

Review

Integration Challenges of Turbine-Powered UAVs: Thermal, Structural, Acoustic, and Operational Perspectives

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Abstract

Unmanned aerial vehicles (UAVs) increasingly demand higher flight speeds, longer endurance, improved payload capacity, and greater operational flexibility across a wide range of applications. While battery-electric propulsion systems dominate small UAV platforms, their limited energy density significantly constrains range and mission duration. Consequently, turbine-based propulsion systems, including micro turbojets, turboprops, turboshafts, and hybrid-electric gas turbine architectures, are attracting growing attention as alternatives for advanced UAV operations. Unlike previous reviews that primarily focus on propulsion technologies or individual subsystem performance, this review provides an integrated assessment of the multidisciplinary challenges associated with turbine-powered UAVs, encompassing thermal, structural, aerodynamic, acoustic, operational, and stealth considerations within a unified framework. The presented synthesis identifies current knowledge gaps and emerging research directions, providing a comprehensive reference for the design and development of next-generation turbine-powered unmanned aerial platforms.

Keywords: UAV propulsion; micro gas turbine; micro turbojet engine; hybrid-electric propulsion; unmanned aerial vehicles

1. Introduction

The global landscape of aviation and aerial warfare has been fundamentally reconfigured over the past few decades by the exponential proliferation and rapid technological diversification of Unmanned Aerial Vehicles (UAVs) [1]. Initially constrained to low-speed, high-altitude missions and duties within permissive environments, uncrewed platforms have rapidly transitioned into critical components of modern tactical and strategic operations [2]. In contemporary security environments, the reliance on advanced autonomous aerial architectures has expanded significantly, with global armed forces and civil entities actively leveraging these platforms to ensure real-time command, tactical dominance, and enhanced operational efficiency [3]. This shifting paradigm has triggered massive growth in the UAV market, driving continuous capital investment and industrial diversification [1,4]. As these platforms are increasingly deployed to project force, counter asymmetric threats, or perform complex dual-use public good missions, a profound engineering demand has emerged for high-performance systems capable of operating within highly contested, anti-access/area-denial (A2/AD) zones [4,5].

Concurrently, the increasing diversity of UAV missions has driven the development of specialized subclasses of uncrewed aerial systems, including high-speed, long-endurance,



Academic Editor: Eugene Wong

Received: 5 June 2026

Revised: 13 July 2026

Accepted: 22 July 2026

Published: 23 July 2026

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and multi-role platforms optimized for different operational requirements [6,7]. Concomitantly, the rise in high-performance drones optimized for speed, maneuverability, and agility presents a severe challenge to existing counter-UAS interception framework [8]. To maintain operational viability against peer and near-peer adversaries, modern unmanned airframes must sustain extreme flight envelopes, executing aggressive rapid-ascent maneuvers and high-speed cruise flight over extended distances [9]. Furthermore, these fast-flying platforms demand advanced vision-based, terrain-referenced, and inertial navigation architectures capable of operating reliably in global navigation satellite system (GNSS)-denied or heavily contested electromagnetic environments [10].

As the operational boundaries of unmanned systems push into higher velocity and longer-range regimes, the inherent limitations of traditional propulsion methodologies have become critical technical bottlenecks [11]. Historically, small-to-medium drones and commercial multirotors have relied extensively on lithium-ion or lithium-polymer battery-electric systems [11,12]. However, battery-powered platforms are severely penalized by low specific energy and energy density, which rigidly limits flight endurance, payload capacity, and performance under adverse weather conditions [12,13]. Conversely, internal combustion engines (ICE), while offering superior energy density through hydrocarbon fuels, introduce heavy maintenance overheads, high mechanical vibrations, elevated acoustic signatures, and high rates of in-flight shutdown (IFSD) when scaled down to smaller airframes [12,14]. To break through these performance ceilings, the aerospace engineering community has focused on turbine-powered UAV architectures, utilizing micro gas turbines (MGTs) and ultra-micro gas turbines (UMGTs) as primary powerplants or integrated hybrid configurations [14,15].

The growing interest in turbine-powered UAVs is largely attributed to the high power-to-weight and thrust-to-weight ratios achievable with turbomachinery across multiple scales [11,16]. Miniaturized gas turbine engines utilize hydrocarbon fuels that possess an energy density significantly higher than modern electrical energy storage devices, allowing small-scale aircraft to achieve high payload fractions and extended range profiles [14,17]. Compared to reciprocating piston engines, micro gas turbines offer smooth, low-vibration rotational operation due to the complete absence of reciprocating components, thereby minimizing high-frequency structural fatigue on sensitive electronic and optical payloads [12,14]. Furthermore, steady-flow turbine devices feature fewer moving parts, simpler lubrication requirements, and a high level of operational reliability over extended periods [11,16]. Another major asset of turbine technology is fuel flexibility; MGTs are naturally capable of burning a wide spectrum of liquid aviation fuels, straight-run or hydrotreated kerosenes, synthetic biofuels, or alternative energy blends with minimal alterations to the core combustor geometry [17,18]. Although these characteristics provide important operational advantages, they are accompanied by challenges associated with higher specific fuel consumption at small scales, elevated thermal loads, and increased integration complexity. Consequently, the suitability of turbine propulsion depends on the mission profile and the overall airframe-propulsion integration rather than on propulsion performance alone.

To fully capitalize on these benefits while mitigating the high specific fuel consumption characteristic of small-scale Brayton cycles, advanced hybrid-electric and range-extended propulsion topologies are being actively explored [13,19,20]. Recent developments indicate that hybrid propulsion architectures are becoming one of the principal research directions in sustainable aviation, owing to their potential to improve fuel efficiency, operational flexibility, and emissions performance across different aircraft classes [20].

In these architectures, a highly efficient micro gas turbine or internal combustion range-extender operates at a constant, optimized thermodynamic state to drive an electrical generator, which continuously charges a buffer battery pack or supplies power directly

to distributed multirotor or compound-wing flight systems [19,21]. This configuration combines the high hovering agility of multirotors with the superior energy density of liquid hydrocarbon fuels, profoundly increasing the operational range, flight endurance, and payload capabilities of the aircraft [21,22]. However, optimizing the power management, thermal output, and transient throttle response of such dual-power systems presents a highly coupled, non-linear control challenge that requires precise dynamic modeling and regularized regression optimization techniques to maintain system voltage stability across disparate flight modes [22,23].

The successful implementation of a high-performance turbine powerplant within an uncrewed airframe underscores that multidisciplinary system integration matters above all else in modern aerospace design [15,24]. The design of turbine-powered UAVs generally requires aerodynamics, materials, and flight controls in isolation; instead, the entire platform must be treated as a highly coupled, multi-physical system [15,25]. For example, the downscaling of gas turbine components to the micro and ultra-micro levels induces severe thermal and viscous losses [11,16]. The high heat flux from the high-temperature turbine stage conducts directly down the short monolithic rotor shaft toward the compressor stage, causing diabatic flow conditions that heat the incoming air, degrade compressor efficiency, and induce rotordynamic instabilities [15,17]. Addressing these phenomena demands the utilization of cutting-edge additive manufacturing (3D printing) technologies to fabricate complex, internally cooled superalloy or ceramic turbomachinery components capable of surviving rotational speeds that frequently exceed 400,000 RPM [15]. Additive manufacturing has become an important enabling technology for micro gas turbines by allowing the fabrication of complex geometries that are difficult or impossible to produce using conventional manufacturing methods. Typical applications include integrated combustors, lightweight turbine wheels, lattice cooling structures, optimized heat exchangers, and fuel injectors with conformal internal passages. These capabilities contribute to component weight reduction, improved thermal management, and greater design flexibility while reducing the number of assembled parts. Nevertheless, challenges remain regarding material qualification, surface finish, dimensional accuracy, and the long-term durability of components operating under high thermal and mechanical loads [26].

Furthermore, the physical integration of the propulsion system introduces complex aero-propulsive interactions between the engine exhaust, distributed propellers, and the lifting surfaces of the airframe [25,27]. The relative position of the propulsion units ahead of or integrated into the wing deeply modifies the local chordwise pressure distribution, changing the lift-to-drag characteristics and altering stall behavior at high angles of attack [27]. To resolve these highly coupled aerodynamic, thermal, and structural design conflicts, modern aerospace engineers employ advanced Multidisciplinary Design Optimization (MDO) frameworks [15] which are detailed in Table 1. These digital paradigms integrate high-fidelity computational fluid dynamics (CFD) and finite element analysis (FEA) to evaluate sweeping and spanning morphing geometries, hybrid fuel-delivery networks, and advanced composite airframe structures, ensuring the vehicle maintains optimal aerodynamic efficiency while satisfying strict packaging and weight constraints [15,25].

Recent studies further emphasize that the design of compact turbine systems increasingly relies on coupled multi-physics analyses that account for the interactions between aerodynamic loading, thermal effects, and structural deformation, particularly under demanding operating conditions. In parallel, advances in electrified propulsion architectures and high-temperature materials continue to support the development of more efficient and thermally resilient propulsion systems for future aerospace applications [28].

Table 1. Representative multidisciplinary design variables for turbine-powered UAV optimization.

Discipline	Design Variable	Typical Objective	Representative Values from Literature	Primary Trade-Off
Aerodynamics	Lift-to-drag ratio	Maximize	10–20	Speed vs. endurance
Aerodynamics	Compressor pressure recovery	Maximize	>0.95	Compact inlet vs. efficiency
Thermal	Exhaust gas temperature	Control	500–900 °C	Efficiency vs. thermal signature
Thermal	Surface temperature	Minimize	Material dependent	Cooling mass
Structures	Structural mass	Minimize	Mission dependent	Strength vs. weight
Structures	Natural frequency	Avoid resonance	Above engine excitation frequencies	Stiffness vs. mass
Propulsion	Specific fuel consumption	Minimize	Literature values	Endurance vs. thrust
Fuel	Fuel fraction	Optimize	20–50% MTOW	Payload vs. endurance
Stealth	Radar cross-section	Minimize	Mission dependent	Internal volume vs. observability
Stealth	IR signature	Minimize	Exhaust temperature reduction	Cooling penalty
Acoustics	Noise emission	Minimize	Mission dependent	Nozzle losses
Operations	Endurance	Maximize	Mission dependent	Payload vs. fuel

The importance of multi-physical system integration is further amplified when designing turbine-powered platforms to satisfy modern stealth requirements [15,29]. In high-threat, contested missions, the survivability of an unmanned tactical asset is heavily dependent on low observability, which requires the comprehensive minimization of the platform's radar, infrared, acoustic, and visual signatures [29,30]. However, the geometric and structural modifications required to achieve low observability frequently impose severe performance penalties on the propulsion and aerodynamic efficiency of the aircraft [15]. To suppress the radar cross-section (RCS), modern UCAVs typically employ tailless flying-wing planforms, such as the generic SACCON configuration, which utilize carefully aligned edges and highly blended airframe geometries to scatter monostatic radar waves away from hostile receivers [15,29]. These configurations rely on rapid, non-linear fly-by-wire flight control laws to maintain stability during high-agility manoeuvres and high angle-of-attack flight regimes [29].

From a propulsive perspective, a primary source of radar reflection is the exposed face of the engine's rotating compressor blades [15]. To reduce the direct line-of-sight to the compressor face, the turbine engine is typically integrated deep within the fuselage and supplied through a highly curved serpentine or S-shaped inlet duct [15]. While an S-duct successfully conceals the turbomachinery from incoming radar waves, it induces significant aerodynamic total pressure losses and flow distortion at the compressor face, severely complicating engine stability and increasing the risk of catastrophic compressor stall [15]. Concomitantly, the hot exhaust gases, exposed tailpipe structures, and aerodynamically heated skin panels generate a high infrared (IR) signature, making the drone an easy target for modern infrared-tracking and heat-seeking anti-aircraft systems [30,31]. Suppressing this thermal emission demands the integration of specialized passive cooling technologies, such as high-aspect-ratio asymmetric or flat nozzles that rapidly mix the hot core exhaust

with cold ambient bypass air, alongside the use of advanced radar-absorbing and low-emissivity composite coatings [15,29].

