, structures, propulsion, and mission performance remains an active area of research.

2. Research methodology

2.1 Evolution of UAV Design Methodologies

The design methodology of Unmanned Aerial Vehicles (UAVs) has evolved significantly over the last four decades due to advances in aerospace engineering, computational methods, and optimization techniques. Early UAV development primarily relied on conventional aircraft design procedures, where aerodynamic design, structural analysis, propulsion selection, and flight performance evaluation were performed sequentially. Although this approach simplified the engineering process, it often failed to capture the complex interactions among different engineering disciplines, resulting in multiple design iterations and reduced overall efficiency. The introduction of Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) in the 1990s and early 2000s substantially improved the accuracy of aerodynamic and structural analyses. These computational tools enabled engineers to evaluate aircraft performance before prototype manufacturing, thereby reducing development costs and technical risks. However, most design activities were still performed independently, limiting opportunities for achieving globally optimized solutions. A major milestone in aerospace engineering was the emergence of Multidisciplinary Design Optimization (MDO), which integrates aerodynamics, structural mechanics, propulsion systems, flight dynamics, and optimization algorithms into a unified computational framework. Unlike traditional sequential design approaches, MDO simultaneously evaluates interactions among engineering disciplines, enabling designers to identify solutions that improve overall aircraft performance while satisfying multiple operational and structural constraints. Recent developments in artificial intelligence, machine learning, surrogate modeling, and digital engineering have further enhanced the capability of multidisciplinary optimization. These technologies enable rapid evaluation of large design spaces, reduce computational cost, and improve engineering decision-making throughout the UAV development process. Consequently, modern UAV design is increasingly based on integrated digital workflows that combine simulation, optimization, and intelligent analysis [1,2,10,11,13,14].



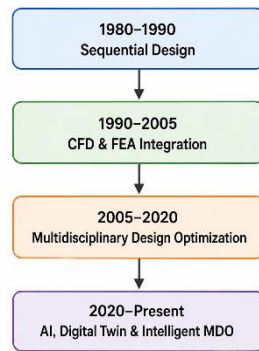


Fig. 1. Historical evolution of UAV design methodologies from conventional sequential design approaches to intelligent multidisciplinary optimization frameworks

2.2 Existing Multidisciplinary Design Optimization Architectures

Several Multidisciplinary Design Optimization architectures have been developed to improve coordination among engineering disciplines during aircraft design. The most commonly applied architectures include Multidisciplinary Feasible (MDF), Individual Discipline Feasible (IDF), Collaborative Optimization (CO), Bi-Level Integrated System Synthesis (BLISS), and Analytical Target Cascading (ATC). Among these methods, MDF offers high solution accuracy because all disciplinary analyses are simultaneously satisfied during each optimization iteration. However, this approach requires substantial computational resources. IDF improves computational efficiency by introducing compatibility constraints between engineering disciplines, while Collaborative Optimization distributes optimization tasks among subsystem teams, making it particularly suitable for large-scale aerospace projects. BLISS and ATC are designed to improve optimization efficiency for hierarchical engineering systems by decomposing complex design problems into manageable subsystems. Recent research trends focus on combining these optimization architectures with surrogate models, artificial intelligence algorithms, and high-performance computing platforms to accelerate optimization while maintaining solution accuracy [7,8,9,17,18].

Table 1

Comparison of Common MDO Architectures

Architecture	Advantages	Limitations
MDF	High solution accuracy	High computational cost
IDF	Faster convergence	Additional compatibility constraints
CO	Supports multidisciplinary teams	Coordination complexity
BLISS	Efficient subsystem optimization	Difficult implementation
ATC	Suitable for hierarchical systems	Sensitive to target allocation

