

Optimizing the Design of Unmanned Aerial Vehicles for High Performance in Defence Applications

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ABSTRACT: This paper investigates energy-efficient design strategies for high-altitude, high-endurance unmanned aerial vehicles (UAVs). Key factors affecting UAV performance were studied and analyzed, including aerodynamic optimization, propulsion systems, and advanced energy storage technologies. The study highlighted the importance of aerodynamic design principles, such as wing optimization and drag reduction, along with the use of lightweight materials, such as carbon fibre reinforced polymers (CFRP), to enhance UAV performance. Various propulsion technologies, including solar-electric, hydrogen fuel cells and hybrid systems, were examined for their potential to maximize energy use and minimize environmental impact. The paper also discussed the integration of advanced battery technologies and energy management systems to improve operational autonomy. In addition, four flyover studies were analyzed to better understand the theoretical framework. The paper concluded with insights into future trends, such as solid-state batteries and additive manufacturing, that are shaping the next generation of energy-efficient UAVs.

KEYWORDS: Unmanned aerial vehicles, UAV, Energy management, Optimization, High performance, Additive manufacturing.

I. INTRODUCTION

The rapid development of unmanned aerial vehicles (UAVs) has significantly impacted various sectors, including military operations, surveillance, environmental monitoring, and more. UAVs, especially those designed for high-altitude, long-endurance (HALE) missions, offer unparalleled capabilities for extended operations in

diverse environments. These UAVs are capable of sustained flights at high altitudes, making them ideal for applications such as border surveillance, forest monitoring, and scientific data collection. However, the effectiveness of HALE UAVs depends largely on innovative design strategies that improve their aerodynamic performance, propulsion systems, energy storage, and overall operational efficiency. Given the increasing demand for UAVs to undertake complex tasks with minimal energy consumption, exploring energy-efficient design strategies becomes crucial. These strategies include optimizing aerodynamic design, propulsion technologies, energy storage systems, and the use of lightweight materials, with the aim of achieving longer flight duration and higher UAV payload capacity [1].

The purpose of this paper is to explore energy-efficient design strategies for HALE UAVs. The focus is on providing a comprehensive analysis of the key factors affecting UAV performance, including aerodynamic principles, wing design optimization, propulsion systems, and advanced energy storage technologies. By examining current developments in these areas, this paper aims to highlight the importance of an integrated design approach that not only improves the operational performance of UAVs but also extends their mission capabilities. Furthermore, this study delves into the latest technological innovations, such as the integration of lightweight materials and hybrid propulsion systems, to demonstrate their potential to enhance the endurance and performance of HALE UAVs.

II. BACKGROUND

Four cases of successful HALE UAV applications are presented to provide real-world examples of these design principles in practice, thus delimiting the relevant operational framework. These HALE UAVs are the:

- Northrop Grumman's RQ-4 Global Hawk,
- Airbus Zephyr,
- Orion by Aurora Flight Sciences,
- Scaled Composites Proteus.

The following sections integrate these design elements, presenting a holistic view of the design of energy-efficient HALE UAVs, capable of performing long-duration, high-altitude missions. Their common features include the operational space and mode, the structural design and materials, the variety of payloads, the performance of engines, and the flexibility of missions.

All four HALE UAVs have the ability to fly at high stratospheric altitudes, from 30,000 to 70,000 ft., therefore flying above commercial air traffic and weather systems. They avoid so the turbulence that typically increases fuel consumption and emissions in manned aircrafts, thereby improving their fuel efficiency that permits an extended endurance, from 30 to 120 hours, covering so very wide operation areas [2]. Especially Airbus Zephyr can remain airborne for several weeks, using solar panels embedded in its wings to power its electric motors during the day and charge its batteries for nighttime flight [3]. Their flight endurance reduces the need for multiple takeoffs and landings, avoiding the resource-intensive logistical infrastructure, typically associated with manned aircraft operations, minimizing fuel consumption and related emissions, as well as reducing aircraft wear and tear [4].

The common structural features of the above HALE UAVs include the usage of a combination of advanced composite materials, like carbon fiber, fiberglass and high-strength alloys. These materials are selected for their high strength-to-weight ratio, which significantly reduces the overall mass of the UAV and contribute to their lightweight yet durable structure [5]. Additionally, these materials are chosen for their resistance to harsh conditions, such as ultraviolet radiation or corrosion, which can cause significant damage to conventional materials. This durability reduces the need for frequent maintenance and repairs, thus extending the UAV's lifespan, ensuring longevity, minimizing waste and resource use during their operational life [6]. Operating in the stratosphere, where air resistance is lower, the HALE UAVs

maximize the lift-to-drag ratio, reducing the energy required to maintain flight and extending their operational range. This lightweight construction not only improves the aerodynamic design and therefore performance, by optimizing the lift-to-drag ratio and reducing drag, but also increases their payload capacity. The HALE UAVs' modular design is one of their most important features, allowing them to accommodate a wide range of payloads, such as radar, infrared sensors, monitoring equipment and high-resolution cameras, without requiring structural modifications. This modular structure is consistent with the principles of sustainable design, where adaptability and multi-functionality are key to extending the life cycle of UAVs. They can be equipped with various equipment, allowing them to seamlessly transition between different mission profiles [7]. This adaptability reduces the need for multiple specialized UAVs, increases the operational flexibility, thus saving materials and facilitating the production and deployment of multiple aerial platforms [8].