Finally, low-observability mandates strict control over the vehicle's acoustic footprint, as high-frequency noise emissions can compromise low-altitude tactical operations [17,32]. Micro gas turbines emit unique acoustic signatures characterized by high-frequency compressor whine and intense jet mixing noise, which propagate through the lower atmospheric boundary layer [17,32]. Mitigating these acoustic signatures requires a deep understanding of RPM fluctuation correction methods, sound attenuation linings, and exhaust nozzle acoustics to prevent detection by ground-based acoustic sensor arrays [33]. Therefore, optimizing a turbine UAV is a delicate balancing act where thermal, structural, acoustic, and operational demands are constantly in tension. Given the intricate web of multi-physical couplings, structural constraints, and strict operational signatures, there is a clear imperative within the aerospace engineering literature to outline a unified pathway forward.

Several recent review articles have examined specific aspects of UAV propulsion, including hybrid-electric propulsion systems, micro gas turbine technologies, and sustainable aviation concepts. However, these studies primarily focus on propulsion architectures, energy efficiency, or individual subsystem technologies, while providing limited discussion of the multidisciplinary integration challenges associated with turbine-powered UAVs. In particular, the coupled effects of thermal management, inlet and exhaust integration, structural loading, vibration, fuel storage, acoustic signatures, and operational requirements are generally addressed independently rather than within a unified system-level framework. This review addresses this gap by organizing the existing literature according to the principal integration challenges encountered during the design of turbine-powered UAVs, thereby providing a comprehensive multidisciplinary perspective and identifying future research priorities for next-generation unmanned aerial platforms.

This review paper provides a state-of-the-art evaluation of the critical integration challenges associated with turbine-powered UAVs, systematically organizing these technical barriers from thermal, structural, acoustic, and operational perspectives.

Although several reviews have examined UAV propulsion technologies, gas turbine development, or hybrid-electric propulsion independently, a comprehensive assessment of the multidisciplinary integration challenges associated with turbine-powered UAVs remains limited. Existing reviews typically focus on propulsion performance, engine design, or specific subsystems without systematically addressing the interactions between propulsion, thermal management, structural integration, inlet and exhaust design, fuel storage, vibration, acoustic signatures, and operational requirements. This review addresses this gap by providing a unified system-level perspective on turbine-powered UAV integration while identifying current research challenges and future development directions.

2. Operational Requirements of Turbine-Powered UAVs

Turbine-powered unmanned aerial vehicles (UAVs) have become increasingly important in modern aerospace and defense applications due to their high power-to-weight ratio, operational flexibility, and ability to support demanding mission profiles. Compared to battery-electric or piston-engine systems, turbine propulsion enables higher cruise speeds, improved altitude capability, increased payload capacity, and extended operational range, making these systems particularly suitable for complex and strategic missions [12,34]. As UAV missions continue to expand in complexity, turbine and hybrid-turbine propulsion architectures are increasingly adopted in applications requiring high endurance, rapid response capability, vertical take-off and landing (VTOL), autonomous swarm coordination, and expendable operations.

The operational requirements of turbine-powered UAVs are fundamentally mission-driven. Different UAV categories prioritize distinct combinations of endurance, speed, maneuverability, survivability, payload integration, autonomy, and production cost. Consequently, propulsion system selection is closely linked to mission objectives and aerodynamic configuration. Long-endurance UAVs prioritize fuel efficiency and persistent surveillance capability, whereas high-speed UAVs emphasize thrust availability and rapid ingress–egress performance. VTOL platforms require sustained power generation during hover, while loitering munitions focus on expendability, low cost, and high-speed terminal attack capability. Swarm UAV systems further introduce requirements related to distributed coordination, scalability, and autonomous mission execution [35,36].

Table 2 summarizes the primary operational requirements associated with the major categories of turbine-powered UAVs discussed in this chapter.

Table 2. Operational requirements of major turbine-powered UAV classes.

UAV Class	Primary Mission	Key Operational Requirement	Preferred Propulsion	Typical Speed Regime	Endurance Requirement	Main Design Trade-Off
Long-endurance UAV	ISR, patrol, surveillance	Persistent flight capability	Turboprop/hybrid-electric	Low–medium subsonic	Very high	Speed vs. fuel efficiency
High-speed UAV	Reconnaissance	Rapid ingress–egress	Turbojet/turbofan	High subsonic/transonic	Medium	Endurance vs. survivability
VTOL UAV	Urban operations, logistics	Hover capability	Turboshaft/hybrid-electric	Low–medium	Medium	Hover efficiency vs. payload
Loitering munition	Precision aim	Low-cost expendability	Micro turbojet	Medium–high	Low–medium	Cost vs. operational capability
Swarm UAV	Distributed missions	Coordination scalability	Small turbine/hybrid	Variable	Mission dependent	Autonomy vs. communication complexity

Recent advances in micro gas turbines, hybrid-electric architectures, distributed propulsion systems, and autonomous flight control have significantly expanded the operational envelope of turbine-powered UAVs. Improvements in lightweight materials, additive manufacturing, digital engine control, and AI-assisted mission management have enabled increasingly compact and efficient propulsion systems suitable for both reusable and attritable UAV platforms. At the same time, modern conflicts and surveillance requirements have accelerated the transition toward distributed and mass-deployable unmanned systems, where operational effectiveness increasingly depends on flexibility, scalability, and cost-efficiency rather than platform survivability alone [37].

2.1. Long-Endurance UAVs

Long-endurance unmanned aerial vehicles (UAVs) are designed to sustain extended flight durations in missions such as ISR, maritime patrol, environmental monitoring, and border surveillance. These platforms are characterized by high aerodynamic efficiency, optimized fuel utilization, and stable long-duration flight capability. In such systems, endurance becomes the primary operational requirement, strongly influencing aerodynamic configuration, propulsion architecture, structural weight distribution, and onboard energy management strategies [38].

Operationally, long-endurance UAVs are expected to maintain persistent coverage over large geographical regions while carrying advanced sensor payloads such as electro-optical (EO), infrared (IR) and synthetic aperture radar (SAR) systems. Consequently, propulsion

systems must provide reliable steady-state operation with low specific fuel consumption over prolonged cruise and loiter conditions. Turboprop engines are commonly preferred for medium- and high-altitude endurance missions because they provide high propulsive efficiency, good fuel economy, and adequate payload capability while maintaining reliable performance at moderate cruise altitudes [39,40].

Representative systems such as the RQ-4 Global Hawk [41] demonstrate the importance of aerodynamic efficiency and fuel economy in persistent ISR operations. High aspect-ratio wings, lightweight structural configurations, and optimized cruise conditions enable endurance aircraft to achieve flight durations exceeding 24 h while maintaining stable payload operation and large-area surveillance capability [42–44].

The propulsion architectures employed in endurance-oriented UAVs present different operational advantages and limitations, as summarized in Table 3.

Table 3. Comparison of propulsion systems used in endurance-oriented UAVs.

Propulsion Type	Advantages	Limitations	Typical UAV Classes	Operational Suitability
Piston engine	High fuel efficiency	Lower altitude capability	MALE UAVs	Long-duration ISR
Turboprop	Good efficiency and altitude capability	Lower maximum speed	HALE/ISR UAVs	Persistent surveillance
Turbojet	High speed and compact integration	High fuel consumption	Fast reconnaissance UAVs	Rapid-response ISR
Hybrid-electric turbine	Flexible energy management	Increased integration complexity	Advanced endurance UAVs	Adaptive mission profiles

Although piston-engine propulsion remains dominant in certain endurance-oriented UAV classes due to superior fuel efficiency at low-to-medium power settings, gas turbine systems provide important advantages in operational altitude, payload capability, reduced vibration, and compact integration [45]. Turbine-powered endurance UAVs are therefore particularly suitable for missions requiring operation in high-altitude environments, integration of large sensor packages, or extended range beyond conventional piston-engine capabilities.

Despite continuous improvements in propulsion efficiency, endurance-oriented UAV design remains governed by major system-level trade-offs involving fuel mass, aerodynamic efficiency, payload capability, and cruise speed. These interactions are summarized in Table 4.

Table 4. Major design trade-offs in turbine-powered UAV systems.

Requirement Increase	Positive Effect	Negative Effect
Higher cruise speed	Faster response and wider coverage	Increased fuel consumption
Larger payload	Improved mission capability	Reduced endurance
Higher endurance	Longer ISR persistence	Increased fuel mass
Smaller airframe	Reduced detectability	Reduced payload volume
Distributed propulsion	Increased redundancy	Higher control complexity
VTOL capability	Runway independence	Lower aerodynamic efficiency

2.2. High-Speed UAVs

High-speed fixed-wing UAVs constitute a major class of turbine-powered unmanned systems designed for reconnaissance, target simulation, and rapid-response missions. Un-

like endurance-oriented UAVs, these platforms prioritize high cruise speed, rapid deployment, and survivability in contested operational environments. Consequently, propulsion systems are selected primarily based on thrust availability, acceleration capability, and aerodynamic integration rather than maximum fuel economy.

Operational requirements for high-speed UAVs include rapid ingress–egress capability, short mission response time, high-altitude penetration, and the ability to cover large operational areas within limited time intervals [12,30,46]. These requirements favor turbojet and low-bypass turbofan propulsion systems capable of sustaining high subsonic or transonic cruise conditions while maintaining compact aerodynamic integration and acceptable payload capacity.

Beyond single-platform missions, recent research has increasingly focused on multi-UAV and swarm-based operations for fixed-wing configurations. Cluster guidance for fixed-wing UAVs is a significant research topic due to the need for precise coordination, robust path planning, and reliable perception under dense formation constraints [47]. In the context of competitive and experimental scenarios, key challenges include visual blind spots during close gate approaches and inter-vehicle occlusion in tightly packed formations.

To address these issues, recent studies have proposed vision-based guidance strategies combining gate-frame absolute pose estimation with multi-source information fusion. Experimental validation using a seven-aircraft fixed-wing formation demonstrated successful performance, achieving the highest score in the Fast-Crossing Race of the second Unmanned Aerial Contest, confirming the effectiveness of dense formation guidance strategies [48].

In addition to formation flight, multi-fixed-wing UAV systems are widely studied for cooperative coverage missions in dynamic environments [49]. These scenarios integrate vehicle constraints, terrain characteristics, and evolving mission requirements into a unified planning framework. Dynamic cooperative path-planning algorithms have been developed to ensure complete area coverage while optimizing UAV allocation, entry/exit trajectories, and inter-region transitions. Three-dimensional trajectory generation is typically achieved using altitude descent methods, enabling consistent integration between planar coverage paths and altitude constraints. Simulation and mixed-reality experiments have demonstrated that such approaches significantly reduce computational cost and total path length, improving efficiency in complex multi-UAV mission planning scenarios [50].

One of the primary application domains of high-speed fixed-wing UAVs is reconnaissance and surveillance. These platforms are typically equipped with electro-optical (EO), infrared (IR), and synthetic aperture radar (SAR) payloads, enabling rapid acquisition of intelligence over large operational areas. Their high cruise speed allows timely deployment and efficient coverage of wide regions [33]. Representative systems include the RQ-4 Global Hawk [41], which provides high-altitude persistent surveillance, as well as smaller tactical UAVs used for situational awareness.

Another major category is armed unmanned systems. These platforms integrate high-speed flight capabilities with precision functionality, carrying guided munitions such as laser-guided bombs. Some UAVs rely on high-speed penetration and rapid ingress–egress capabilities, where aerodynamic performance and thrust availability directly influence mission survivability and effectiveness [46]. The MQ-9 Reaper [51] exemplifies this class, offering combined reconnaissance and surveillance capabilities in a single operational platform, shown in Figure 1.

Target drones represent a third category of high-speed fixed-wing UAVs, designed to simulate hostile aircraft behavior for training and evaluation purposes. These systems replicate speed, maneuverability, and radar signatures of real threats, enabling realistic testing of air defense systems and pilot training. Examples include the BQM-167 Skeeter [52] and Kratos BQM-177 [52], which can reproduce high subsonic and near-transonic flight profiles.



Figure 1. An MQ-9 Reaper (U.S. Air Force Photo/Lt. Col. Leslie Pratt) [51].

The operational environments associated with different UAV classes introduce additional design constraints related to altitude, survivability, and mission complexity, as shown in Table 5.

Table 5. Operational environment constraints for turbine-powered UAV categories.

