Fuel Consumption Optimization for Prallel Hybrid Propulsion System of Small-scale Unmanned Aerial Vehicles

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Abstract

One of the primary concern in extended flight endurance of fully-electric small-scale unmanned aerial vehicles (UAVs) is the limited propulsive power source and hence short flight endurance. As applications of these aerial vehicles are ever increasing, there is a demand for several hours of uninterrupted flights. As a result a hybrid propulsion system of electric and fuel draws significant attention of aerospace companies. To this end, this work presents a parallel hybrid propulsion system and its fuel consumption optimization for a fixed-wing UAV with vertical takeoff and landing (VTOL) capabilities. Unlike previous works, the fuel consumption optimization of the propulsive system presented in this work takes the aerodynamic performance of the UAV and the surrounding environment, such as atmospheric pressure, temperature, density, and wind velocity, into account to achieve fuel efficient navigation in the entire UAV's flight envelope. A fuel consumption optimization strategy is developed as an energy management system (EMS), demonstrating significant improvements in endurance and fuel efficiency. Simulation results show that, for a given mission profile, the parallel hybrid propulsion system could safe about 8% fuel as compared to a fully engine-based propulsive system.

Keywords: Unmanned aerial vehicle; Hybrid propulsion; Fuel consumption optimization; energy management system

1. Introduction

Technological evolution in aviation industries mainly focuses on three key enhancements: aerodynamic performance [1], structural weight reduction, and propulsion system efficiency. These key enhancements are inter-linked. A required propulsive power can be reduced by enhancing aerody-

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namic performance [2] and/or by reducing structural weight [3, 4] of an aircraft. On the contrary, aircraft weight reduction

Fuel consumption optimization in unmanned aerial vehicles (UAVs) has become a crucial area of research and development as demands for longer endurance, higher efficiency, and environmentally sustainable aerial operations continue to grow. Small-scale UAVs, in particular, face stringent design constraints due to their limited payload capacity and energy storage capabilities. Traditional propulsion systems: either fully internal combustion engine (ICE) or fully electric often fail to simultaneously meet endurance, power, and operational flexibility requirements. To overcome these limitations, parallel hybrid propulsion systems, which integrate an ICE with a battery-powered brushless DC motor, have emerged as a promising solution.

In a parallel hybrid configuration, both the ICE and electric motor can provide propulsion either individually or simultaneously, depending on the flight phase and performance requirements. For instance, the electric motor can support VTOL, acceleration, or climb maneuvers where high thrust-to-weight ratio is required, while the ICE can dominate during cruise to maximize endurance. This dynamic sharing of power not only enhances mission flexibility but also reduces the specific fuel consumption (SFC) of the system by operating each component in its most efficient regime.

Fuel consumption optimization within such a system involves careful management of power distribution between the ICE and electric motor, selection of operating points, and intelligent control strategies. Key methods include constraint-based design, where performance envelopes are plotted as thrust-to-weight ratio versus wing-loading, and energy management algorithms that adjust power split in real time. Optimization objectives often include minimizing total fuel burn, extending range and endurance, and improving overall system reliability. Additionally, lightweight structural design, aerodynamic efficiency, and advanced battery management further contribute to overall fuel savings.

For small-scale UAVs, optimization is particularly challenging due to limited onboard computation, weight restrictions, and rapidly changing mission profiles. However, advances in energy management systems (EMS), including adaptive and machine learning-based controllers, have shown promising results in achieving near-optimal fuel utilization across diverse flight conditions.

These approaches ensure that hybrid UAVs can meet the competing requirements of endurance, payload capacity, and operational versatility, while also addressing broader goals such as reducing emissions and enhancing sustainability in unmanned aviation. The strategies followed to develop EMS in this work are presented as follows.

2. UAV Aerodynamic Performance

The demand for UAVs with long endurance, efficiency, and operational flexibility continues to grow in both civilian and defense sectors. VTOL fixed-wing UAVs are particularly attractive as they combine the efficiency of wing-borne flight with the versatility of multi-copters.

