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Sistema de gestión de energía para aeronaves híbridas con pila de combustible

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Resumen

Este artículo presenta el diseño, la implementación y la validación experimental del sistema de gestión de energía para un sistema de propulsión híbrido de pilas de combustible y baterías para vehículos aéreos no tripulados (UAV). La integración de pilas de combustible y baterías en sistemas de propulsión de UAV combina la alta energía específica de las pilas de combustible con la alta potencia específica de las baterías, lo que da como resultado una solución energética más eficiente y ligera. Se propone un sistema de gestión de la energía (EMS), para optimizar la distribución de la energía y mejorar el rendimiento global. El montaje experimental incluye un diseño de banco de pruebas equipado con un convertidor CC/CC programable y un gemelo digital para la monitorización en tiempo real y el sistema predictivo de gestión energética. Los resultados experimentales y de simulación demuestran mejoras significativas en la eficiencia energética, la reducción de emisiones y la mejora de la fiabilidad operativa.

Palabras clave: Control óptimo de sistemas híbridos, Aeroespacial, UAVs, Modelado y simulación de sistemas de potencia, Control adaptativo neuronal y difuso, Control basado en datos

Energy Management System for a Hybrid Fuel Cell Unmanned Aerial Vehicle

Abstract

This paper presents the design, implementation, and experimental validation of the energy management system for a hybrid fuel cell and battery powertrain system for unmanned aerial vehicles (UAVs). The integration of fuel cells and batteries in UAV powertrains combines the high specific energy of fuel cells with the high specific power of batteries, resulting in a more efficient and lightweight energy solution. A novel energy management system (EMS), featuring advanced control algorithms such as fuzzy logic, is proposed to optimize energy distribution and enhance overall performance. The experimental setup includes a test-bench design equipped with a programmable DC/DC converter and a digital twin for real-time monitoring and predictive energy management system. Simulation and experimental results demonstrate significant improvements in energy efficiency, reduced emissions, and enhanced operational reliability. This study underscores the potential of hybrid powertrain systems in advancing the sustainability and efficiency of UAV operations.

Keywords: Optimal control of hybrid systems, Aerospace, UAVs, Modeling and simulation of power systems, Neural and fuzzy adaptive control, Data-based control

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1. Introduction

The aviation industry poses a significant environmental challenge due to its substantial contribution to greenhouse gas emissions, primarily carbon dioxide (CO_2). Globally, aviation accounts for approximately 2.8% of CO_2 emissions from fossil fuels and industry (Lee et al., 2021). The sector's emissions have doubled from 0.5 to 1 billion tonnes between 1990 and 2019, highlighting its growing impact on climate change. Along with emitting CO2 from burning fuel, planes also affect the concentration of other atmospheric gases and pollutants. They generate a short-term increase but a long-term decrease in ozone and methane, and increased emissions of water vapor, soot, sulfur aerosols, and water contrails (Lee et al., 2021). While some of these impacts result in warming, others induce a cooling effect. But overall, the warming effect is stronger Lee et al. (2021).

Beyond greenhouse gas emissions, aviation activities have implications for air quality, with pollutants like particulate matter and nitrogen dioxide affecting regional and global air quality (Yim et al., 2015). Noise pollution from aircraft operations, especially near airports, is another environmental concern associated with aviation Basner et al. (2017).

To address these issues, the aviation sector is exploring sustainable solutions such as sustainable aviation fuels (SAF) and advancing technological innovations to enhance operational efficiency and reduce environmental impacts.

Hydrogen fuel cells provide better energy density than batteries, making them a promising alternative for aviation applications (Baroutaji et al., 2019). Fuel cells offer rapid refuelling times, efficient energy conversion, and zero harmful emissions during flight (Staffell et al., 2019). Using fuel cells in aviation can significantly reduce the sector's environmental impact and contribute to decarbonization efforts. Additionally, if green hydrogen (that comes from renewable sources) is used, the net effect is zero.

This paper is structured as follows. Section 2 presents an up-to-date review of hybrid powertrain systems in UAVs, including fuel cell and battery hybrids, and discusses the importance of digital twins in aviation. Section 3 describes the proposed hybrid powertrain system. Section 4 introduces previous experimental tests and the data collected. Section 5 explains the energy management system developed. Section 6 shows the simulation and experimental results of the proposed architecture. Finally, Section 7 provides an in-depth discussion of the energy management strategy and outlines potential future developments.