Regarding the UAV's propulsion systems, they incorporate energy-efficient technologies and noise reduction measures, ensure that emissions are maintained low during extended operations, exhibit low-energy operation by using highly efficient motors that consume minimal energy, further extending their endurance. The engines are equipped with advanced energy management systems that adjust consumption based on the UAVs' flight profiles, ensuring optimal performance throughout the mission [9].

Finally, the UAVs' ability to conduct persistent surveillance means that fewer manned flights are required for surveillance operations [10].

III. CONSTRUCTION

The optimization of UAVs for high performance on the topic of construction regards mainly the issues of materials used and the aerodynamic design.

Materials

The use of lightweight materials in the construction of UAVs is a critical aspect that significantly affects their performance, efficiency and operational capabilities. UAVs, which are commonly used for various applications including military, surveillance and environmental monitoring, benefit greatly from the incorporation of advanced composite materials. These materials offer a unique combination of properties such as high strength, low weight and excellent durability, making them ideal for aerospace applications.

One of the main materials used in UAV construction is the carbon fiber reinforced polymer (CFRP). CFRP is preferred for its superior strength-to-weight ratio, compared to traditional materials such as aluminum and steel. This high strength and low weight are particularly beneficial for UAVs, as they allow for longer flight times, higher payload capacities, and improved maneuverability. Incorporating carbon fiber composites into UAVs not only improves their structural integrity, but also their thermomechanical properties, which are crucial for maintaining performance under varying environmental conditions [11].

The vacuum forming technique is commonly used to manufacture these composites. This process involves placing carbon fibers in a mold and then impregnating them with epoxy resin. It is then sealed in a vacuum bag and cured, which helps achieve optimal resin distribution and minimize voids within the composite structure. This method is efficient and cost-effective, making it suitable for producing high-quality UAV components. The resulting composites exhibit remarkable tensile and flexural strengths, making them ideal for applications where both light weight and high strength are required.

Another important advantage of using lightweight materials such as CFRP in UAVs is the reduction of fuel consumption. Since UAVs are often powered by electric batteries or small motors, reducing the overall weight can lead to a significant improvement in energy efficiency. This efficiency translates into longer mission duration and the ability to carry additional equipment or sensors without compromising performance. It is emphasized that the use of advanced composite materials allows UAVs to achieve better energy efficiency, thus extending their operational range and effectiveness [12].

Furthermore, the advent of additive manufacturing (AM) has revolutionized the production of UAV components. AM, also known as 3D printing, allows the creation of complex structures that are difficult or impossible to achieve with traditional manufacturing methods. This capability is particularly useful for producing lightweight and complex designs that can improve the aerodynamic performance and overall performance of UAVs. It is noted that AM allows for the direct fabrication of complex internal structures without the need for molds, which is a significant advantage for the construction of lightweight UAVs [13].

The ability to print UAV parts using AM also enables rapid prototyping and iterative design,

which can speed up the development process and reduce costs. For example, by using fused deposition modelling (FDM) and selective laser sintering (SLS), researchers can quickly produce and test different UAV designs to optimize their performance. This flexibility in design and production is a key factor in the increasing adoption of AM in the aerospace industry.

In conclusion, the use of lightweight materials, such as carbon fibre reinforced polymers, and advances in additive manufacturing techniques, are crucial to enhancing the performance, efficiency, and capabilities of UAVs. These materials and methods provide significant benefits, including improved structural strength, reduced fuel consumption, and the ability to produce complex and optimized designs. As technology continues to evolve, the role of lightweight materials and additive manufacturing in UAV construction will likely expand, leading to even more advanced and capable unmanned aerial systems.

Aerodynamics

Reducing aerodynamic drag is crucial for improving aircraft performance and efficiency. Several techniques, both passive and active, have been developed and tested to minimize drag forces on various aircraft components. Natural laminar flow (NLF) airfoils are designed to delay the boundary layer transition from laminar to turbulent flow, significantly reducing skin drag. These airfoils can increase the laminar area over the wing by up to 60% of the chord length, which reduces drag at low angles of attack [14]. Riblets, i.e., micro-cavities aligned with the flow direction, are another passive technique known to reduce turbulent skin drag by altering the boundary layer characteristics in the near-wall region. Laboratory conditions have shown that riblets can achieve a drag reduction of 8-10% [15]. They are particularly effective when applied in locations such as the main wing, fuselage and nose, where the boundary layer transits from laminar to turbulent flow [16].