2.1. Mission Requirements

Mission requirements are often set by customers or by aerospace companies based on market demand. Either ways, these requirements are among main factors which dictate selection of propulsive systems. For instance a UAV mission that requires long range or several hours of flight endurance imply the need for supplementary or substitute to battery based propulsion system. In this work a hypothetical mission requirements given in Table 1 are used for the design of an aerial mapping UAV and its propulsion system.

Table 1: Hypothetical Mission Requirements

Parameter	Value	Unit
Endurance	4	h
Range	300	m
Cruise altitude	2500	”
Service ceiling	3000	”
Cruise speed	27	m/s
Max speed	32	”
Stall speed	18	”
Climb rate	2.5	”
Max. takeoff mass	45	kg
Payload mass	8	”

The aerodynamic performance of the UAV has to meet all the mentioned requirements. The commonly used approach to design an aircraft that can address a given mission requirement is to obtain a constraint diagram [5, 6]. A constraint diagram not only depicts an available design space for the aircraft but also guides the designer to select an appropriate propulsive system for the aircraft [7–9]. In the conceptual design of an aerial mapping UAV, we referred to Raymer's book [9]. The obtained constraint diagram of the design UAV is shown in Fig. 1.

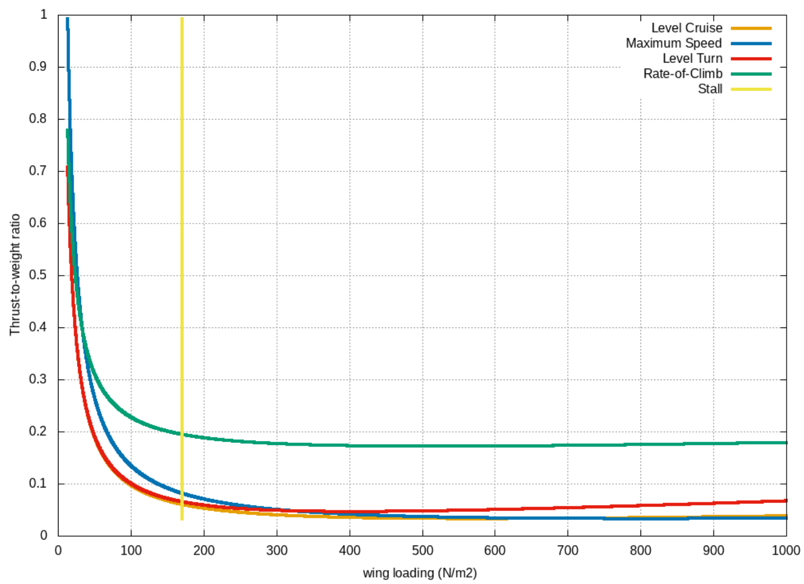


Figure 1: Constraint diagram showing feasible region and selected design point.

Referring to the constraint diagram plotted as Thrust-to-weight ratio versus wing-loading, the UAV design space is shown to be constraint to the left side of a vertical line representing stall speed and above the curved line representing rate-of-climb. The intersection of these two lines indicates the minimum thrust-to-weight ratio based on which the required propulsive system is selected. The intersection has a coordinate of (0.193,170.4) which corresponds to the Thrust-to-weight ratio of 0.193 and the wing-loading of 170.4 N/m^2. With the total takeoff mass given in Table 1, the minimum required thrust of a propulsive system (to be designed) is 85.17 N.

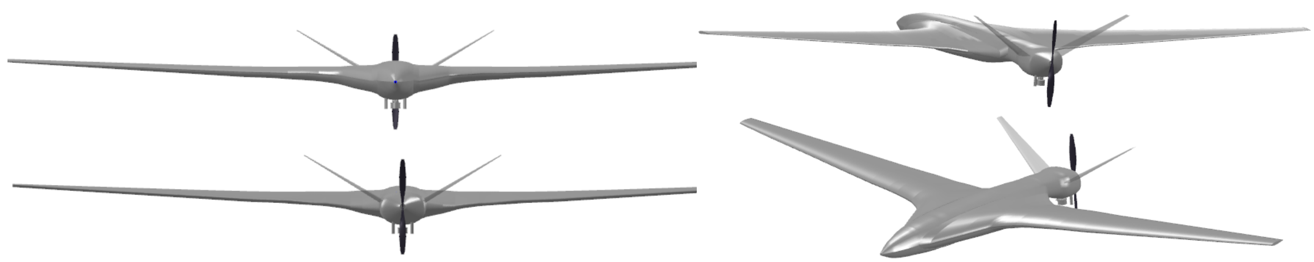
2.2. Airframe Configuration

The obtained wing-loading is used for aircraft initial sizing. Accordingly, the designed UAV has the sizes displayed in Table 2.