2. State of the Art

For over 15 years, the aviation industry has been actively exploring and developing alternative electrified propulsion and power system architectures. Initially, most of these systems incorporated batteries or generators, often in conjunction with jet fuel-burning turbines or internal combustion engines, creating hybrid systems (Brandon and Kurban, 2017). Recently, there has been a significant surge of interest in using fuel cell systems, either independently or as part of hybrid systems, particularly with hydrogen as a fuel source (Airbus, 2022).

NASA has developed and depicted six electrified powertrain architectures (Figure 1) for aviation applications, which have become the de facto standard in the field . However, these models were created prior to the heightened focus on fuel cell architectures (of Sciences et al., 2016).

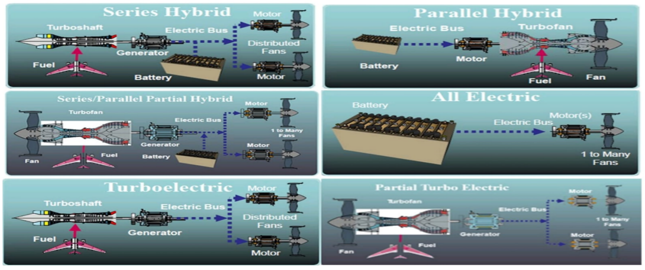


Figure 1: Proposed NASA electric propulsion architectures.

2.1. *Only Fuel Cell Powered*

Figure 2 illustrates the most basic fuel cell architecture. In this design, the fuel cell must be appropriately sized to handle the maximum power requirements during flight. It is important to note that most aviation applications require a compressor to supply air at sufficient pressure for the fuel cell to operate efficiently. Additionally, the inlet and exhaust systems must be meticulously designed to ensure efficient operation and minimal drag across various mission conditions.

This basic fuel cell architecture is currently being tested by companies such as ZeroAvia (ZeroAvia, 2024) and Universal Hydrogen (Hydrogen, 2024), among others. Variations of this architecture include distributed propulsion systems, where multiple propulsors (propellers or fans) are driven by a single fuel cell, or configurations where each propulsor is connected to a separate fuel cell.

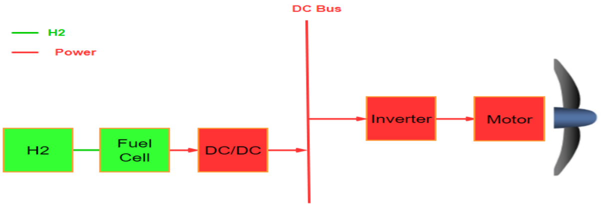


Figure 2: Fuel cell architecture.

2.2. *Fuel Cell - Battery Hybrid*

Figure 3 presents an enhanced fuel cell architecture that incorporates a battery for energy storage. This addition allows for more efficient management of high-power flight conditions with a smaller fuel cell. In this configuration, the fuel cell can be sized to meet cruise power requirements, while the combined power of the fuel cell and battery can accommodate the higher demands of takeoff and climb to cruise altitude. The fuel cell can also be sized to recharge the battery during flight.

This architecture is currently under investigation by the NASA and Universities. Additionally, companies like Universal Hydrogen, H3 Dynamics, and others are preparing to conduct flight tests using a nacelle with this architecture. Boeing previously flew an aircraft with this configuration in 2008.

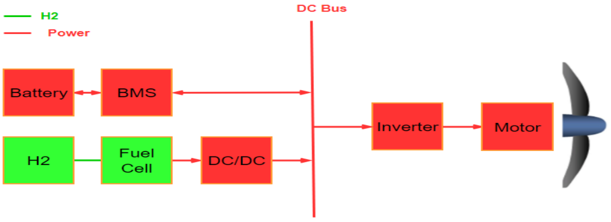


Figure 3: Fuel cell and battery hybrid architecture.

Other types of aircraft, midsize and widebody, are exploring the possibility of burning hydrogen and also hybridising with batteries (de Frutos et al., 2023).

2.3. *Digital twins*

Digital twin technology represents a significant advancement in the management and operation of unmanned aerial vehicles (UAVs). A digital twin is a virtual model designed to reflect a physical object (Tao et al., 2018) accurately. For UAVs, this technology encompasses real-time data synchronization between the physical UAV and its digital counterpart, enabling enhanced monitoring, predictive maintenance, and optimization of operations (Negri et al., 2017).