UAV Class	Typical Altitude	Operational Environment	Threat Exposure	Navigation Complexity
Long-endurance UAV	High altitude	Wide-area ISR	Medium	Moderate
High-speed UAV	Medium–high altitude	Contested airspace	High	High
VTOL UAV	Low altitude	Urban/maritime/confined areas	Medium	Very high
Loitering munition	Low–medium altitude	Tactical battlefield	Very high	Medium
Swarm UAV	Variable	Distributed operational environment	High	Very high

2.3. VTOL UAVs

Vertical take-off and landing (VTOL) UAVs represent a distinct operational category characterized by the ability to operate without conventional runways while maintaining hovering and low-speed maneuvering capability [53,54]. These systems are increasingly employed in reconnaissance, urban logistics, maritime surveillance, search and rescue, and remote-area operations where operational flexibility and deployment independence are critical mission requirements.

Unlike fixed-wing UAVs, VTOL platforms must continuously generate lift through propulsion during hover, which leads to significantly higher power demand and energy consumption due to induced-flow losses and the absence of aerodynamic wing-borne lift [55,56]. Consequently, propulsion system selection becomes strongly influenced by power density, transient response capability, and energy management efficiency. Turbine-powered VTOL UAVs, particularly those employing micro turboshaft engines or hybrid-electric architectures, offer substantial advantages in endurance and payload capability compared to purely battery-electric systems.

Hybrid-electric VTOL architectures are increasingly investigated to enhance operational flexibility and overall energy efficiency by combining the high energy density of fuel-based systems with the controllability and adaptability of electric propulsion across multiple flight phases [57–59]. Serial hybrid systems allow turbines to operate near optimal steady-state conditions, while distributed electric propulsion improves redundancy and

maneuverability. Parallel hybrid systems further support transient power demands during take-off and hover conditions.

Operational requirements for VTOL UAVs include stable hover capability, precise low-speed control, confined-area operation, rapid deployment, and high maneuverability, particularly due to the distinct control demands of hover and transition flight regimes [60,61]. However, these systems also face major challenges associated with hover efficiency, thermal management, vibration, and propulsion-system complexity.

2.4. Loitering Munitions

Loitering munitions (LMs), also referred to as one-way attack UAVs, combine characteristics of unmanned aircraft and guided weapons within a single expendable platform. Their operational concept involves launch, autonomous or semi-autonomous loitering over a target area, target acquisition, and terminal self-destruction upon engagement.

Operational requirements for loitering munitions include rapid deployment, low production cost, autonomous navigation, extended stand-off range, and high-speed terminal attack capability. Depending on mission profile, these systems may prioritize endurance during loiter phases or high-speed penetration during terminal engagement [62,63]. This paradigm directly influences loitering munition design philosophy, which is fundamentally characterized by its expendable nature. Unlike conventional reusable UAVs, LMs are designed for a single mission cycle culminating in terminal impact, eliminating the requirement for recovery and reuse [64]. This operational concept enables significant simplification of airframe, avionics, and propulsion subsystems.

Micro turbojet and small gas turbine engines are increasingly adopted in high-performance loitering munitions due to their compact configuration, scalability, and high thrust-to-weight ratio, which enable high-speed flight and effective integration into small unmanned airframe designs [33,65]. Compared to electric propulsion systems, turbine-powered loitering munitions provide higher cruise speed, improved penetration capability, and extended operational range.

The expendable nature of loitering munitions enables their employment in distributed and networked engagement architectures, where multiple systems can be coordinated to overwhelm defenses through saturation attack strategies and cooperative target allocation [66,67]. Consequently, these systems are increasingly optimized for low-cost mass production using commercial off-the-shelf (COTS) components, modular avionics, and simplified propulsion architectures.

2.5. Swarm UAV Systems

Swarm UAV systems represent an emerging operational paradigm in which multiple autonomous or semi-autonomous UAVs cooperate through networked coordination to perform distributed and parallel missions, enabling scalable and efficient multi-platform task execution [68,69]. These systems are increasingly investigated for reconnaissance, distributed sensing, logistics support, surveillance, and coordinated operations.

Operational requirements for swarm UAV systems extend beyond conventional propulsion considerations to include robust inter-agent communication, autonomous and distributed decision-making, and real-time mission adaptation mechanisms, enabling coordinated execution of complex multi-agent missions under dynamic environmental constraints [70,71]. In turbine-powered swarm systems, propulsion architectures must additionally balance endurance, cost, payload capability, and manufacturability to support deployment at large scale.

Recent developments in swarm UAV research are strongly connected to emerging propulsion and manufacturing technologies, as summarized in Table 6.

Table 6. Emerging technologies in turbine-powered UAV systems.

Technology	Application	Expected Benefit	Current Limitation
Hybrid-electric propulsion	VTOL and endurance UAVs	Improved mission flexibility	Increased system mass
AI-based energy management	Swarm and hybrid UAVs	Optimized endurance	Computational complexity
Additive manufacturing	Loitering munitions	Rapid scalable production	Material limitations
Distributed propulsion	VTOL/swarm systems	Redundancy and maneuverability	Control complexity
Structural batteries	Electric UAVs	Reduced structural mass	Low technology maturity
Ceramic matrix composites	Micro gas turbines	Improved thermal efficiency	High manufacturing cost

Operational requirements for swarm UAV systems extend beyond propulsion considerations to include robust inter-agent communication, autonomous and distributed decision-making, and real-time mission adaptation mechanisms, enabling coordinated operation under dynamic and communication-constrained environments [70,72]. This trend strongly influences propulsion-system selection, favoring compact, low-cost turbine engines and simplified hybrid architectures capable of supporting scalable manufacturing and operational flexibility.

To summarize recent research directions, Table 7 presents representative studies related to turbine-powered UAV operational concepts and propulsion architectures.

Table 7. Summary of representative studies on turbine-powered UAV systems.

UAV Category	Main Contribution	Propulsion Type	Key Finding
Long-endurance UAV	Endurance optimization	Turboprop	Improved fuel efficiency
VTOL UAV	Hybrid propulsion integration	Turboshaft-electric hybrid	Increased hover endurance
Loitering munition	Low-cost expendable design	Micro turbojet	Improved production scalability
Swarm UAV	Cooperative guidance algorithms	Hybrid-electric	Improved mission coordination
High-speed UAV	Rapid-response capability	Turbojet	Enhanced penetration performance

Overall, the literature consistently shows that propulsion system selection is highly mission-dependent, and no single propulsion architecture is optimal for all UAV categories. While turbine-powered systems provide clear advantages for high-speed and long-endurance missions, hybrid-electric solutions are emerging as attractive alternatives for VTOL and multi-role platforms. Nevertheless, further experimental validation is required to quantify the operational trade-offs associated with these architectures under realistic mission conditions.

3. Thermal Management

Thermal management represents one of the most critical integration challenges associated with micro gas engines in UAV platforms. Unlike large-scale aircraft turbines, where the propulsion system is integrated into relatively spacious airframes with dedicated cooling pathways and thermal protection structures, UAVs operate under extremely constrained mass and volumetric limitations [73]. As a result, the high exhaust gas temperatures (EGT) generated by micro gas turbines can significantly affect structural integrity, onboard electronics, aerodynamic surfaces, and mission survivability. Effective thermal management therefore becomes essential not only for propulsion efficiency and engine durability, but also for the safe integration of the engine within compact unmanned airframes.

One of the primary thermal challenges originates from the elevated exhaust temperatures produced by micro turbojets and turboshaft engines. Depending on engine size and operating regime, EGT values commonly range between 500 °C and 900 °C, while localized hot spots near combustor walls and turbine sections may exceed 1000 °C [74]. At the micro-scale, the high surface-area-to-volume ratio intensifies conductive heat transfer between the hot section and adjacent structural components. This phenomenon, often referred

to as thermal soak-back, can lead to significant preheating of intake air, degradation of nearby composite materials, and thermal stress accumulation within the airframe structure. Excessive thermal exposure may also accelerate fatigue cracking, adhesive degradation, and delamination in lightweight composite fuselages frequently used in UAV construction subjected to severe heat stresses [75].

The compact geometry of UAV platforms further complicates the dissipation of thermal energy. Unlike conventional aircraft with large nacelles and dedicated ventilation systems, many UAVs integrate the engine directly into slender fuselage architectures where thermal isolation distances are minimal. Consequently, thermal shielding becomes essential to prevent radiative and convective heat transfer toward sensitive avionics, fuel tanks, batteries, and payload systems. Advanced shielding solutions commonly include multi-layer thermal barriers, ceramic insulation blankets, reflective metallic coatings, and actively cooled heat shields positioned around the exhaust duct and combustor region. In other specific UAV applications, thermal shielding also plays a critical role in reducing infrared (IR) signatures, thereby decreasing vulnerability to heat-seeking detection systems. Beyond structural considerations, advanced nozzle geometry modifications (such as castellated designs or trailing edge modifications) have emerged as a critical method for mitigating this thermal signature, ensuring rapid mixing of hot exhaust gases with ambient air and reducing the overall infrared footprint with minimal thrust penalties [76].

Material selection is another major consideration in the thermal integration of micro gas engines. Conventional polymer-based UAV structures often cannot withstand sustained exposure to turbine exhaust temperatures, particularly near the nozzle and hot-section interfaces. As a result, localized reinforcement using heat-resistant alloys, ceramic matrix composites [77] (CMCs), or carbon-carbon structures is increasingly required in turbine-powered UAV designs. Nickel-based superalloys such as Inconel are frequently employed in exhaust ducts and turbine mounting interfaces because of their resistance to oxidation and thermal creep under high-temperature operation. Meanwhile, ceramic materials such as silicon carbide (SiC) and silicon nitride (Si_3N_4) are attracting attention for next-generation microturbine applications due to their ability to tolerate substantially higher operating temperatures while reducing cooling requirements and structural mass.

Notably, recent thermal-structural assessments of convergent nozzles demonstrate that utilizing advanced unidirectional epoxy glass fiber reinforced polymers (E-GFRP-UD) can reduce thermal stresses by over 65% compared to conventional structural steel while maintaining minimal deformation, making them highly promising candidates for lightweight micro gas turbine engine applications [78]. Meanwhile, highly exposed internal components, such as the bearing housing positioned near the radial-flow turbine, require advanced passive strategies, utilizing double-layer heat shields and volute improvements to block severe thermal soak-back from the hot section without adding the weight of active fluid cooling systems [79].

Thermal management challenges become even more pronounced in hybrid-electric UAV architectures, where turbine engines coexist with temperature-sensitive batteries and power electronics. Excessive thermal radiation from the turbine can degrade battery performance, accelerate lithium-ion aging mechanisms, and increase the risk of thermal runaway events. Consequently, hybrid UAVs often require carefully segregated thermal zones, dedicated ventilation pathways, and active cooling systems to maintain acceptable operating temperatures for both propulsion and electrical subsystems. To address extreme thermal loads in confined spaces, novel battery thermal management systems (BTMS) utilizing advanced graphene directional heat transfer structures have been proposed to rapidly dissipate localized heat toward the outer airframe [80]. Furthermore, protecting onboard electronic equipment increasingly relies on the topological optimization of complex

3D cooling fins and pin structures designed to maximize the dissipation of high localized heat fluxes [81]. In some configurations, the turbine exhaust itself is utilized as part of a thermal management strategy, where waste heat is redirected toward recuperators or auxiliary heating systems to improve overall cycle efficiency.

Beyond airborne constraints, integrating multi-energy microgrids (MEMs) with Thermal Energy Storage (TES) systems at the ground infrastructure (vertiports) offers a vital systemic solution; these TES networks can absorb and recycle the immense thermal loads generated during ultra-fast charging cycles of eVTOL and hybrid UAV fleets, preventing grid-level thermal stress and optimizing total fleet turnaround efficiency [82].

The aerodynamic interaction between hot exhaust gases and the surrounding airframe also introduces additional design constraints. High-temperature exhaust plumes can alter local airflow conditions, affect empennage stability, and induce thermal deformation in nearby aerodynamic surfaces. Furthermore, exhaust recirculation phenomena may occur during low-speed flight or VTOL operations, causing the engine to ingest heated air that reduces compressor efficiency and overall thrust generation. These effects are particularly significant in compact UAVs where the intake and exhaust systems are positioned in close proximity.