2.3 Current Research Trends

Recent advances in aerospace engineering have significantly influenced the development of multidisciplinary design optimization for Unmanned Aerial Vehicles (UAVs). Modern research increasingly integrates Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), Artificial Intelligence (AI), Machine Learning (ML), Digital Twin technology, and cloud-based high-performance computing into the aircraft design process. These technologies enable engineers to evaluate thousands of design alternatives rapidly while improving prediction accuracy and reducing development costs. Artificial intelligence has emerged as a promising tool for accelerating optimization by replacing computationally expensive simulations with surrogate models capable of predicting aerodynamic and structural performance. Machine learning algorithms are also being employed to identify relationships among design variables, optimize mission planning, and support autonomous engineering decision-making. Meanwhile, Digital Twin technology allows engineers to create virtual representations of UAV systems, enabling continuous performance monitoring, predictive maintenance, and real-time optimization throughout the aircraft lifecycle. Another important research direction is the integration of sustainability considerations into UAV design. Recent studies focus on reducing energy consumption, minimizing structural weight through advanced composite materials, improving battery technologies, and developing environmentally friendly propulsion systems. These trends demonstrate that multidisciplinary optimization is evolving beyond traditional aircraft performance objectives toward intelligent, sustainable, and autonomous engineering systems [16,17,18,20].

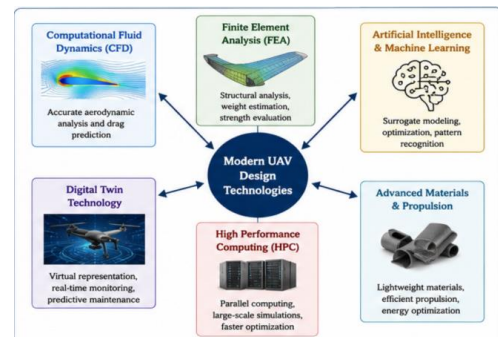


Fig. 2. Integration of modern computational technologies within multidisciplinary UAV design

2.4 Research Gap

Although considerable progress has been achieved in multidisciplinary optimization, several limitations remain in the existing literature. Most published studies investigate only specific engineering disciplines, such as aerodynamic optimization, structural weight reduction, propulsion system design, or flight performance analysis, without fully integrating these disciplines into a unified design framework. Consequently, the interactions among engineering subsystems are often overlooked, resulting in suboptimal design solutions and increased development effort. Furthermore, many existing methodologies emphasize optimization during the detailed design stage, whereas limited attention has been given to integrating multidisciplinary optimization into the conceptual design



phase, where engineering decisions have the greatest influence on aircraft performance and lifecycle cost. In addition, only a relatively small number of studies combine mission analysis, aircraft sizing, configuration selection, aerodynamic optimization, structural analysis, propulsion integration, and flight performance evaluation within a single systematic methodology. Therefore, there remains a need for an integrated engineering framework capable of supporting the complete UAV development process while maintaining effective communication among all engineering disciplines. Addressing this gap can improve design efficiency, reduce development time, enhance aircraft performance, and provide a more systematic foundation for future UAV research and industrial applications [4,6,7,20].

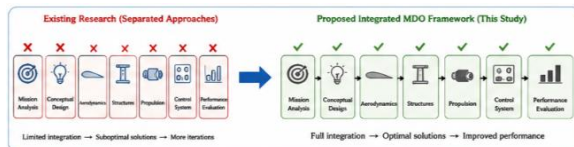


Fig. 3. Existing studies mainly optimize individual engineering disciplines, whereas an integrated multidisciplinary framework combines all major design stages into a unified process