Active flow control techniques include high-lift devices, such as flaps or tail fins, which enhance lift production and maximum lift coefficient. These devices slow the stalled aircraft and reduce the need for low wing loading during takeoff and landing, although they come with significant weight penalties. Variable Camber (VC) systems, which use tail fins to adjust the pressure distribution of the aerofoil or wing, optimize aerodynamic performance for off-design conditions. This system can improve the lift-to-drag ratio by 2-3% during cruising conditions, but

is less suitable for medium-sized UAVs due to weight [14].

Winglets are widely used in aircraft design to mitigate the effect of wingtip turbines, thereby reducing induced drag. Winglets can provide significant improvements in aerodynamic performance, especially for UAVs where induced drag plays a dominant role due to higher wingtip loading and limited wing span. Optimized winglets can lead to a reduction in overall drag of more than 10%, although their geometry must be carefully designed and tested [16]. Another technique involves drag-reducing paints applied to the aircraft surface to interact with the flow and reduce frictional drag. However, their performance may deteriorate over time and they currently have a low level of technological readiness [14].

The rheological modification of the fuselage shape can reduce its contribution to drag by about 10-15% of the total drag force. This often requires complex shapes that can be addressed with advanced composite materials and modern manufacturing techniques. The front wing and other components, such as camera gimbals and cooling systems, also contribute to the total drag. Optimization of these components through design changes and aerodynamic improvements can further reduce the total drag [14]. In addition, drag reduction with riblets has been tested specifically on a low-speed, fixed-wing UAV. The results showed that riblets applied to various parts of the aircraft surface can lead to a significant reduction in drag. For example, covering the upper surface of the wing with riblets achieved a reduction in overall drag of 1.7% with only 29% surface coverage, reinforcing the cost-benefit ratio of this technique [16].

The effectiveness of riblets on the performance of a medium-altitude, high-endurance (MALE) UAV has also been examined using computational fluid dynamics (CFD) methods. The results showed that riblets applied to specific locations, such as the main wing, fuselage, and nose fin, could provide drag reduction benefits during both stall and cruise flight segments. The drag reduction benefit was clearly demonstrated in the polar drag diagrams of the aircraft, highlighting the potential for increased flight performance in terms of endurance and increased payload weight [15].

These drag reduction techniques collectively aim to improve aircraft performance by reducing fuel consumption and increasing aerodynamic efficiency. While some techniques are already in use, others are still in the research stages, showing promise for future applications in both

manned and unmanned aircraft [9].

IV. PROPULSION

UAVs rely on advanced propulsion systems to sustain flight for extended periods. Various propulsion systems have been explored to meet the unique requirements of HALE UAVs, including internal combustion engines, turbocharging systems, and electric propulsion. In the latter case, the various energy storage systems in UAVs are of great importance.

The motor

One of the most important propulsion systems for UAVs is the hydrogen-fuelled internal combustion engine with a turbocharger system. This system is specifically designed to enhance the engine's performance at high altitudes where air density is significantly lower. The engine uses a series of turbochargers to increase the pressure of the intake air, thereby improving combustion efficiency. Due to the low ignition energy of hydrogen, misfire or pre-ignition can occur; therefore, the fuel-to-air ratio is reduced to avoid these problems. This requires increasing the intake air pressure to approximately 1.7 bar, using a multi-stage turbocharger system with intercoolers to maintain sufficient engine power [9].

Similarly, liquid-cooled turboprop engines have been explored as a propulsion option for UAVs. A spark-ignition engine, combined with a turbocharger system, can be optimized for performance at altitudes ranging from 50,000 to 100,000 feet. The addition of a turboprop power turbine can further improve performance by reducing brake specific fuel consumption (BSFC). This type of propulsion system offers significant endurance and altitude performance, having set records for long-endurance flight [17].

On the other hand, solar-electric propulsion is another viable option, especially for missions requiring long-duration. Solar UAVs incorporate motor-propeller propulsion systems powered by solar energy collected during the day. This energy is stored and then used during night flights. The integration of distributed propulsion systems along the large wingspan of the UAVs can alter the stability of the aircraft and requires careful adjustment to optimize flight quality and system efficiency [18].

Another emerging technology is the use of hybrid solid oxide fuel cell/gas turbine systems. This hybrid approach aims to increase overall efficiency and reduce fuel consumption, which is crucial to achieving the one-week endurance target for HALE UAVs. Configuring the fuel cell

capacity in discrete stacks, with a parallel fuel distribution system and in-series air supply, can improve system efficiency. For such systems operating on hydrogen, efficiencies of up to 66.3% (lower calorific value) have been predicted [19].

Finally, electric propulsion systems are also gaining ground, especially with advances in battery and high-power density motor technology. These systems offer the potential for quieter operation and reduced maintenance costs. However, they are often limited by current energy storage technologies, which limit the endurance of UAVs [20].