Table 2: UAV Initial Sizing

Parameter	Value	Unit
Wing span	4.7	m
Fuselage length	1.25	”
Wing area	1.98	m^2
Aspect ratio	11	- - -

The UAV configuration of the conceptual design has the form displayed in Fig. 2. The design and aerodynamic performance analysis of this UAV were done using OpenVSP [10]: open source software for vehicle design and aerodynamic performance computation.



(a) Front and back view

(b) oblique view

Figure 2: UAV configuration in conceptual design

The mission profile of this UAV includes flight segments such as vertical takeoff, climb, cruise, loiter, descent and vertical land. The climb and decent angles of the flight is set to 4 and 10 degrees at which the lift is high. This is to effectively reduce fuel consumption during these flight scenario.

3. UAV Propulsion System

Propulsion system architectures for UAVs are generally categorized into:

- Fully electric for high efficiency).
- Fully engine: often internal combustion engine (ICE) for long endurance.
- Hybrid (electric and engine) either in parallel, series, or combined configuration.

The limitation of fully electric UAVs is low flight endurance. The fully engine based UAVs have longer flight endurance as compared to fully electric counterpart but have poor VTOL performance. The hybrid propulsive system takes advantages of both electric (high efficiency) and engine (long endurance). Based on the aforementioned hypothetical mission requirements, the hybrid propulsion system is preferred and its optimal fuel consumption strategy is designed in this work.

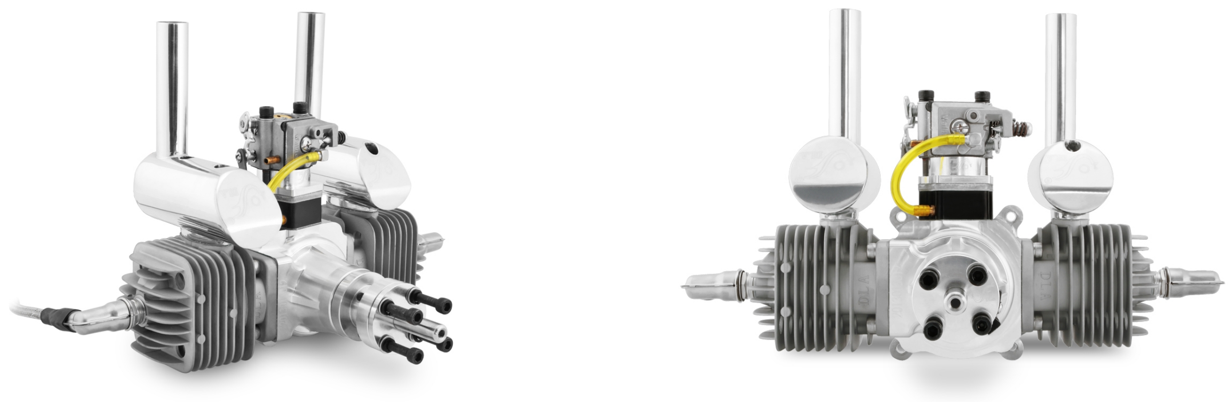
3.1. Engine Selection

As small-scale UAVs often operate at low altitude, the efficient engine type in this flight environment is a propeller based piston-engine. From design constraint diagram, it is obtained that the thrust-to-weight ratio is 0.193 from which the minimum required thrust for the UAV is calculated to be 85.17 N. With the maximum speed of 32 m/s, the required engine power is 2.725 kW which corresponds to 3.65 HP. It is based on this horsepower (HP) that engines commonly used for small scale UAV are listed as shown in Table 3. Engines whose HP are in the range (5.0 HP, 8.0 HP) are listed in the table. These horsepowers are the values at sea level and these values significantly reduce as UAV cruises at altitude of 2.5 km where the air density drops, approximately, to 0.9 kg/m^3 as compared to its value at sea level: 1.225 kg/m^3.