3. Proposed Integrated Multidisciplinary Design Optimization Framework

The design of modern Unmanned Aerial Vehicles (UAVs) requires the integration of multiple engineering disciplines to achieve high performance, operational efficiency, and reliability. Traditional aircraft development generally follows a sequential design methodology in which conceptual design, aerodynamic analysis, structural evaluation, propulsion selection, and flight performance assessment are performed independently. Such an approach often increases development time, requires repeated design iterations, and may lead to suboptimal engineering solutions. To overcome these limitations, this study proposes an Integrated Multidisciplinary Design Optimization (IMDO) Framework that combines all major engineering disciplines within a unified design environment. The proposed framework establishes continuous interaction between mission requirements, conceptual aircraft design, aerodynamic optimization, structural analysis, propulsion system integration, flight dynamics, control system evaluation, and overall performance assessment. Instead of treating each discipline separately, the framework enables simultaneous information exchange throughout the design process, allowing engineers to evaluate the influence of design decisions on the complete aircraft system. The proposed framework begins with the definition of mission requirements, including payload capacity, operational range, endurance, cruise speed, service ceiling, and environmental conditions. These requirements provide the basis for conceptual aircraft design, where the general configuration, wing geometry, fuselage dimensions, empennage arrangement, and propulsion concept are initially determined. Following conceptual design, an initial weight estimation and constraint analysis are performed to establish feasible design boundaries. Parameters such as wing loading, thrust-to-weight ratio, stall speed, take-off distance, climb performance, and cruise efficiency are evaluated to ensure that the selected configuration satisfies mission objectives. The resulting design then proceeds to multidisciplinary optimization, where aerodynamic,

structural, propulsion, and flight dynamics analyses are performed simultaneously. Aerodynamic optimization employs Computational Fluid Dynamics (CFD) simulations to improve lift generation while minimizing drag. Structural optimization utilizes Finite Element Analysis (FEA) to reduce structural weight without compromising safety or stiffness. Propulsion optimization focuses on selecting efficient power systems and propeller configurations capable of satisfying mission endurance requirements. Flight dynamics analysis evaluates aircraft stability, controllability, maneuverability, and overall flight performance. The optimization process is iterative, allowing information generated by one engineering discipline to influence the others. For example, modifications in wing geometry directly affect aerodynamic characteristics, structural loads, propulsion requirements, and aircraft stability. Consequently, continuous multidisciplinary interaction significantly improves overall design quality compared with conventional sequential design approaches. Finally, all engineering analyses are integrated into a system-level optimization process where multiple objective functions and engineering constraints are simultaneously considered. This integrated methodology enables designers to identify globally optimal UAV configurations characterized by improved aerodynamic efficiency, reduced structural weight, enhanced endurance, lower energy consumption, and greater operational reliability. The proposed Integrated Multidisciplinary Design Optimization Framework provides a systematic engineering methodology suitable for conceptual, preliminary, and detailed UAV design. It also establishes a flexible platform that can be expanded through the integration of artificial intelligence, digital twin technology, and autonomous optimization algorithms in future aerospace applications [1,3,4,7,9,10,11,12,14,15,19].

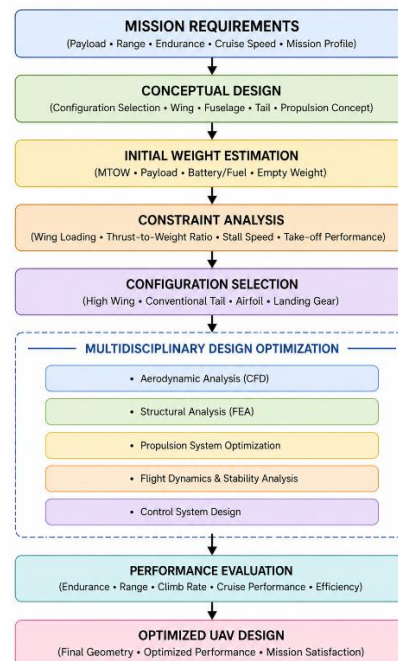


Fig. 4. Proposed Integrated Multidisciplinary Design Optimization (IMDO) framework illustrating the sequential integration of mission analysis, conceptual design, aircraft sizing, constraint analysis, multidisciplinary optimization, and performance evaluation leading to an optimized UAV configuration