Crucially, when operating at high altitudes, the low-pressure and low-density atmospheric conditions significantly reduce the operating Reynolds number of micro radial-flow turbines, dropping below the critical threshold. At these low Reynolds numbers, viscous forces dominate, promoting boundary layer thickening on the rotor blade suction surfaces, flow separation, and heightened secondary flow losses, which drastically degrade overall turbine performance and aerodynamic efficiency [83].

To mitigate these challenges, modern UAV propulsion research increasingly focuses on integrated thermal management strategies combining computational fluid dynamics (CFD), conjugate heat transfer analysis, and infrared signature modeling [73,84]. Advanced approaches include actively cooled exhaust nozzles, distributed heat exchangers, adaptive thermal coatings, and stealth-oriented exhaust geometries designed to mix hot exhaust gases with ambient air before discharge. Instead of merely dissipating waste heat, advanced high-altitude long-endurance (HALE) platforms employ waste heat recovery systems to optimize the global thermodynamic cycle [75]. By integrating ultra-lightweight ceramic micro-channel recuperators, thermal energy from the exhaust is extracted to preheat air before combustion, simultaneously reducing specific fuel consumption and lowering the thermal load of the exhaust plume before it exits the aircraft [85]. Such solutions aim not only to improve propulsion efficiency and structural reliability, but also to enhance survivability and mission endurance in demanding operational environments.

Ultimately, thermal management remains a multidisciplinary design problem that directly links propulsion performance, structural engineering, materials science, and stealth technology. As UAV propulsion systems continue to evolve toward higher power densities and more compact turbine architectures, effective thermal integration will become increasingly important for enabling reliable, lightweight, and operationally survivable unmanned aerial platforms.

Although numerous studies propose passive shielding materials, advanced coatings, and improved exhaust geometries, there is currently no consensus regarding the most effective thermal management strategy for compact turbine-powered UAVs. Most existing investigations focus on individual thermal mitigation techniques, whereas relatively few studies evaluate integrated thermal management approaches that simultaneously consider propulsion efficiency, structural integrity, infrared signature reduction, and system weight.

4. Inlet and Exhaust Design

The aerodynamic integration of the inlet and exhaust systems represents a major engineering challenge in turbine-powered UAV platforms. Unlike large aircraft engines, where intake geometries and exhaust ducts can be optimized within relatively spacious nacelles, micro gas turbines must operate within highly constrained airframes characterized by compact fuselage geometries, rapidly changing flight attitudes, and severe packaging limitations. Consequently, improper inlet or exhaust integration can significantly degrade compressor performance, reduce thrust generation, increase thermal loads, and compromise overall propulsion stability.

One of the primary concerns associated with UAV inlet design is compressor inlet distortion. Micro gas turbines are highly sensitive to non-uniform airflow entering the compressor stage, particularly because most UAV-scale engines rely on compact centrifugal compressors operating near their aerodynamic stability limits. Distorted inlet flow can generate localized regions of low momentum, turbulence, or swirl that disrupt the pressure distribution across the compressor face. This phenomenon may reduce compressor efficiency, increase vibration levels, and in severe cases trigger rotating stall or compressor surge events. At the micro-scale, where compressor stages already operate under low Reynolds number conditions and narrow surge margins, even relatively small disturbances can significantly affect engine stability.

The effect of inlet distortion on compressor operation is commonly evaluated through total-pressure contour analysis at the compressor face, as illustrated in Figure 2. Non-uniform pressure regions and circumferential distortion sectors create asymmetric aerodynamic loading on the impeller blades, generating unsteady flow structures that propagate through the compression stage. Experimental and numerical investigations reported in the literature demonstrate that distorted inlet conditions can substantially reduce compressor pressure ratio and surge margin, particularly during transient throttle variations or aggressive UAV maneuvers. Furthermore, the compact nature of UAV fuselages frequently forces intake ducts to include sharp bends or compact S-shaped geometries, which intensify secondary flow formation and boundary layer separation inside the inlet channel.

Circumferential pressure distortion produces non-uniform total pressure distributions at the compressor inlet, causing individual rotor passages to operate under different incidence angles and local mass flow conditions. As a result, blade loading becomes circumferentially asymmetric, promoting localized flow separation and the development of rotating stall cells. These effects are particularly pronounced in micro gas turbines, where the reduced Reynolds number increases boundary-layer thickness and viscous losses, thereby reducing compressor stability margins and increasing sensitivity to inlet flow disturbances. Consequently, even moderate inlet distortion may produce a disproportionate reduction in compressor performance compared with larger gas turbine engines.

Intake placement strongly influences the severity of these aerodynamic disturbances. In turbine-powered UAVs, air intakes are commonly positioned dorsally, laterally, or beneath the fuselage depending on mission requirements and airframe geometry. Dorsal intake configurations may reduce foreign object ingestion during takeoff and landing operations, but they are highly susceptible to boundary layer ingestion generated along the upper fuselage surface. Lateral intakes offer improved accessibility and simplified duct routing but may experience asymmetric flow conditions during sideslip maneuvers or crosswind operations. Meanwhile, blended or embedded intake architectures are increasingly investigated for stealth-oriented UAVs because they reduce radar cross-section and improve aerodynamic integration, although these configurations often intensify flow distortion at the compressor inlet.

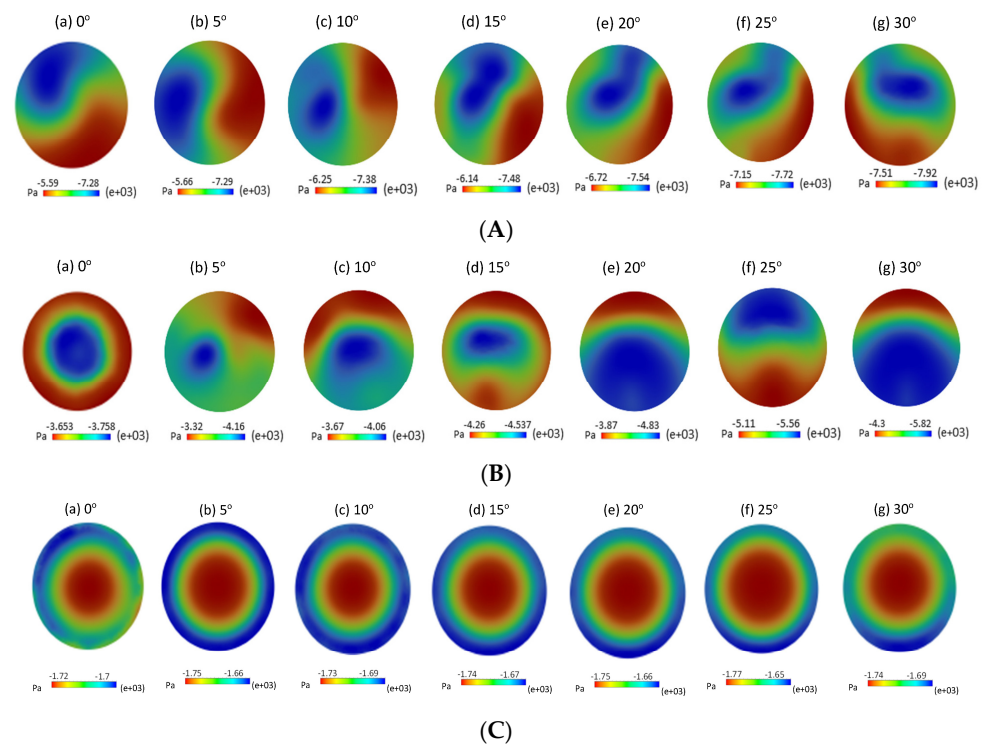


Figure 2. Pressure contour distributions at the Aerodynamic Interface Plane (AIP) under varying inflow angles for different intake geometries: (A) flat-lip intake at an inflow velocity of 35 m/s; (B) flat-lip intake at an inflow velocity of 70 m/s; and (C) bell-mouth round-lip intake at an inflow velocity of 35 m/s [86].

Figure 2A,B illustrate the evolution of inlet pressure distortion patterns at the Aerodynamic Interface Plane (AIP) under varying inflow angles and intake geometries, as reported by Sanchez Villacreses et al. [86]. Figure 2A,B present the pressure contours obtained using a flat-lip intake configuration operating at inflow velocities of 35 m/s and 70 m/s, respectively, while Figure 2C shows the corresponding behavior for a bell-mouth round-lip intake at 35 m/s. The results demonstrate that increasing inflow angles progressively generate larger asymmetric low-pressure regions and more severe circumferential distortion at the compressor face, particularly for the flat-lip geometry. In contrast, the bell-mouth round-lip intake shown in Figure 2C produces a significantly smoother and more uniform pressure distribution across the AIP, indicating improved aerodynamic flow conditioning and reduced inlet distortion sensitivity. These findings highlight the critical influence of intake geometry on compressor stability and overall propulsion efficiency in turbine-powered UAVs. Proper inlet shaping can substantially reduce pressure nonuniformities, improve surge margin, and mitigate performance degradation during aggressive maneuvers or crossflow operating conditions.

The pressure distributions shown in Figure 2 illustrate how inlet geometry directly influences the aerodynamic quality of the flow delivered to the compressor. The flat-lip configuration generates progressively larger low-pressure regions as the inflow angle increases, indicating stronger circumferential pressure distortion and greater flow non-uniformity at the Aerodynamic Interface Plane (AIP). In contrast, the bell-mouth round-lip configuration produces a more uniform pressure field, which is expected to improve compressor inlet conditions and increase the available stability margin. These observations highlight the importance of intake geometry in reducing distortion-induced performance degradation and maintaining stable engine operation under varying flight conditions.

Representative intake integration strategies used in turbine-powered UAVs are illustrated in Figure 3, highlighting the relationship between intake position, airflow uniformity,

and overall propulsion integration complexity. The selection of intake location must simultaneously balance aerodynamic efficiency, structural packaging constraints, thermal isolation requirements, and operational survivability. In addition, the intake geometry must ensure adequate mass flow delivery across a wide range of flight speeds and angles of attack without generating excessive pressure losses.

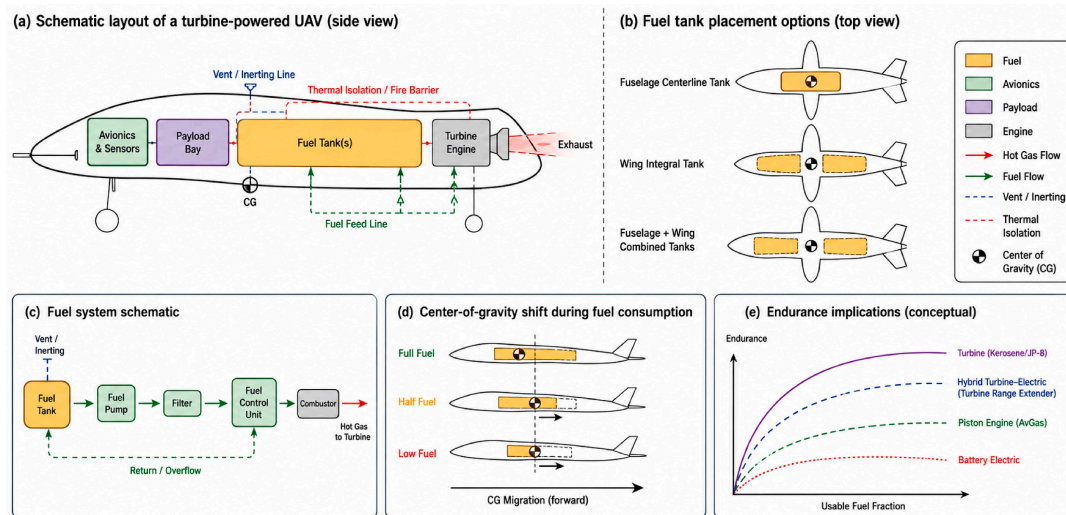


Figure 3. Conceptual schematic of fuel storage integration strategies in turbine-powered UAVs, illustrating (a) a representative side-view layout showing the relationship between fuel tanks, payload systems, avionics, and turbine propulsion components; (b) common fuel tank placement configurations including fuselage-integrated, wing-integrated, and combined storage architectures; (c) a simplified turbine fuel delivery system schematic; (d) center-of-gravity migration during progressive fuel consumption; and (e) conceptual endurance trends associated with battery-electric, piston-engine, turbine-powered, and hybrid turbine-electric UAV propulsion systems. The figure highlights the multidisciplinary challenges associated with fuel packaging, thermal isolation, propulsion integration, and endurance optimization in compact unmanned aerial platforms.