Energy efficiency

Energy-efficient propulsion technologies are crucial for the performance and endurance of UAVs. These technologies aim to maximize energy utilization, extend flight time, and reduce environmental impact. Specific energy-efficient propulsion technologies and their analyses based on research findings are presented below.

Solar-electric propulsion: Solar-electric propulsion systems use solar panels to collect solar energy, which is then stored in batteries or used directly to power the UAV's electric motors. This technology is particularly well-suited for HALE UAVs, as they operate at high altitudes, receiving abundant sunlight. A study investigated the energy management of solar-powered HALE UAVs, focusing on energy balance mechanisms during daytime and nighttime operations. By integrating solar cells with regenerative fuel cells, the energy collected during the day can be stored and used at night, ensuring continuous operation [21].

Hybrid propulsion systems: Hybrid propulsion systems combine internal combustion engines with electric propulsion to improve energy efficiency and reduce fuel consumption. In evaluating hybrid propulsion and energy harvesting systems for UAVs, researchers at the University of Victoria Centre for Aerospace Research (UVIC-CfAR) demonstrated that hybrid systems can achieve increased endurance by capturing and utilizing thermal energy from exhaust gases [22]. This approach provides the advantage of distributed propulsion and redundancy, which is crucial for mission-critical UAVs.

Hybrid Solid Oxide Fuel Cell (SOFC) and Gas Turbine Systems: Solid oxide fuel cells (SOFC) combined with gas turbines represent another energy-efficient propulsion option. These systems generate electricity through the chemical reaction of hydrogen and oxygen, offering higher efficiency and lower emissions compared to traditional propulsion systems. Researchers have

analyzed such systems for HALE UAVs, achieving an overall system efficiency of 66.3% (LHV) when operating on hydrogen. By modularizing the fuel cell capacity and parallel fuel distribution, this technology can significantly extend the endurance of UAVs [19].

Turbocharging systems: Turbocharging systems are designed to improve the performance of internal combustion engines at high altitudes. In a study focused on the HALE UAV, a hydrogen-fueled internal combustion engine was used with a series of turbochargers to boost the intake air pressure to the required level for efficient combustion. The system uses multiple turbochargers with intercoolers, ensuring efficient engine performance at altitudes where air density is low [23].

Distributed electric propulsion: Distributed electric propulsion involves the use of multiple electric motors distributed along the wings or body of the UAV. This configuration improves flight performance and energy conversion by enabling optimized power distribution and reducing aerodynamic drag. A study on distributed electric propulsion for UAVs with a fuel cell and electrical storage system demonstrated an increase in flight endurance and a reduction in noise, providing an emission-free propulsion solution [24].

In conclusion, energy-efficient propulsion technologies for UAVs include solar-electric, hybrid propulsion, hybrid fuel cell systems, turbocharging systems, and distributed electric propulsion. These technologies aim to maximize energy usage and extend the lifespan of UAVs.

Hybrid Systems

Hybrid propulsion systems for HALE UAVs combine the advantages of different power sources, such as internal combustion engines, electric motors, fuel cells and solar energy. These systems are designed to optimize energy efficiency, reduce emissions and extend the operational range and endurance of UAVs.

Parallel and series hybrid-electric propulsion: Hybrid-electric propulsion systems combine internal combustion engines (ICEs) with electric motors in either a parallel or series configuration. In a parallel configuration, both the IC and the electric motor can drive the propeller simultaneously, allowing the system to switch between the power sources or use both depending on the phase of flight. Researchers tested a parallel hybrid-electric propulsion system that combined a 28 cc two-stroke IC with a 200-Watt generator. The results showed that this configuration offers lower specific fuel consumption and promotes stable

operation with reduced vibrations [25]. In a series hybrid configuration, the ICE powers a generator, which then charges the batteries or directly powers the electric motor. This arrangement provides flexibility in power management and can be optimized for different flight phases. Related research demonstrated the effectiveness of a parallel hybrid-electric propulsion system for small fixed-wing UAVs. Their study incorporated an ideal operating line (IOL) control strategy, achieving a fuel saving of 6.5% compared to a motor-only configuration [26].

Hybrid Fuel Cell Propulsion: Hybrid fuel cell propulsion systems use fuel cells, such as polymer electrolyte membrane fuel cells (PEMFCs), in combination with batteries or supercapacitors. Fuel cells provide high energy density, while batteries offer high power density for peak power requirements. Researchers examined hybrid fuel cell propulsion systems for UAVs, emphasizing the integration of fuel cells with other energy sources to extend flight duration and improve fuel economy. The study highlighted the need for effective energy management strategies to optimize the performance of these systems [27].

Hybrid propulsion for multimodal UAVs: Hybrid propulsion systems can also be adapted for multimodal UAVs that can operate in different environments, such as air and water. Researchers developed an integrated hybrid propulsion system for a multimodal UAV, designed for aerial and aquatic operations. The system featured hybrid propellers optimized for both aerial and underwater propulsion, demonstrating the versatility of hybrid systems for various mission profiles [28].