Digital twins facilitate real-time monitoring by continuously collecting and analyzing data from various sensors on the UAV (Rasheed et al., 2020). This real-time data integration helps in tracking the UAV's performance, identifying potential issues before they become critical, and ensuring optimal functioning of all components. Predictive maintenance, enabled by advanced analytics and machine learning, allows operators to foresee and mitigate potential failures, thereby reducing downtime and extending the UAV's operational life (Lee et al., 2018).

Projects such as AEROASTRO at the Massachusetts Institute of Technology design digital aircraft twins enabling the optimisation of every detail of the aircraft, picture taken from (Ham, 2021) is shown in the Figure 4.

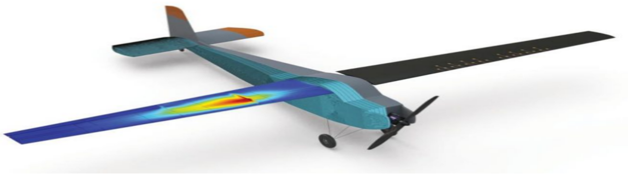


Figure 4: Creating "digital twins" at scale, AEROASTRO, MIT.

3. Case Study

This paper presents the conceptual design, simulation, and experimental validation of the EMS for a fuel cell and battery hybrid powertrain, a test-bench design is illustrated in Figure 5. An energy management system mainly including a programmable DC/DC converter and an energy management controller is designed and tested to manage the hybrid fuel cell and battery power system for a UAV.

The selected components are detailed in Table 2. A critical consideration in aircraft design is weight; thus, evaluating factors such as energy and power in relation to weight—denoted as specific power and specific energy—is essential.

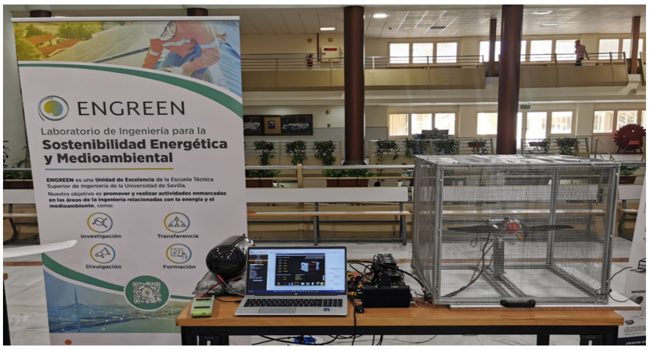


Figure 5: Powertrain designed on test-bench.

As shown in Figures 5 and 6, the designed powertrain has a DC/DC converter which sets fuel cell power output, and the battery has a passive role which will balance the energy grid. This fuel cell could lose some power output during the operational phase due to the purge process, this will be stabilized with a battery. Due to the purging process of the fuel cell and its low dynamics, the battery will supply excess power in high power flight manoeuvres, such as take-off, climb or turns, while the fuel cell will provide power in the cruise phase.

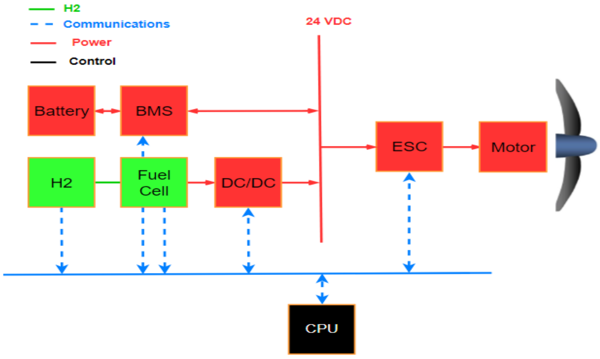


Figure 6: Schematic of powertrain design.

A battery management system (BMS) plays a crucial role in expanding the battery pack's lifetime and the overall system's security. An electronic speed controller (ESC) is used to control the motor, which is controlled by one of RCBenchamark's 1585 Series sensors.

The Series 1585 from RCbenchmark, is a specialized thrust stand designed for testing UAVs. It is capable of measuring up to 5 kgf (kilograms-force) of thrust and 2 Nm (Newton meters) of torque. It enables automated control and data logging which is a key factor in the testing phases.

4. Experimental approach

Before developing optimal energy management systems, it is necessary to conduct a series of tests to characterize the fuel cell and the propulsion system. The data collected during this characterization phase will later be used to create data-driven models that will implement digital twins of the components.