Exhaust integration introduces an additional set of aerodynamic and thermal challenges. High-velocity exhaust jets generated by micro turbojets and turboshaft engines interact strongly with the surrounding airframe, potentially inducing thermal degradation, local flow separation, and empennage instability. In compact UAVs, the exhaust plume may also interact directly with the intake system, particularly during low-speed flight, hover conditions, or VTOL operations. This exhaust recirculation phenomenon can lead to the ingestion of heated air into the compressor, reducing inlet air density and causing measurable thrust degradation.

For stealth-oriented UAVs, exhaust system design is further constrained by infrared (IR) signature reduction requirements. The hot exhaust plume generated by turbine propulsion represents one of the most detectable features of unmanned aerial vehicles. Consequently, modern UAV exhaust systems increasingly incorporate shielding structures, plume mixers, elongated exhaust ducts, and cooling-air dilution strategies intended to reduce exhaust gas temperature before discharge into the atmosphere. Some advanced concepts also employ flattened or distributed exhaust nozzles to improve thermal dissipation while simultaneously reducing radar observability.

The structural integration of the exhaust system must also account for thermal expansion, vibration loading, and high-cycle fatigue induced by pulsating flow structures. Lightweight composite UAV fuselages often require localized reinforcement near the exhaust region using metallic heat shields or ceramic thermal barriers to prevent thermal degradation of nearby structural components. Computational Fluid Dynamics (CFD) simu-

lations and conjugate heat transfer models therefore play a central role in optimizing both inlet and exhaust architectures during the UAV design process.

Overall, inlet and exhaust integration remains a multidisciplinary optimization problem involving aerodynamics, propulsion stability, thermal management, stealth technology, and structural design. As UAV platforms continue to evolve toward more compact and higher-performance turbine-powered configurations, advanced intake shaping, adaptive flow control strategies, and thermally integrated exhaust architectures will become increasingly important for ensuring propulsion efficiency, survivability, and operational reliability.

Existing studies consistently demonstrate that inlet geometry strongly influences compressor stability and overall propulsion efficiency. However, most investigations rely on numerical simulations or isolated experimental configurations, and comparatively few studies examine inlet–airframe interactions under realistic flight conditions. Additional experimental validation and multidisciplinary optimization are therefore needed to improve the robustness of future turbine-powered UAV designs.

5. Fuel Storage

Fuel storage constitutes a major design constraint in turbine-powered UAV systems because the propulsion advantages offered by micro gas engines are directly linked to the availability, distribution, and management of onboard fuel. Although hydrocarbon fuels such as kerosene and Jet-A possess substantially higher gravimetric energy density than electrochemical batteries, integrating sufficient fuel volume within compact UAV airframes remains a complex multidisciplinary challenge involving endurance optimization, structural packaging, thermal safety, and mission adaptability.

One of the principal advantages of micro gas turbine propulsion is the compatibility with energy-dense liquid fuels, particularly kerosene-based aviation fuels. Compared with battery-powered propulsion systems, liquid hydrocarbon fuels enable significantly longer endurance and higher mission flexibility, especially in medium- and large-scale UAVs intended for surveillance, cargo transport, or long-range reconnaissance. However, the operational benefits of kerosene propulsion also introduce logistical considerations related to fuel availability, transportation, storage infrastructure, and maintenance compatibility. Some UAV platforms often rely on heavy-fuel propulsion concepts designed to operate using JP-8 or similar battlefield-standard fuels in order to simplify logistical chains and improve interoperability with existing aviation support infrastructure.

The physical integration of fuel tanks within UAV airframes presents substantial design challenges due to the limited internal volume available in compact unmanned platforms. Unlike conventional aircraft, UAVs frequently contain densely packed avionics, payload systems, batteries, and communication hardware competing for internal space. Consequently, fuel storage architecture strongly influences the overall vehicle layout, center-of-gravity location, and aerodynamic configuration. Improper fuel distribution can lead to significant center-of-mass migration during flight, negatively affecting stability, control authority, and flight endurance. Designers must therefore carefully position fuel tanks to minimize trim variations as fuel is consumed throughout the mission profile.

Fuel storage requirements become particularly critical in long-endurance UAVs, where mission duration is directly constrained by fuel mass fraction and propulsion efficiency. Although turbine engines generally exhibit lower propulsive efficiency than piston engines at low subsonic flight speeds, their superior power-to-weight ratio and compatibility with high-energy-density fuels can still provide substantial endurance advantages for larger UAV categories. Endurance optimization therefore depends on achieving an effective balance between fuel quantity, engine efficiency, aerodynamic drag, and payload mass. In many turbine-powered UAVs, a significant portion of the total takeoff mass

may be dedicated exclusively to fuel storage, particularly in reconnaissance or persistent surveillance missions.

The integration of fuel storage systems within turbine-powered UAVs represents a major multidisciplinary design challenge directly affecting endurance, stability, thermal safety, and payload capability. Unlike conventional manned aircraft, unmanned aerial platforms operate under severe volumetric and mass constraints, requiring careful optimization of the internal arrangement between fuel tanks, propulsion systems, avionics, payload compartments, and structural elements. The placement and geometry of fuel tanks strongly influence center-of-gravity location and migration during fuel consumption, while simultaneously competing with other onboard subsystems for limited internal space. Furthermore, the proximity between fuel storage and high-temperature turbine components introduces additional thermal management and safety considerations. Figure 3 illustrates several representative fuel integration architectures and their implications for propulsion packaging, fuel distribution, and endurance optimization in turbine-powered UAV configurations.

The geometry and structural integration of fuel tanks also introduce important safety and survivability considerations. Turbine-powered UAVs generate elevated thermal loads near the combustor and exhaust regions, requiring adequate thermal isolation between fuel systems and hot engine components. Excessive fuel heating may increase vapor formation, alter fuel properties, or elevate ignition risks under high-temperature operating conditions. Consequently, modern UAV designs increasingly employ insulated fuel compartments, fire-resistant barriers, and strategically separated thermal zones to reduce the probability of fuel-related failures.

Fuel sloshing effects represent another important challenge, particularly during aggressive maneuvers, VTOL transitions, or high-angle flight conditions. Dynamic fuel motion within partially filled tanks can generate transient shifts in mass distribution, potentially affecting vehicle stability and fuel feed reliability. To mitigate these effects, UAV fuel systems frequently incorporate internal baffles, collector tanks, and pressurized fuel delivery architectures designed to maintain stable fuel flow under varying acceleration loads.

Hybrid-electric UAV architectures introduce additional fuel storage considerations because the vehicle must simultaneously accommodate both liquid fuel systems and battery packs within highly constrained airframes. While turbine range extenders can significantly increase operational endurance, the combined integration of fuel tanks, electrical power electronics, and thermal management systems often produces severe packaging and cooling challenges. This has motivated growing research into conformal fuel tanks, lightweight composite storage structures, and multifunctional airframe concepts where structural components simultaneously serve as fuel storage volumes.

Recent experimental propulsion concepts involving hydrogen-fueled micro turbines further complicate onboard fuel storage requirements. Although hydrogen offers exceptional gravimetric energy density and low-emission combustion characteristics, its extremely low volumetric density necessitates either cryogenic storage systems or high-pressure tanks that are difficult to integrate within compact UAV geometries. As a result, hydrogen propulsion currently remains more feasible for larger unmanned aircraft or hybrid demonstrator platforms rather than miniature turbine-powered drones.

Overall, fuel storage remains a central factor governing the endurance, payload capability, survivability, and operational flexibility of turbine-powered UAVs. Future developments will likely focus on lightweight conformal tanks, thermally integrated fuel architectures, and advanced fuel-management systems capable of supporting increasingly compact, long-endurance, and hybrid-electric unmanned aerial platforms.

Despite considerable advances in fuel storage concepts, the literature primarily focuses on maximizing endurance while comparatively less attention has been devoted to the interaction between fuel storage architecture, thermal management, structural integration, and center-of-gravity evolution throughout the mission. These coupled effects remain an important area for future research, particularly for hybrid-electric turbine-powered UAVs.

6. Vibrations and Structural Loads

The integration of micro gas engines into UAV platforms introduces significant vibration and structural loading challenges that can strongly influence airframe durability, propulsion reliability, sensor performance, and overall mission effectiveness. Although gas turbines generally produce smoother rotational motion than reciprocating piston engines, micro-scale turbines operate at extremely high rotational speeds—often exceeding 100,000 RPM—which generates complex dynamic loading conditions within compact and lightweight UAV structures. These high-frequency vibrations propagate through the engine mounts, fuselage, and payload interfaces, potentially inducing fatigue damage, structural resonance, and degradation of sensitive onboard equipment.

One of the principal sources of vibration in micro gas turbine systems originates from rotor imbalance and high-speed turbomachinery dynamics. Even minor geometric imperfections or asymmetries in the rotating assembly can produce substantial centrifugal forces at ultra-high rotational speeds. Furthermore, aerodynamic instabilities such as compressor surge, rotating stall, or combustion oscillations may generate transient pressure fluctuations that amplify vibration levels throughout the propulsion system. In micro-scale engines, where component tolerances are extremely small and structural stiffness is often limited by weight constraints, these dynamic effects become particularly severe.

The lightweight construction of UAV airframes further intensifies vibration sensitivity. Many unmanned platforms employ thin composite structures optimized for minimum mass rather than high damping capability. Consequently, turbine-induced vibrations can excite structural resonance modes within the fuselage, wing roots, empennage, or payload support structures. Repeated cyclic loading may gradually lead to fatigue cracking, delamination of composite laminates, loosening of fasteners, and degradation of adhesive joints. In long-endurance UAVs, where the engine may operate continuously for many hours, cumulative fatigue effects become especially important for maintaining structural integrity and operational reliability.

Payload systems are also highly vulnerable to vibration-induced disturbances. Electro-optical cameras, infrared sensors, communication systems, and navigation instruments require stable operating environments to maintain imaging quality and measurement accuracy. Excessive vibration can introduce motion blur, sensor drift, and tracking instability, particularly in reconnaissance UAVs employing high-resolution surveillance equipment. For this reason, turbine-powered UAVs frequently require vibration isolation systems, damped mounting structures, and carefully tuned support architectures to decouple sensitive payloads from engine-induced dynamic loads.

The interaction between propulsion vibration and aerodynamic loading further complicates structural integration. During aggressive maneuvers, gust encounters, or VTOL transitions, aerodynamic forces combine with propulsion-induced oscillations to produce complex multi-axis structural loading conditions. In rotary-wing UAVs powered by micro turboshaft engines, additional vibratory sources originate from rotor dynamics, blade passage frequencies, and gearbox interactions. These coupled vibration mechanisms can significantly increase the difficulty of predicting fatigue life and structural response.

Representative examples of structural monitoring approaches for turbine-powered UAVs are shown in Figure 4, including vibration-sensitive regions near the engine mounts,

fuselage interfaces, and payload support structures. Modern UAV designs increasingly employ Structural Health Monitoring [75] (SHM) systems incorporating accelerometers, strain gauges, and Fiber Bragg Grating [85] (FBG) sensors capable of detecting localized structural deformation and vibration propagation in real time. Such monitoring systems are particularly important in high-speed UAVs and target drones, where repeated thermal and dynamic loading cycles can generate barely visible structural damage that may propagate rapidly during operation.