3. Results and Discussion

The literature reviewed in this study demonstrates that multidisciplinary design optimization has become one of the most effective methodologies for improving the overall performance of unmanned aerial vehicles. Unlike traditional sequential design approaches, MDO enables the simultaneous consideration of multiple engineering disciplines, resulting in more balanced and efficient aircraft configurations. The proposed Integrated Multidisciplinary Design Optimization (IMDO) framework provides a systematic workflow that connects mission analysis, conceptual design, weight estimation, constraint analysis, aerodynamic optimization, structural evaluation, propulsion system integration, flight dynamics, control system analysis, and overall performance assessment within a unified engineering environment. This continuous interaction among engineering disciplines reduces repeated design iterations and improves communication throughout the aircraft development process. One of the principal advantages of the proposed framework is its ability to support system-level optimization rather than isolated subsystem optimization. Changes introduced in aerodynamic design immediately influence structural loading, propulsion requirements, aircraft stability, and mission performance. Likewise, structural modifications affect aircraft mass distribution, energy consumption, and flight characteristics. The proposed framework continuously exchanges design information among these engineering disciplines, allowing engineers to identify globally optimal design solutions while satisfying operational constraints. The integration of Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) further improves engineering accuracy during the preliminary design stage. CFD enables detailed evaluation of lift generation, drag characteristics, and airflow distribution, whereas FEA provides accurate prediction of structural stresses, deformation, and safety margins. When these analyses are performed within an integrated optimization environment, the resulting aircraft configuration achieves improved aerodynamic efficiency together with reduced structural weight. Artificial Intelligence and Machine Learning technologies provide additional opportunities for accelerating multidisciplinary optimization. Surrogate models can significantly reduce computational cost by approximating complex aerodynamic and structural analyses, while intelligent optimization algorithms enable rapid exploration of large design spaces. Furthermore, Digital Twin technology supports continuous monitoring of aircraft performance throughout its operational lifecycle, providing valuable information for predictive maintenance and future design improvements [7,8,9,16,17,18,19,20].

Table 2
Comparison of Conventional Design and Proposed IMDO Framework

Design Aspect	Conventional Design	Proposed IMDO Framework
Design Process	Sequential	Integrated
Engineering Interaction	Limited	Continuous

Design Iterations	High	Reduced
Computational Efficiency	Moderate	High
System Optimization	Partial	Comprehensive
Design Flexibility	Limited	High
Development Time	Longer	Shorter
Overall Performance	Moderate	Improved

The findings indicate that integrated multidisciplinary optimization has considerable potential to improve UAV development by reducing engineering complexity while enhancing aircraft performance, operational reliability, and design efficiency. As computational technologies continue to evolve, future UAV development is expected to rely increasingly on intelligent optimization frameworks capable of supporting autonomous engineering decision-making across the complete aircraft lifecycle.

4. Conclusion

This paper reviewed the application of Multidisciplinary Design Optimization (MDO) in the design of Unmanned Aerial Vehicles and proposed an Integrated Multidisciplinary Design Optimization (IMDO) framework. The study highlights the importance of integrating aerodynamics, structures, propulsion, flight dynamics, and performance evaluation into a unified design process. The proposed framework improves engineering collaboration, reduces design iterations, and supports the development of efficient and reliable UAV systems. Future research should focus on integrating Artificial Intelligence, Digital Twin technology, and advanced optimization algorithms to further enhance UAV design efficiency and decision-making. The presented framework provides a practical reference for researchers and engineers involved in next-generation UAV development and multidisciplinary aircraft design [1,4,7,20].

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T. Alimov, J. Shukurov, Y. Ergashev, N. Abdujabarov <i>An integrated framework for multidisciplinary design optimization of unmanned aerial vehicles.....</i>	61
E. Khujamkulov <i>Digital national microprocessor-based semi-automatic interlocking system for improving the throughput capacity of Uzbekistan Railways.....</i>	67
O. Mukhitdinov, S. Khudaykulov, D. Kaniev <i>Energy equations of a channel suspension-carrying flow with full account for the work of interphase interaction forces.....</i>	71
Mu Zhendi <i>Network diagnosis and governance-coupled optimization in seaport–dry port multimodal transport corridors under the maritime Silk Road.....</i>	78
N. Sotivoldieva <i>Scientific and theoretical foundations of resource management in ensuring product quality and safety at light industry (sewing and knitting) enterprises.....</i>	87