Once the polarization curve of the fuel cell was obtained, the hydrogen flow rate dependent on the electric current was determined using an experimental linear model (Herwerth et al., 2007). In equation (1), i_{out} refers to the output current of the fuel cell, and n_c refers to the number of cells in the proton exchange membrane (PEM) fuel cell. The flow rate is measured in grams per minute at normal conditions, for this fuel cell maximum power (300W) will have a flow rate of 0.0189 kg/h.

$$\dot{m}_{H_2} = 6.3 \cdot 10^{-4} \cdot i_{out} \cdot n_c \tag{1}$$

The hydrogen tank used, despite being capable of reaching up to 300 bar, will have a pressure of 15 bar in this case study, corresponding to a mass of 6.29 grams of hydrogen.

The data collected during the tests were obtained at a frequency of 1 Hz for the fuel cell and 80 Hz for the propulsion system. High sampling frequencies enable better characterization of equipment with faster dynamics, allowing for the creation of more accurate models.

As shown in Figure 7, a polarization curve was obtained at 25ºC, 50% relative humidity and 0.7 bar of hydrogen supply pressure.

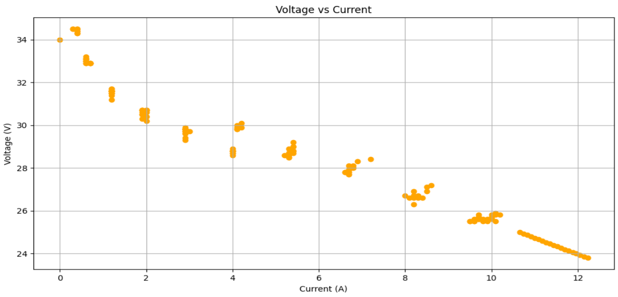


Figure 7: Experimental polarization curve obtained.

5. Energy Management System

Implementing hybrid powertrains necessitates the development of novel algorithms for energy management systems aimed at optimizing energy consumption. This presents a complex challenge due to the varying power requirements encountered along different aircraft flight paths.

5.1. Fuzzy Logic Control Strategy

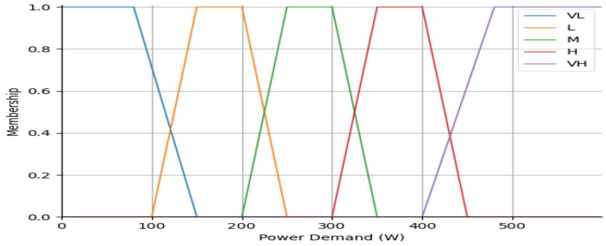
Advanced fuzzy energy management strategies, known for their robustness and flexibility, have been simulated for practical use in fuel cell vehicles, micro-grids and aircraft (Yin et al., 2016). Researchers have also explored the application of fuzzy logic in managing hybrid fuel cell-battery systems for UAVs (Zhu et al., 2014). However, these studies remain largely theoretical, focusing on modelling and simulations, with a limited experimental investigation into the actual performance of hybrid fuel cell-battery power systems for UAVs (Gao et al., 2005).

In this approach, the core algorithm of the fuzzy logic controller has two input variables and one output variable: the demand power P_D and state of charge (SOC) as the input variables and the desired fuel cell power (P_{fc}) as the output variable. The bus voltage is set to 24 VDC which is higher than the battery voltage, 23 VDC. The value of P_D is read from the telemetry of the electronic speed controller (ESC).

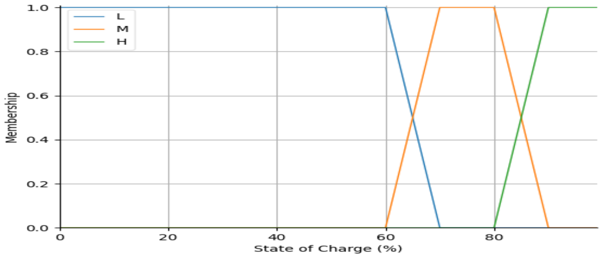
The variation of battery SOC is defined by

$$\Delta SOC = -\frac{i_{out}\Delta t}{C_{ref}} \tag{2}$$

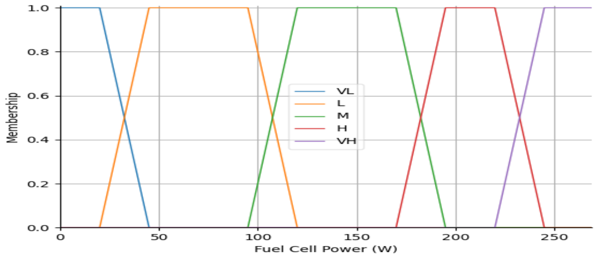
where i_{out} is the battery output current and C_{ref} is reference battery capacity.