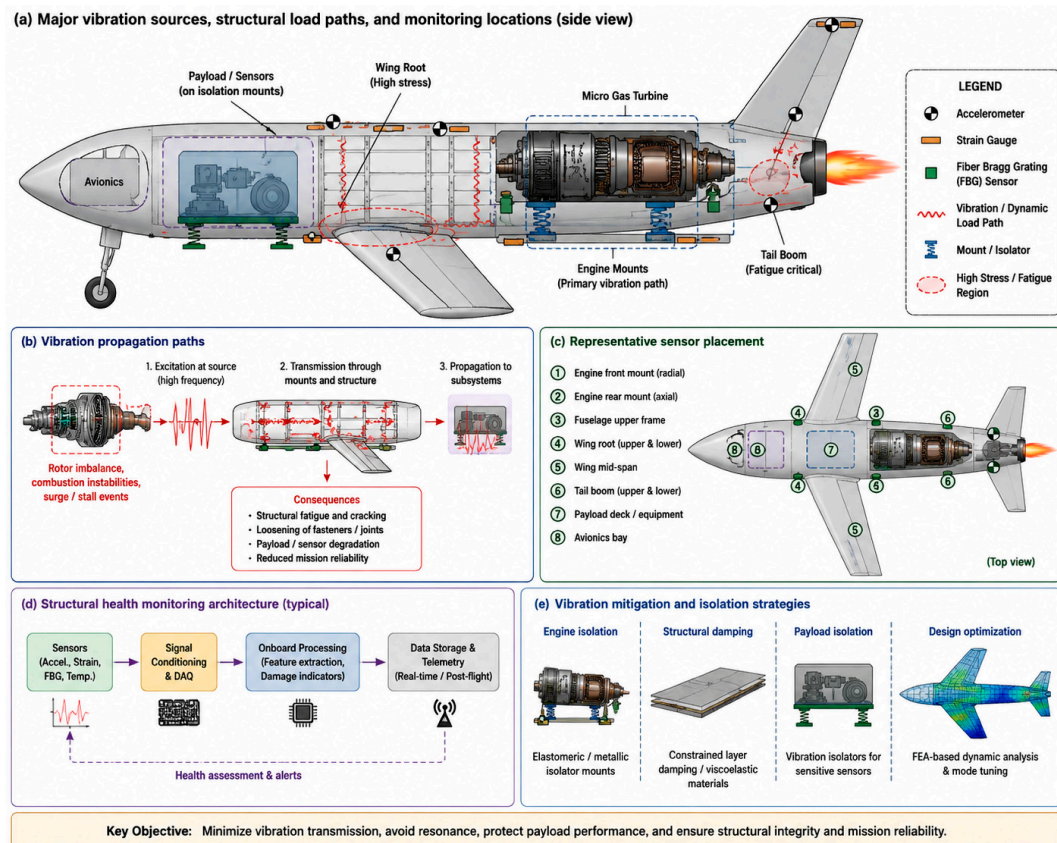


Figure 4. Conceptual structural vibration and monitoring architecture diagram for turbine-powered UAVs, illustrating major vibration propagation paths, structural load concentration regions, engine mounting interfaces, and representative sensor locations used for structural health monitoring and vibration mitigation.

Figure 4 highlights that vibration generated by the rotating assembly is transmitted through multiple structural paths before reaching sensitive onboard equipment. Consequently, the vibration response measured at the payload or avionics compartment does not depend solely on the engine excitation but also on the dynamic characteristics of the supporting structure, engine mounts, and airframe. This coupled behaviour explains why vibration mitigation must be considered at the system level rather than by optimizing individual components independently.

To mitigate these challenges, UAV designers utilize a combination of passive and active vibration-control strategies. Passive approaches include elastomeric engine mounts, tuned mass dampers, composite sandwich structures, and vibration-isolating payload supports designed to attenuate high-frequency oscillations. Meanwhile, active control methods increasingly rely on adaptive flight control systems and real-time vibration monitoring algorithms capable of identifying unstable operating regimes before critical resonance conditions develop. Advanced finite-element analysis (FEA) and aeroelastic simulations

are also extensively employed during the design stage to predict structural response under coupled aerodynamic and propulsion loading environments.

Another important consideration involves the interaction between vibration and thermal loading. Elevated temperatures near the engine mounting region can alter material stiffness, accelerate fatigue accumulation, and reduce damping effectiveness, thereby increasing structural vulnerability to dynamic stresses. Consequently, turbine-powered UAV integration requires simultaneous consideration of thermal management and structural vibration mitigation rather than treating them as independent design problems.

Overall, vibration and structural load management remain fundamental challenges in turbine-powered UAV design due to the combination of lightweight airframes, compact geometries, and ultra-high-speed propulsion systems. Future developments will likely focus on integrated structural health monitoring, adaptive vibration suppression systems, lightweight damping materials, and digitally optimized airframe architectures capable of maintaining structural reliability under increasingly demanding propulsion and mission conditions.

Although numerous vibration mitigation techniques have been reported, their effectiveness often depends on the specific propulsion architecture, structural configuration, and operating conditions. Consequently, standardized methodologies for evaluating vibration performance in turbine-powered UAVs remain limited, highlighting the need for integrated experimental and numerical investigations.

7. Acoustic and Infrared Signatures

Acoustic and infrared (IR) signatures constitute critical operational considerations in turbine-powered UAV design, particularly for surveillance and stealth-oriented missions. Unlike electrically powered drones [86], micro gas turbines generate distinctive thermal and acoustic emissions resulting from high-speed rotating machinery, combustion processes, and high-temperature exhaust jets [30]. These signatures can significantly increase the detectability of unmanned platforms by both human observers and advanced sensing systems, thereby reducing survivability in contested operational environments.

One of the primary acoustic sources in micro gas turbine propulsion systems originates from the extremely high rotational speeds of the compressor and turbine assemblies. Micro gas engines frequently operate at rotational speeds exceeding 100,000 RPM, generating strong tonal noise components associated with blade-passing frequencies and aerodynamic turbulence within the compressor stage. Additional acoustic contributions arise from combustion instabilities, exhaust jet turbulence, and structural vibration transmission through the airframe. In compact UAVs, the close proximity between the propulsion system and lightweight structural components can amplify resonance phenomena and radiated noise levels, particularly in thin composite fuselage structures with limited acoustic damping capability.

Acoustic detectability is especially important for reconnaissance and loitering UAVs operating at low altitude or in urban environments, where noise signatures may compromise covert operation. Compared with piston engines, micro gas turbines generally produce smoother broadband noise characteristics with reduced low-frequency vibration; however, the high-frequency tonal components generated by the turbomachinery remain highly detectable. Consequently, significant research efforts have focused on acoustic suppression techniques including optimized intake shaping, serrated exhaust nozzles, passive acoustic liners, and vibration-isolated engine mounts designed to reduce structural-borne noise transmission.

Representative acoustic mitigation strategies used in turbine-powered UAVs are illustrated in Figure 5, including intake acoustic liners, exhaust mixing geometries, vibration

isolation systems, and distributed shielding structures. In some advanced configurations, exhaust nozzles are specifically designed to promote rapid mixing between hot exhaust gases and ambient airflow, thereby simultaneously reducing both acoustic intensity and infrared emissions.

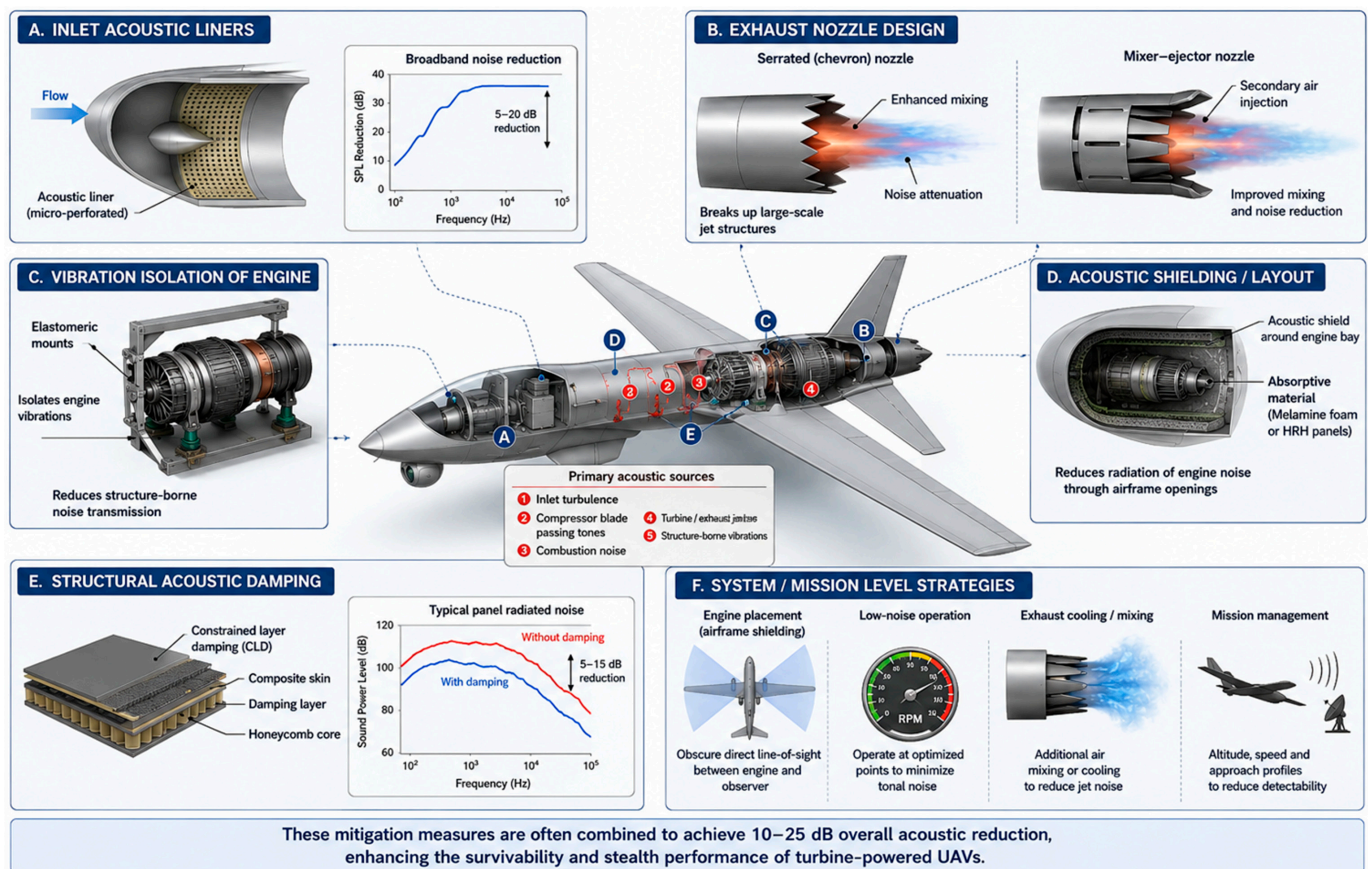


Figure 5. Representative acoustic mitigation strategies used in turbine-powered UAVs, illustrating (A) inlet acoustic liners for broadband noise attenuation; (B) serrated and mixer-ejector exhaust nozzle geometries designed to enhance plume mixing and reduce jet noise; (C) vibration-isolated engine mounting systems for minimizing structure-borne acoustic transmission; (D) acoustic shielding and absorptive materials integrated around the engine bay; (E) structural damping approaches employing constrained-layer composite architectures; and (F) system-level stealth-oriented strategies including optimized engine placement, low-noise operating conditions, and exhaust cooling techniques. The figure highlights the multidisciplinary approaches employed to reduce acoustic detectability and improve survivability in turbine-powered unmanned aerial vehicles.

The noise mitigation strategies summarized in Figure 5 illustrate that acoustic signature reduction cannot rely on a single design solution. Instead, effective suppression requires the combined application of exhaust-nozzle optimization, acoustic liners, structural vibration control, and operational measures. Since each technique primarily targets different noise-generation mechanisms, the overall acoustic performance depends on their integrated implementation and the specific operational requirements of the UAV platform.

Infrared signature management represents an even more critical challenge for other-types of UAV applications. The elevated exhaust gas temperatures produced by turbine propulsion systems generate strong thermal emissions that can be detected by infrared search-and-track (IRST) systems, thermal imaging sensors, and heat-seeking guidance technologies. In compact UAVs, the turbine exhaust plume often becomes the dominant contributor to the platform's overall thermal signature, particularly during high-thrust operating conditions.

The infrared visibility of a turbine-powered UAV depends not only on exhaust gas temperature, but also on plume geometry, atmospheric mixing behavior, engine placement, and external airframe heating. Hot metallic surfaces surrounding the exhaust nozzle and turbine casing may also contribute substantially to IR detectability, especially during prolonged operation where thermal soak-back increases the external surface temperature of the airframe. Consequently, modern UAV applications increasingly employ integrated thermal suppression architectures designed to minimize both plume temperature and hot-surface visibility.