Advantages and challenges: Hybrid propulsion systems offer several advantages, such as increased flight endurance, reduced fuel consumption, and lower noise emissions. They provide flexibility in power management and the ability to switch between power sources depending on mission requirements. However, the complexity of hybrid systems requires sophisticated control strategies for power distribution and energy management. In addition, the integration of different power sources requires careful design to balance weight and optimize performance.

In conclusion, hybrid propulsion systems for HALE UAVs leverage the advantages of multiple energy sources, enhancing energy efficiency and operational capabilities. By combining technologies such as solar energy, internal combustion engines, electric motors and fuel cells, these systems allow UAVs to achieve longer flight durations with improved performance.

Energy Storage

Energy storage is crucial for UAVs, as it directly affects their flight endurance, operational capabilities, and ability to sustain flight during periods when solar or primary energy sources are unavailable. Efficient energy storage systems enhance the autonomy of these UAVs, making them suitable for long-duration missions, especially in remote or harsh environments.

Solar energy storage systems: Solar energy is a primary power source for many UAVs, especially those designed for extended missions. The energy harnessed by the solar panels is stored in batteries or fuel cells to sustain flight during nighttime or low-light conditions. One study highlighted the importance of energy storage capacity in the size and capabilities of the aircraft. Their analysis showed that energy storage systems, specifically regenerative fuel cells, significantly affect the size and endurance of solar UAVs. They concluded that specific energy storage in the order of 250–500 Wh/kg is required to enable the most useful missions, indicating the critical role of advanced storage systems in UAV performance [28].

Lithium-polymer (LiPo) batteries: The evolution of LiPo batteries has changed the game in UAV development. LiPo batteries offer high energy density and lightweight characteristics, making them ideal for UAV applications where weight is a critical factor. Researchers discussed the impact of LiPo battery energy storage on improving the flight performance of small unmanned aerial systems (UAS). They conducted experiments to measure energy consumption in various flight maneuvers, revealing how energy storage could be optimized to improve flight duration and efficiency. This research highlights the importance of accurate energy consumption modeling for effective autonomous mission design, especially for HALE UAVs [29].

Hybrid energy storage systems: To overcome the limitations of conventional energy storage, hybrid systems have been developed that combine various energy storage technologies, such as batteries, fuel cells, and solar panels. Researchers proposed a hybrid energy storage system for UAVs that includes photovoltaic panels, rechargeable fuel cells, and batteries. This combination allows the UAV to harness solar energy during the day and store excess energy for use during periods of low solar radiation, thus achieving great endurance. By integrating multiple energy storage systems, HALE UAVs can effectively manage their energy supply, ensuring continuous operation even under varying

environmental conditions [30].

Reconfigurable energy storage: Innovative energy storage designs, such as the proposed Hydron system, offer reconfigurable architectures that maximize flight time by dynamically managing the power supply based on the UAV's flight patterns. The system uses a minimum capacitance supercapacitor (UC) as an isolator to mitigate power fluctuations and a reinforcement learning-based switch control to select the appropriate operating mode. This approach ensures efficient energy use, extending the UAV's flight time and optimizing battery performance [31].

Structural integration of energy storage: Another approach to enhance energy storage involves integrating it into the UAV structure. Researchers have proposed integrating batteries and thin-film photovoltaics into the aircraft wing structure. This integration not only increases storage capacity but also optimizes weight distribution and structural integrity. By integrating energy storage into the UAV structure, the overall storage capacity can be maximized without significantly affecting the weight and aerodynamics of the UAV [9].

In summary, energy storage is crucial for HALE UAVs, affecting their endurance, operational range and overall efficiency. Advances in battery technology, hybrid systems, reconfigurable storage and structural integration are critical developments that ensure that UAVs can meet the demanding requirements of long-duration missions.

Batteries

Battery technologies are crucial for powering UAVs, offering different trade-offs in terms of energy density, weight, rechargeability, and power output. Various types of batteries have been developed and optimized for UAV applications, each with its own distinct advantages and limitations.

Lithium-ion (Li-ion) batteries: Lithium-ion batteries are among the most widely used power sources for UAVs due to their high energy density, light weight, and relatively long-life cycle. They provide a significant amount of power while maintaining a compact form factor, making them suitable for various UAV applications, from consumer drones to military HALE UAVs. However, one limitation is their relatively low operating range in extreme temperatures, which can reduce flight duration. Advanced battery management systems have been developed to monitor and optimize their performance in UAVs. For example, researchers designed a battery

management system (BMS) to monitor the charging and discharging of lithium-ion batteries in real time for UAVs, improving their operational safety and efficiency [20].

Lithium-polymer (LiPo) batteries: LiPo batteries are a subtype of lithium-ion batteries that have a polymer electrolyte instead of a liquid. This gives them the advantage of being more flexible in shape and size, making them ideal for integration into UAVs, where weight and space constraints are critical. Researchers have investigated the use of LiPo batteries for UAVs, highlighting their potential to provide a purely electric propulsion system for small UAVs. LiPo batteries can provide high discharge rates, which is beneficial for UAVs that require rapid bursts of power during takeoff or maneuvering. However, they also require careful thermal management to avoid overheating and potential safety hazards [32].