(a) P_D



(b) SOC



(c) P_{fc}

Figure 8: Membership functions.

In the fuzzification process, the battery's state of charge is categorized into three levels: low (L), middle (M), and high (H). Similarly, power demand is classified into five levels: very high (VH), high (H), middle (M), low (L), and very low (VL). The fuzzy output power (P_{fc}) also falls into five categories: VH, H, M, L, and VL.

The fuzzy logic control rule base consists of 15 rules, detailed in Table 1. Figures 8(a) to 8(c) illustrate the membership functions for P_D, SOC, and P_{fc}. The Mamdani fuzzy inference approach is utilized, with the centroid method employed for defuzzification.

5.2. Passive Control Strategy

The passive control strategy is implemented to compare with the proposed fuzzy logic control. For the passive control strategy, the fuel cell through the DC/DC converter connects with the battery in parallel.

To match the battery, the output voltage of the DC/DC converter is set to be 24V and battery voltage is approximately 23V. The output current of the battery and the fuel cell will not be controlled actively, just depends on their characteristics passively. In normal conditions fuel cell will supply power until its maximum and then battery will supply the excess demand power. In some scenarios, the battery could supply power, due to the purging process and instabilities.

Table 1: Rule base of fuzzy logic control

P_{fc}		P_D				
		VH	H	M	L	VL
SOC	L	VH	VH	H	M	L
	M	VH	H	M	L	L
	H	H	M	L	VL	VL

6. Results

Although tests were conducted with the passive control strategy, the results discussed in this section have been obtained through simulation. For this simulation, models were developed based on data from the fuel cell, converter, and battery, derived from the experimental tests.

The primary state variables analyzed are SOC and LOH. The objective is to maintain these variables at balanced levels to ensure high specific power levels.

Both energy management strategies were tested using a real flight profile to conduct a meaningful comparison. The selected flight profile has an approximate duration of 33 minutes and can be divided into four stages:

1. Warm-up for 5 min at a thrust (T) < Weight (W).
2. Climb with T > W (T ~ 1.25W) for 10 min.
3. Flight to a fixed point with T = W for 5 min.
4. Transition from flight to a fixed point to forward flight for 13 min.

Figure 9 illustrates the power profile of the flight, highlighting the four phases mentioned above.

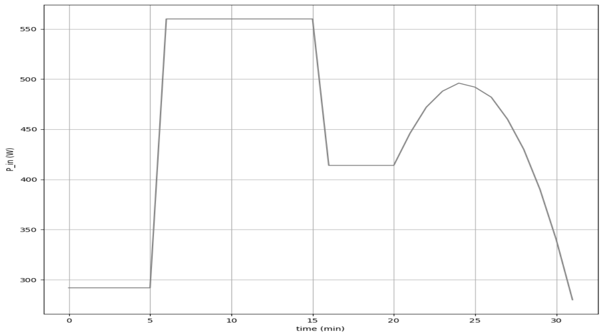
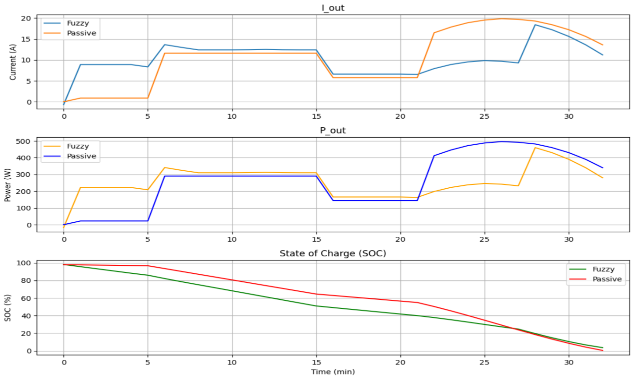
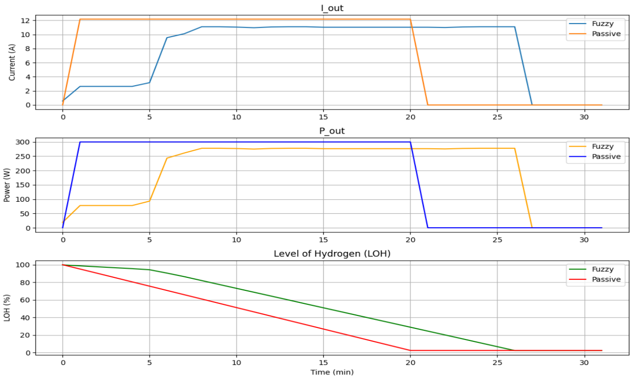


Figure 9: Flight mission power profile.