Several passive and active IR-reduction strategies have been investigated in the literature. Passive approaches include elongated exhaust ducts, thermal shielding structures, ceramic coatings, and exhaust-air mixing systems that dilute hot gases before atmospheric discharge. Flattened or shielded exhaust geometries are frequently used to reduce the direct line-of-sight exposure of the turbine plume to ground-based sensors. In addition, embedded engine configurations and S-shaped exhaust ducts can partially obscure the hottest engine components from external observation angles.

Advanced concepts also investigate active thermal management systems involving secondary cooling airflow injection, adaptive exhaust vectoring, and heat exchanger integration intended to reduce plume temperature during sensitive mission phases. Hybrid-electric propulsion architectures may further reduce detectability by enabling low-signature electric-only operation during surveillance or terminal approach segments.

The trade-off between propulsion performance and signature reduction remains a major design challenge in turbine-powered UAVs. Aggressive thermal suppression measures may increase exhaust backpressure, reduce thrust efficiency, or add structural complexity and mass. Similarly, acoustic attenuation systems often require additional ducting volume and specialized materials that may conflict with strict UAV packaging constraints. As a result, stealth-oriented UAV propulsion design increasingly relies on multidisciplinary optimization methods combining computational aeroacoustics, infrared plume modeling, thermal-fluid simulations, and structural integration analysis.

Overall, acoustic and infrared signature management has become a central aspect of modern turbine-powered UAV development, particularly for high-survivability applications. Future advancements will likely focus on integrated stealth-oriented propulsion architectures combining low-observable inlet geometries, thermally adaptive exhaust systems, advanced acoustic damping materials, and hybrid propulsion concepts capable of minimizing detectability across multiple sensing domains simultaneously.

The reviewed monitoring approaches demonstrate significant progress in improving propulsion system reliability; however, most techniques have been validated under controlled laboratory conditions. Their implementation in operational turbine-powered UAVs remains limited by constraints related to sensor integration, computational requirements, environmental robustness, and system weight. Future research should focus on hybrid-electric propulsion, hydrogen-based propulsion concepts, alternative fuels, and advanced energy systems to improve the sustainability and operational flexibility of next-generation turbine-powered UAVs [87].

8. Reliability and Maintenance

Reliability and maintenance remain fundamental challenges in the adoption of micro gas engines for UAV propulsion, particularly in applications requiring long operational endurance, autonomous deployment, or operation in remote and contested environments. Although turbine engines generally offer smoother operation and fewer moving parts than reciprocating piston engines, the extreme rotational speeds, elevated thermal loads,

and compact geometries associated with micro gas turbines introduce unique reliability concerns that directly affect operational availability and lifecycle cost.

One of the principal reliability challenges in micro gas turbines arises from the high rotational speeds of the turbomachinery assembly. Many micro gas engines operate at rotational speeds exceeding 100,000 RPM, generating substantial centrifugal stresses on compressor and turbine components. Even minor manufacturing imperfections, rotor imbalance, or bearing degradation can progressively induce vibration amplification, thermal instability, and mechanical fatigue. Because the tolerances within micro-scale turbomachinery are extremely small, component wear that would be relatively insignificant in larger engines may rapidly degrade performance or lead to catastrophic failure in compact turbine architectures.

Thermal loading further contributes to reliability degradation through creep, oxidation, and thermal fatigue mechanisms. Repeated startup-shutdown cycles generate cyclic thermal expansion and contraction within turbine blades, combustor liners, and exhaust structures, progressively weakening material integrity over time. In compact UAV platforms, limited cooling capability and restricted airflow paths can intensify these thermal stresses, particularly near the combustor and turbine hot sections. Consequently, the durability of turbine-powered UAVs depends heavily on advanced materials, thermal barrier coatings, and efficient thermal management architectures capable of maintaining acceptable component temperatures during prolonged operation [88–90].

Bearing systems constitute another major reliability concern in micro gas turbines. Due to the extremely high shaft speeds involved, conventional rolling-element bearings experience significant lubrication, wear, and thermal management challenges. Several experimental propulsion systems therefore investigate air bearings, magnetic bearings, or hybrid support systems intended to reduce frictional losses and improve operational lifespan. However, these technologies also introduce increased system complexity and manufacturing sensitivity. Bearing failure remains one of the most common failure modes in small turbine engines, particularly under aggressive throttle transients or foreign object ingestion events [91].

Fuel system reliability is equally important in turbine-powered UAV operations. Contaminants, fuel vapor formation, pressure fluctuations, or injector fouling may significantly affect combustion stability and engine responsiveness. In field-deployed UAV systems, heavy-fuel compatibility requirements further complicate fuel management because fuels such as JP-8 or diesel exhibit different atomization and ignition characteristics compared with lighter aviation fuels. Reliable fuel filtration [92], stable fuel delivery systems [93], and robust electronic control architectures [94] are therefore essential for ensuring consistent propulsion performance across varying environmental and operational conditions.

Environmental exposure also strongly influences turbine reliability in UAV applications. Dust, sand, moisture, salt particles, and airborne debris may damage compressor blades, obstruct cooling passages, or accelerate erosion within turbine stages. These effects are particularly severe in low-altitude reconnaissance missions, desert operations, and maritime environments where airborne contaminants are abundant. Foreign Object Damage (FOD) [95] can rapidly degrade compressor efficiency and increase the probability of imbalance-induced vibration or compressor instability. As a result, turbine-powered UAVs often require specialized intake protection systems and regular inspection intervals to maintain operational reliability.

Maintenance requirements for micro gas turbines differ substantially from those associated with electric propulsion systems. Unlike electric motors, turbine engines require periodic inspection of bearings, fuel injectors, turbine blades, combustion chambers, and lubrication systems. Maintenance complexity increases further in compact UAV platforms

because the engine is frequently deeply integrated within the fuselage, complicating accessibility and component replacement procedures. Consequently, propulsion maintainability has become an increasingly important consideration during UAV system design, particularly for modular UAV platforms intended for rapid field servicing.

Representative maintenance and reliability monitoring approaches used in turbine-powered UAVs are illustrated in Figure 6 and described per component in Table 7, including vibration-based diagnostics, thermal monitoring, exhaust gas analysis, and structural health monitoring systems integrated with onboard telemetry architectures. Modern turbine-powered UAVs increasingly rely on predictive maintenance strategies capable of identifying early-stage component degradation before critical failure occurs. Such approaches frequently incorporate real-time sensor networks, machine learning algorithms, and digital twin models capable of continuously evaluating engine health and estimating remaining useful life.

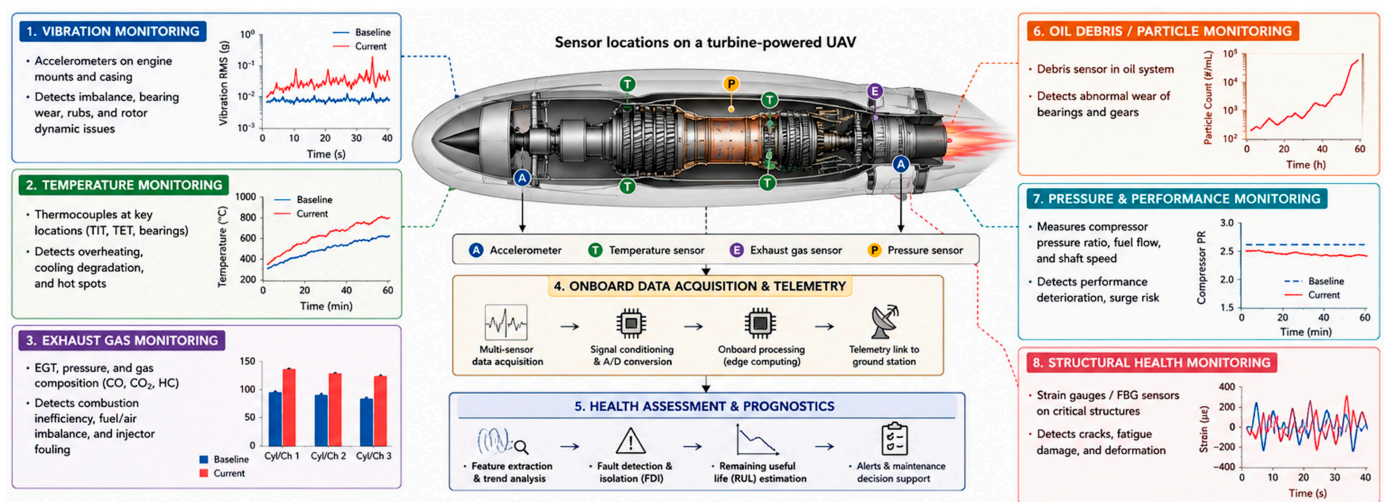


Figure 6. Representative maintenance and reliability monitoring approaches used in turbine-powered UAVs, illustrating integrated propulsion health-management architectures and sensor-based diagnostic methodologies.

The reliability monitoring methods summarized in Table 8 provide an overview of the principal sensing approaches used to assess the condition of turbine-powered UAV propulsion systems. While the table categorizes these techniques according to their monitoring objectives and capabilities, Figure 6 complements this information by illustrating the typical placement of the corresponding sensors within a representative turbine-powered UAV architecture. Together, the table and figure provide both a functional and spatial perspective on health monitoring and diagnostic system integration.

The growing integration of autonomous operational capabilities further increases the importance of propulsion reliability. Future unmanned systems may be required to perform long-duration missions with minimal human supervision, demanding propulsion architectures capable of sustained operation under highly variable environmental conditions. Consequently, reliability-centered design approaches increasingly emphasize fault tolerance, redundancy, adaptive control systems, and self-monitoring capabilities capable of maintaining propulsion functionality even under degraded operating conditions.

Unlike conventional aero-engines, ultra-micro gas turbines operate under significantly different scaling constraints that strongly influence failure mechanisms and reliability. The extremely high rotational speeds, often exceeding several hundred thousand revolutions per minute, increase the sensitivity of the rotating assembly to manufacturing tolerances, rotor imbalance, and bearing clearances. Consequently, geometric deviations that would be

negligible in larger engines may produce substantial increases in vibration levels, bearing loads, and shaft dynamic instabilities in miniature turbomachinery.

Table 8. Reliability issues, monitoring methods, and maintenance strategies for turbine-powered UAV propulsion systems.

Component/ System	Typical Reliability Issues	Primary Causes	Key Monitoring Methods	Mitigation Strategies	Typical Maintenance Actions
Compressor	Blade erosion, fouling, surge, rotor imbalance	Foreign object ingestion (FOD), dust, icing, rotor imbalance	Vibration monitoring, pressure monitoring, compressor performance mapping	Inlet filtration, anti-erosion coatings, surge control, balance correction	Borescope inspection, blade cleaning, rotor balancing, blade replacement
Combustor/ Injector	Combustion instability, injector coking, liner cracking	Fuel contamination, poor atomization, thermal fatigue	Exhaust gas temperature (EGT), exhaust gas composition monitoring, temperature sensing	Fuel filtration, optimized fuel-air control, improved liner cooling	Injector cleaning/testing, liner inspection, combustor replacement
Turbine	Blade creep, oxidation, thermal fatigue	High turbine inlet temperature, insufficient cooling, overspeed	Temperature monitoring, vibration monitoring, EGT margin tracking	Thermal barrier coatings, cooling optimization, advanced material selection	Borescope inspection, blade replacement, coating renewal
Bearings/Shaft System	Bearing wear, lubrication failure, shaft imbalance	High rotational speed, lubricant degradation, contamination	Vibration analysis, oil debris monitoring, temperature sensing	High-quality lubrication systems, oil filtration, magnetic/air bearings	Oil replacement, bearing inspection, shaft alignment verification
Fuel System	Fuel leakage, unstable fuel flow, vapor lock	Contaminants, seal degradation, pressure fluctuations	Pressure monitoring, flow-rate monitoring, EGT analysis	Leak-proof design, pressure regulation, redundant filtration	Filter replacement, leak inspection, fuel-line cleaning
Control Elec- tronics/ECU	Sensor drift, ECU malfunction, signal noise	Thermal cycling, vibration exposure, electrical interference	System diagnostics, telemetry monitoring, redundant sensor validation	Sensor redundancy, shielding, health-monitoring software	Software update, sensor recalibration, ECU replacement
Structure/Engine Mounts	Fatigue cracking, loosening, resonance damage	Vibration loading, maneuver loads, thermal cycling	Structural health monitoring (SHM), strain gauges, accelerometers	Vibration isolation, damping materials, reinforced mount structures	NDT inspection, fastener replacement, structural repair
Exhaust System	Thermal cracking, deformation, IR signature increase	High exhaust temperature, thermal fatigue, oxidation	Thermal imaging, temperature sensors, structural monitoring	Heat shielding, thermal coatings, exhaust cooling/mixing	Exhaust inspection, coating repair, nozzle replacement
Intake System	Flow distortion, pressure loss, FOD damage	Aggressive maneuvers, crossflow, debris ingestion	Pressure contour analysis, airflow monitoring, vibration sensing	Optimized intake geometry, debris protection, boundary-layer management	Intake cleaning, inspection for erosion/damage
Payload Isolation System	Sensor vibration degradation, image instability	Engine vibration transmission, structural resonance	Accelerometers, optical stabilization feedback	Elastomeric isolators, tuned dampers, active stabilization	Isolation mount replacement, recalibration of payload systems

Scaling effects also influence the evolution of several degradation mechanisms. Bearing wear is accelerated by the combined action of high rotational speed and elevated thermal loading, while the reduced Reynolds number characteristic of miniature compressors decreases aerodynamic stability margins and increases susceptibility to rotating stall and surge under distorted inlet conditions. Furthermore, the compact configuration of micro gas turbines promotes thermal soak-back from the turbine to adjacent components, increasing the risk of thermal creep and long-term material degradation in high-temperature regions. These coupled phenomena highlight that reliability assessment methodologies developed for large aero-engines cannot be directly transferred to ultra-micro turbine systems without accounting for scale-dependent aerodynamic, structural, and thermal effects.