Lithium iron phosphate (LiFePO₄) batteries: Lithium iron phosphate batteries are known for their high safety and long life. They offer lower energy density compared to Li-ion and LiPo batteries, but are more stable under different operating conditions, reducing the risk of thermal runaway. This makes them suitable for UAVs used in applications where safety and reliability are of paramount importance, such as military missions or high-risk environmental monitoring missions. They are also more tolerant of overcharging and have a lower self-discharge rate, making them a safer and more durable option for long-duration UAV missions [33].

Lithium-air (Li-air) batteries: Lithium-air batteries are an emerging technology that has the potential to provide significantly higher energy density than traditional lithium-ion batteries. These batteries use oxygen from the air as a reactant, which theoretically allows them to achieve energy density comparable to gasoline. Researchers compared various propulsion options for UAVs, including Li-air batteries. They found that, in theory, Li-air batteries could lead to longer flight times and simpler configurations due to their high energy density. However, the technology is still in an experimental stage, with challenges such as limited recharge cycles and stability issues that need to be addressed before they become viable for UAVs [34].

Nickel-metal hydride (NiMH) batteries: Nickel-metal hydride batteries are another type of rechargeable battery used in UAVs, especially for those requiring moderate energy density and low maintenance. NiMH batteries offer a good balance between energy density, cost, and safety. They do not suffer from the memory effect, which is a

limitation of older nickel-cadmium (NiCd) batteries. Although they have a lower energy density than lithium-ion batteries, they can be more cost-effective and safer to handle, making them a suitable choice for some UAV applications, especially in scenarios where a high power-to-weight ratio is not a primary concern [35].

Solid-state batteries: Solid-state batteries are an emerging technology that promises to offer higher energy density, longer life, and improved safety over current lithium-ion batteries by replacing the liquid electrolyte with a solid one. These batteries have the potential to revolutionize UAV battery technology, enabling longer flight times and faster recharge times. However, they are still in the research and development stage, with challenges such as manufacturing complexity and cost that need to be overcome [36].

In conclusion, the choice of battery technology for UAVs depends on the specific requirements of the application, including energy density, safety, operating temperature range, and cost. Each battery type presents unique advantages and challenges, necessitating careful evaluation to optimize UAV performance for different mission profiles.

Supercapacitors and Fuel Cells

Supercapacitors and fuel cells represent advanced energy storage and power delivery systems with distinct characteristics that make them suitable for specific UAV applications, especially those requiring high endurance and efficiency. Supercapacitors are characterized by their ability to store energy electrostatically rather than through chemical reactions, allowing for rapid charge and discharge cycles. This characteristic makes them ideal for situations where UAVs require a quick burst of energy, such as during takeoff, landing, or sudden maneuvers. Unlike traditional batteries, supercapacitors can withstand more charge and discharge cycles without significant degradation, offering a longer operational lifetime. Researchers have highlighted the importance of using supercapacitors in hybrid power systems, where their high-power density allows them to efficiently handle transient power demands. By absorbing peak loads, supercapacitors can relieve the strain on the main power source, improving the overall efficiency and longevity of the system [37].

Fuel cells, especially polymer electrolyte membrane fuel cells (PEMFCs), have gained attention for their high energy density and ability to provide continuous power for long periods of time. Fuel cells generate electricity through an

electrochemical reaction between hydrogen and oxygen, with water as the only byproduct, making them an environmentally friendly option for UAVs. However, a notable drawback of fuel cells is their relatively slow dynamic response. They cannot adapt quickly to rapid changes in power demand, which can lead to performance problems if not properly managed. To overcome this limitation, researchers have proposed integrating fuel cells with supercapacitors in a hybrid system. In this configuration, the fuel cell serves as the primary power source, providing a constant output, while the supercapacitor acts as an auxiliary source to provide power during sudden peaks in demand. This synergy allows the fuel cell to operate in more stable conditions, reducing mechanical stresses and extending its lifetime [38].

Integrating supercapacitors and fuel cells into a hybrid power system requires careful energy management to optimize the performance of both components. Supercapacitors, with their fast charge-discharge capabilities, can quickly absorb or release energy, thereby balancing the power load on the fuel cell. This feature is particularly beneficial during dynamic flight conditions, where power requirements fluctuate frequently. Researchers conducted an analysis using a hardware-in-the-loop simulator to evaluate a hybrid fuel cell/battery/supercapacitor propulsion system. Their study showed that the supercapacitor effectively balanced the load on the fuel cell, especially in windy flight conditions. By mitigating the impact of rapid load changes, the supercapacitor not only improved the endurance and range of the UAV, but also helped extend the lifespan of the fuel cell by preventing it from being subjected to rapid power fluctuations [39].