In Figure 10(a), the Fuzzy Logic Control strategy exhibits a more dynamic response, with higher initial power output peaks compared to the Passive Control strategy. Specifically, in the first 5 minutes, the Fuzzy strategy reaches higher power levels more rapidly, indicating a more responsive adaptation to the power demands of the UAV. Initially, both strategies exhibit a similar SOC decline, but the Fuzzy strategy manages to retain a higher SOC for a longer duration.



(a) Battery



(b) Fuel Cell

Figure 10: Control strategy comparison in-flight mission designed

In Figure 10(b), the power output subplot indicates that the Passive Control strategy rapidly maximizes the fuel cell's power output. This behavior suggests an aggressive energy consumption approach, leading to early depletion of fuel resources. In contrast, the Fuzzy strategy shows a more moderated and gradual increase in power output, peaking below the maximum but sustaining a stable output until around 25 minutes.

The Passive strategy depletes hydrogen at a faster rate, reflecting higher and less efficient fuel consumption. Conversely, the Fuzzy strategy demonstrates a more conservative hydrogen usage, resulting in a slower depletion rate.

Table 3: Comparison of the final state control strategy.

	SOC	LOH	Time	Capacity
Fuzzy Logic	3.59%	2.34%	33 min	350.22 Ah
Passive Logic	0.42%	2.48%	33 min	371.45 Ah

The final energy state of the powertrain is shown in Table 3, the fuzzy strategy employs a more balanced energy control so that the battery can be used for a longer time than the passive control strategy, which allows more available power to be available, facilitating the necessary in-flight manoeuvres.

7. Conclusion

The Passive Control strategy offers the primary benefit of rapid implementation with minimal hardware requirements.

Table 2: Selected components for designed aircraft powertrain

Component	Model	Type	Specifications	Weight	Volume
Fuel Cell	Protium-300	PEM, 40 cells	300W	1.17 kg	1.54 dm^3
Converter	Cerebral-55	DC/DC	5.5kW	1.46 kg	2.74 dm^3
Battery	-	LiFePO4	6Ah	1.20 kg	0.47 dm^3
BMS	WatchMon CORE	-	16 cells	0.50 kg	0.60 dm^3
ESC	ALPHA	-	120A	0.36 kg	0.17 dm^3
Motor	AXI 4130/16	Brushless	60A	0.40 kg	-
H_2 tank	-	Type III	5L, 350 bar	1.85 kg	9.13 dm^3

This approach proves to be a suitable option for cost-effective solutions and designs with less stringent requirements. By simplifying the energy management controllers, this strategy also contributes to reduced weight and complexity in aircraft powertrains. This makes passive control an attractive choice for applications where simplicity and cost-effectiveness are paramount, such as in smaller UAVs or those with less demanding energy profiles.

The Fuzzy Logic Control strategy, on the other hand, provides a more sophisticated approach to energy management by extending the use of hydrogen throughout the flight mission. This reduction in battery dependency results in a lighter overall battery weight, which is advantageous for the performance and efficiency of the UAV. The adaptability of Fuzzy Logic Control makes it particularly promising for planned missions and surveillance operations that involve high-demand flight profiles. The ability to pre-set and adjust fuzzy logic parameters allows for tailored energy management, enhancing the UAV's operational flexibility and efficiency.

8. Future developments

The promising results obtained from the comparison of Fuzzy Logic Control and Passive Control strategies for energy management in UAVs pave the way for several future research and development directions. Optimization of Fuzzy Logic Parameters, advanced optimization techniques, such as genetic algorithms or particle swarm optimization, can be employed to fine-tune the membership functions and rule sets. Integration with Machine Learning, it can enhance the predictive capabilities of the fuzzy logic control system. By learning from historical flight data, machine learning models can predict future energy demands more accurately, allowing for more proactive energy management.

9. Acknowledgements

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