Overall, reliability and maintenance remain major factors influencing the operational viability and lifecycle economics of turbine-powered UAVs. Future advancements will likely focus on predictive maintenance technologies, additive-manufactured durable components, advanced bearing systems, autonomous health-monitoring architectures, and modular propulsion designs intended to reduce maintenance burden while improving long-term operational reliability in increasingly demanding unmanned mission environments.

9. Future UAV Integration Trends

Future UAV development is increasingly driven by deep system-level integration, where propulsion, airframe design, energy management, and autonomy are no longer treated as independent disciplines but as tightly coupled subsystems. This shift is particularly evident in the evolution of advanced UCAV and UAV platforms, where operational requirement, mission complexity, and modern command-and-control architectures demand highly adaptive and multi-functional systems. In this context, recent studies highlight that next-generation UCAVs must integrate stealth, performance, and autonomy at the system level, while also addressing challenges related to airworthiness, navigation, and operational constraints [15].

A major direction in this evolution is the integration of stealth-oriented propulsion concepts aimed at reducing detectability through multiple mechanisms, including embedded engine architectures, exhaust shielding, and thermal signature management. Beyond classical airframe shaping, propulsion integration now plays a central role in minimizing both infrared and radar signatures. Recent optimization frameworks demonstrate that combining multi-fidelity infrared and radar cross-section (RCS) models with machine-learning-based surrogate models and Bayesian optimization can significantly improve stealth performance while reducing computational cost. Such approaches have achieved notable reductions in both IR and RCS signatures, confirming the effectiveness of integrated propulsion–stealth design methodologies for future UCAV applications [96].

In parallel, boundary-layer ingestion (BLI) and closely related propulsion–airframe integration concepts are gaining increasing attention due to their potential to improve aerodynamic efficiency while also influencing observability characteristics. BLI reduces propulsive power demand primarily by lowering jet kinetic energy and reducing jet mixing losses, while also benefiting from wake recovery effects and reduced nacelle drag through embedded integration. However, these benefits are strongly configuration-dependent, as performance gains vary with ingested boundary-layer fraction and propulsor mass flow. For representative transport configurations, studies indicate that power reductions of approximately 9% are achievable, consistent with both computational and experimental validation [97]. When combined with distributed propulsion in blended-wing-body (BWB) UAV configurations, DP–BLI integration has been shown to preserve aerodynamic efficiency while providing additional power savings and maintaining propulsive efficiency above 80%, contributing to improved endurance and overall performance [98].

Another key trend is distributed propulsion, where thrust is generated by multiple smaller propulsors rather than a few centralized engines. This architecture enables improved lift augmentation, enhanced control authority, and new airframe integration possibilities, particularly for blended or wing-body UAV configurations. Electrically driven distributed fans allow flexible placement across the airframe and enable fine thrust modulation, but they also introduce significant integration challenges related to electrical power distribution, redundancy management, and control synchronization. These challenges make advanced flight control systems and energy management strategies essential for ensuring stable and efficient operation.

More broadly, distributed propulsion systems have been shown to improve fuel efficiency, reduce emissions, and shorten take-off distances through strong aero-propulsive coupling enabled by modern design tools, materials, and control systems. Hybrid-electric integration further extends these benefits by allowing gas turbines and electric motors to operate in complementary regimes, improving system efficiency and enabling more flexible propulsion layouts. In such configurations, propulsion elements can also contribute to stability and control augmentation, making digital control and engine health management critical components of system design. At the same time, these architectures introduce additional complexity in aeroelastic behavior, certification, and system integration [99].

A related paradigm shift is the emergence of swarm UAV systems, where multiple low-cost UAVs operate cooperatively as a distributed network rather than as individual high-performance platforms. In such systems, propulsion units are typically simplified to enable mass production, affordability, and rapid deployment. The effectiveness of swarm systems relies heavily on decentralized control, inter-vehicle communication, and adaptive coordination strategies, where each UAV adjusts its behavior based on local information and global mission objectives. This distributed operational concept emphasizes resilience, scalability, and redundancy over individual platform performance.

Closely related to this is the emerging concept of expendable propulsion systems, particularly in loitering munitions and disposable UAV platforms. These engines are designed for limited operational life, prioritizing cost reduction, simplicity, and mission-specific performance over durability and long-term efficiency. Additive manufacturing and simplified turbomachinery or piston engine designs are increasingly used to reduce production complexity and cost. The integration challenge in this case lies in ensuring sufficient reliability for mission completion while maintaining extremely low unit cost, as well as managing predictable performance degradation over a controlled operational lifespan.

Hybrid-electric propulsion represents another major integration trend, combining internal combustion engines with electric propulsion systems to improve efficiency, flexibility, and mission endurance. In series and parallel hybrid configurations, combustion engines can be optimized for steady-state operation, while electric motors handle transient loads or distributed thrust requirements. This approach is particularly relevant for medium- and long-endurance UAVs, where energy efficiency is critical. Hybrid-electric systems also contribute to reduced acoustic and thermal signatures, indirectly supporting stealth objectives, although they introduce challenges related to battery energy density, thermal management, and system weight. Studies show that such architectures are expected to play a key role in both UAV and regional aircraft development, particularly when combined with distributed propulsion and boundary-layer ingestion concepts [100]. Even at small UAV scale, hybrid-electric configurations demonstrate clear trade-offs between endurance and detectability, where combining combustion and electric power sources enables improved endurance while maintaining reduced acoustic and visual signatures compared to conventional solutions [101].

Overall, across all these emerging directions, a common trend is the increasing complexity of integration. Propulsion systems can no longer be designed independently of aerodynamics, structures, energy systems, and control architecture. The transition toward distributed, hybrid-electric, stealth-optimized, and swarm-enabled UAV systems requires multidisciplinary design optimization supported by high-fidelity simulation tools, digital twins, and advanced control strategies. Consequently, future UAV performance will be defined less by isolated subsystem metrics and more by the effectiveness of integrated, adaptive system-level design.

10. Conclusions

Turbine-powered UAVs offer a viable solution for missions that exceed the capabilities of battery-electric and conventional piston-engine platforms, particularly where high speed, extended endurance, and increased payload capacity are required. However, the literature consistently demonstrates that propulsion performance cannot be considered independently of the surrounding airframe. Successful implementation depends on achieving an integrated balance between propulsion, aerodynamics, structures, thermal management, fuel systems, and mission requirements.

This review shows that propulsion architecture should be selected according to the intended operational profile rather than pursuing a universal solution. Turboprops remain advantageous for long-endurance missions, and turbojets are appropriate for high-speed applications, while hybrid-electric architectures are emerging as promising alternatives for platforms requiring multiple operating modes, such as VTOL and distributed-propulsion UAVs. At the same time, integration challenges—including heat dissipation, inlet and exhaust design, vibration control, fuel packaging, and signature reduction—remain the primary barriers to wider adoption of turbine propulsion in compact UAVs.

The analysis also identifies several research priorities that are insufficiently addressed in the current literature. Future work should focus on integrated multidisciplinary design methodologies, experimental validation of hybrid propulsion architectures, advanced thermal-management strategies, lightweight high-temperature materials, and AI-assisted system optimization capable of simultaneously considering aerodynamic, structural, thermal, and operational constraints. Progress in these areas will be essential for translating advances in turbine technology into practical, reliable, and mission-adaptive UAV platforms.

Based on the reviewed literature, future advances in turbine-powered UAVs are expected to rely less on incremental improvements to individual subsystems and increasingly on integrated multidisciplinary design approaches. Rather than optimizing propulsion, structures, thermal management, or operational performance independently, future research should focus on simultaneously addressing these strongly coupled disciplines within unified design frameworks. Hybrid-electric propulsion, advanced lightweight materials, additive manufacturing, and AI-assisted multidisciplinary optimization are likely to play a central role in achieving this objective. However, despite substantial progress in numerical modelling, experimental validation of fully integrated turbine-powered UAV platforms remains limited. Closing this gap will be essential for translating emerging technologies into reliable operational systems.

Author Contributions: Conceptualization, E.G.P. and R.A.R.; methodology, O.D.; validation, E.G.P.; investigation, E.G.P., O.D. and R.A.R.; resources, R.A.R.; data curation, E.G.P.; writing—original draft preparation, R.A.R., E.G.P. and O.D.; writing—review and editing, O.D. All authors have read and agreed to the published version of the manuscript.

Funding: This work was carried out through the “Nucleu” Program, part of the National Plan for Research, Development and Innovation 2022–2027, supported by the Romanian Ministry of Research, Innovation and Digitalization, project number PN23.12.06.02.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: All generated data is contained in the article or available by request.

DURC Statement: This review is limited to the field of aerospace propulsion integration and focuses on the engineering challenges associated with turbine-powered unmanned aerial vehicles, including thermal management, structural integration, vibration mitigation, acoustic emissions, fuel storage, and hybrid-electric propulsion architectures. The objective of this work is to support the development of safer, more efficient, and more reliable unmanned systems for civilian, scientific, industrial, environmental monitoring, infrastructure inspection, emergency response, and research applications. The authors acknowledge that unmanned aerial vehicle technologies may possess dual-use characteristics and could potentially be employed in both civilian and governmental contexts. However, the present study does not provide operational procedures, weaponization methodologies, manufacturing instructions, or technical guidance intended to enhance capabilities. All information presented is derived from publicly available scientific literature and is discussed exclusively from an engineering and research perspective. The authors confirm adherence to relevant national and international ethical standards concerning dual-use research and advocate for responsible development, regulatory compliance, transparency, and ethical deployment of UAV technologies to maximize societal benefits while minimizing the risk of misuse.

Acknowledgments: During the preparation of this manuscript, the author(s) used ChatGPT 5.1 for the purposes of deep search and language improvement. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

A2/AD	Anti-Access/Area-Denial
AIP	Aerodynamic Interface Plane
AI	Artificial Intelligence
BTMS	Battery Thermal Management System
CFD	Computational Fluid Dynamics
CG	Center of Gravity
CMC	Ceramic Matrix Composite
EO	Electro-Optical
FEA	Finite Element Analysis
GNSS	Global Navigation Satellite System
HALE	High-Altitude Long-Endurance
ICE	Internal Combustion Engine
IFSD	In-Flight Shutdown
IR	Infrared
ISR	Intelligence, Surveillance, and Reconnaissance
MALE	Medium-Altitude Long-Endurance
MDO	Multidisciplinary Design Optimization
MEM	Multi-Energy Microgrid
MGT	Micro Gas Turbine

RCS	Radar Cross Section
RPM	Revolutions Per Minute
SAR	Synthetic Aperture Radar
SiC	Silicon Carbide
Si ₃ N ₄	Silicon Nitride
TES	Thermal Energy Storage
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UMGT	Ultra-Micro Gas Turbine
VTOL	Vertical Take-Off and Landing

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