Managing the power flow between supercapacitors and fuel cells is crucial to achieving optimal performance. Researchers proposed a control algorithm that regulates the power distribution in a hybrid system, using supercapacitors to regulate the DC bus voltage. This approach allows the supercapacitors to respond quickly to sudden power demands, while ensuring that the fuel cell operates under steady-state conditions. Experimental results validated this control strategy, showing that it enhanced the system performance during load cycling and maintained stable operation. The control algorithm also prevented fuel starvation in the fuel cell, a common problem when the fuel cell is exposed to rapid load changes without sufficient time to adjust its output [37].

One of the main advantages of supercapacitors in a hybrid fuel cell system is their

ability to enhance the overall efficiency of the power source. Supercapacitors can store excess energy produced during periods of low power demand, which can then be used during peak loads. This process reduces the need for the fuel cell to cycle frequently, which is not only more efficient but also reduces wear on the fuel cell, extending its lifespan. Furthermore, the rapid power delivery capability of supercapacitors can be exploited to improve UAV performance during critical flight phases, providing immediate power when needed without waiting for the slower response of the fuel cell. The research highlights the compatibility of supercapacitors with fuel cells, suggesting that this combination can effectively address the challenges of dynamic power requirements in UAV operations [37].

Despite their advantages, integrating supercapacitors with fuel cells presents several challenges, particularly in terms of system design and control. The need for precise energy management strategies is paramount to ensure that the power flow between the supercapacitor and the fuel cell is balanced. If not managed properly, the supercapacitor could either discharge too quickly or not be utilized efficiently, leading to suboptimal system performance. However, when successfully implemented, the combination of supercapacitors and fuel cells can provide a robust power solution for UAVs, capable of handling varying power demands, while maximizing energy efficiency and system longevity. This hybrid approach leverages the advantages of both technologies, with the supercapacitor providing a rapid energy delivery and the fuel cell providing a continuous energy delivery for extended flight operations.

Energy Management

Energy management systems (EMS) in UAVs play a critical role in optimizing the distribution and use of energy across multiple power sources, such as batteries, fuel cells, and solar panels. These systems are designed to efficiently manage the flow of energy, ensuring that UAVs can meet diverse operational requirements while maximizing flight endurance and minimizing fuel consumption.

In hybrid UAVs that combine fuel cells and batteries, the EMS must balance the power provided by each source. A study proposed an online fuzzy power management strategy for a fuel cell/battery power system in UAVs. The system uses a single programmable DC-DC converter to efficiently split the power between the two sources. By adjusting the output current of the fuel cell based on the UAV power demand and the battery

state of charge, the EMS ensures optimal power distribution. This strategy favors the use of battery power during peak loads, thereby reducing the hydrogen consumption of the fuel cell. Experimental results showed that this approach successfully extended the endurance of the UAV while maintaining the health of the battery and fuel cell [40].

For solar-powered UAVs, the EMS must adapt to the fluctuation of energy availability due to changing weather conditions and sunlight intensity. Researchers designed an EMS for a small solar-powered UAV, which operates based on the DC bus voltage value to manage the power flow from the photovoltaic (PV) modules and the storage system. This EMS allows the PV modules to operate in multiple operating modes through a self-adaptive control strategy, coordinating the power distribution to ensure the stable operation of the UAV. The system dynamically adjusts the power distribution between the PV modules and the energy storage system to adapt to rapid atmospheric changes, maintaining a stable power supply for the UAV [41].

Hybrid electric UAVs that integrate solar cells, fuel cells, and batteries require more complex EMSs to manage the interactions between multiple energy sources. In such systems, the EMS typically consists of an upper decision layer and a lower control layer. The upper layer uses model predictive control (MPC) to determine the optimal power allocation among the sources, taking into account factors such as fuel efficiency and battery state of charge. Researchers applied this approach to a hybrid UAV power system. The upper decision layer used the equivalent consumption minimization strategy (ECMS) to optimize hydrogen consumption, while the lower control layer managed the output voltage and current to ensure stable system operation. This hierarchical SMP ensured that power distribution was efficient and that each resource was used responsibly [42].

To further improve UAV performance, some EMSs use intelligent control strategies, such as fuzzy logic or adaptive neuro-fuzzy inference systems (ANFIS). These strategies allow the EMS to adapt to dynamic flight conditions and optimize power flow in real time. Researchers investigated an ANFIS-based EMS for a hybrid fuel cell/battery system in a UAV. This system intelligently adjusted the power distribution according to load changes and battery state of charge, maintaining a constant DC bus voltage. Using a learning algorithm, the EMS continuously optimized its performance, ensuring efficient power management and extending the UAV flight duration [43].

Another key aspect of EMS in UAVs is the control of power converters that interconnect different power sources. EMS often uses bidirectional converters to control the charging and discharging cycles of batteries, ensuring their operation within safe limits. Researchers developed a model-based EMS for a hybrid PEM fuel cell/lithium-ion battery system. This system used an adaptive control algorithm to manage the air supply to the fuel cell, optimizing its performance and extending its lifetime. The EMS regulated the power flow between the fuel cell and the battery in real time, ensuring that the fuel cell operated in its optimal power range, while the battery supplied transient power requirements [44].

Overall, UAV power management systems are integral to ensuring efficient power distribution among various power sources, adapting to dynamic flight conditions, and extending the UAV's operational lifetime. Through advanced control strategies and intelligent algorithms, UAV power management systems can optimize the use of fuel cells, batteries, solar panels, and other power sources to meet the diverse requirements of UAV missions.

V. CONCLUSION

The evolution of unmanned aerial vehicles (UAVs) has brought about significant developments in the design of high-altitude, long-endurance (HALE) UAVs, highlighting the importance of energy-efficient strategies. The detailed analysis in this paper highlights that optimizing aerodynamic design, propulsion systems, and energy storage technologies are crucial to improving the performance and operational efficiency of HALE UAVs. The integration of advanced materials, innovative propulsion technologies, and sophisticated energy management systems has demonstrated the potential to extend the flight duration and increase the payload capacity of these aircraft. By adopting a holistic approach that considers aerodynamics, propulsion, and energy efficiency, UAVs can better meet the demanding requirements of various applications, from environmental monitoring to military surveillance.

Aerodynamic optimization, as discussed, is a fundamental aspect of energy-efficient UAV design. Techniques such as wing design optimization, drag reduction, and the use of lightweight materials play a critical role in enhancing the lift-to-drag ratio, which directly affects the strength and efficiency of the UAV. Advanced materials, such as carbon fiber reinforced polymers (CFRP), offer high strength-

to-weight ratios, helping to reduce weight without compromising structural integrity. In addition, the use of Computational Fluid Dynamics (CFD) simulations has become common practice in the iterative design process, allowing engineers to improve the aerodynamic properties of UAVs to achieve optimal performance in various flight conditions.

The propulsion system is another critical element in the pursuit of energy-efficient UAVs. The exploration of various propulsion types, including solar-electric, hybrid propulsion systems, and hydrogen fuel cells, highlights the need for solutions that maximize energy utilization, while minimizing environmental impact. Solar-electric propulsion, for example, harnesses solar energy to power the UAV, offering a viable option for long-duration missions. Hybrid propulsion systems combine different energy sources, such as internal combustion engines and electric motors, to optimize power and efficiency based on mission requirements. Hydrogen fuel cells, with their high energy density and low emissions, are a promising avenue for enhancing the endurance of HALE UAVs, especially when integrated with advanced power management systems.

Energy storage technologies play a crucial role in ensuring the operational autonomy of HALE UAVs. The development of high-capacity batteries, supercapacitors and regenerative fuel cells has expanded the possibilities of efficient energy storage. Lithium-polymer (LiPo) and lithium-ion (Li-ion) batteries are commonly used in UAVs due to their high energy density and lightweight characteristics. Recent developments in battery technology, such as lithium-sulfur (Li-S) batteries, have shown potential to further improve energy storage capacity. Furthermore, the integration of energy storage into the UAV structure, such as the integration of batteries in the wings, is an example of innovative approaches being explored to maximize energy storage without compromising aerodynamic performance.

The future of UAV design lies in the continued evolution of energy efficiency strategies and the integration of cutting-edge technologies. Future trends in UAV design include the development of more advanced propulsion systems, such as hybrid electric and solar systems, capable of achieving even longer flight durations with minimal environmental impact. Ongoing research into solid-state batteries and hydrogen fuel cells promises significant improvements in energy storage capacity and safety. In addition, the adoption of artificial intelligence (AI) and machine learning algorithms for real-time data processing

and autonomous decision-making will enhance the operational efficiency and adaptability of UAVs in dynamic environments. AI-based flight control systems can optimize flight paths, reduce energy consumption, and enable UAVs to perform complex tasks with greater precision and autonomy. Towards this direction, the inclusion of natural language processing and sequencing capabilities to UAVs may significantly enhance their agility to accomplish demanding operations [45].

Finally, the use of additive manufacturing (3D printing) in UAV construction is expected to revolutionize the design and production processes. This technology allows for the creation of complex, lightweight structures that were previously unattainable with traditional manufacturing methods. Additive manufacturing can also facilitate rapid prototyping and customization, allowing the development of UAVs tailored to specific mission requirements. In addition, the integration of distributed propulsion systems and wing shaping technologies will provide UAVs with improved agility, efficiency, and adaptability to various flight conditions.

In summary, the evolution of energy-efficient strategies for UAV design is poised to continue, driven by advances in propulsion systems, energy storage technologies, and autonomous capabilities. The future of HALE UAVs will be characterized by innovative designs that maximize endurance, operational efficiency, and sustainability. By embracing these emerging technologies and trends, the next generation of UAVs will be well-equipped to meet the growing demands of diverse applications, while minimizing their environmental impact.

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