Table 3: Engine type selection

Engine type	horsepower (HP)	weight (kg)	Capacity (cc)
Orbital75	5.2	4.4	75
DLE55	5.5	1.61	55.6
DLA64	7.2	1.87	64
HFE DA70	5.0	1.85	70
HFE DA100	7.4	2.5	100
RCV DF70	5.7	3.0	70

Taking HP, weight, and capacity as performance metrics, the best engine type selected for the designed UAV is DLA 64 cc, shown in Fig.3. It is a high-performance twin-cylinder gasoline engine designed for small scale UAVs.



(a) Engine oblique view

(b) Engine front view

Figure 3: DLA 64 cc twin boxer engine

There are limited experimental data for DLA 64 cc engine performance tests provided by Airmobi Limited: manufacturer of the Skyeye UAV platforms. The plots of these experimental data are given in Fig. 4.

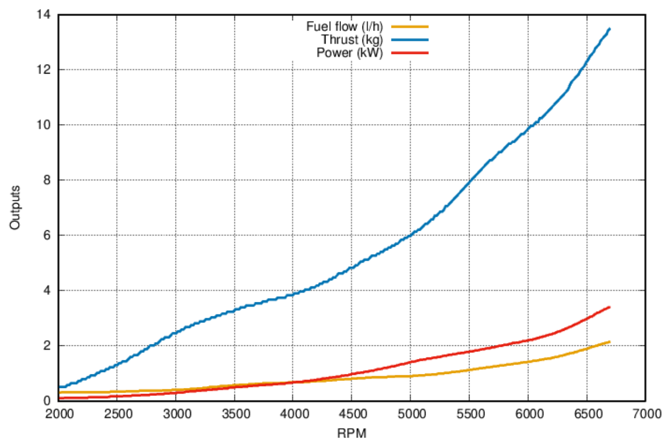


Figure 4: DLA 64 cc Engine Performance

3.1.1. Battery Selection

In the parallel hybrid propulsion system, battery is used as standalone energy source and/or as supplementary energy source. During VTOL mode, the battery is used as standalone energy source to propel the UAV in a vertical direction. Optionally, the battery can be used as standalone energy source during cruise or climb flight phases if stealth or noise-free quality data collection is required. Four Lithium Polymer (Li-Po) batteries of the type given in Fig. 5 are utilized.

Figure 5: Li-Po Battery Selected

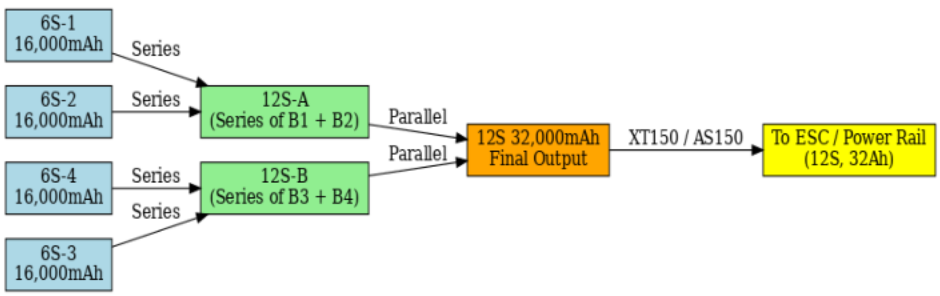


Figure 6: Assembly Architecture of Four Li-Po Batteries

3.1.2. Motor Selection

The VTOL fixed-wing UAV has two distinct flight modes: vertical takeoff/land and cruise flight. For the VTOL mode, four T-motors of 160 KV are used. Four of these motor deliver excess thrust that accelerates the UAV in vertical ascending flight. The selected propeller for this motor is falcon 32x11 that generates a thrust of over 14 N at 60% of throttle deflection. Potenza 65cc 185 KV motor was integrated with DLA 64 cc engine for cruise flight.

(a) T-motor 160 kv

(b) Potenza 180 kv motor

Figure 7: UAV configuration in conceptual design

4. Energy Management System Design

The energy management system designed in this work takes in aerodynamic performance and mission profile of the UAV, atmospheric condition of the environment, battery and engine statuses.

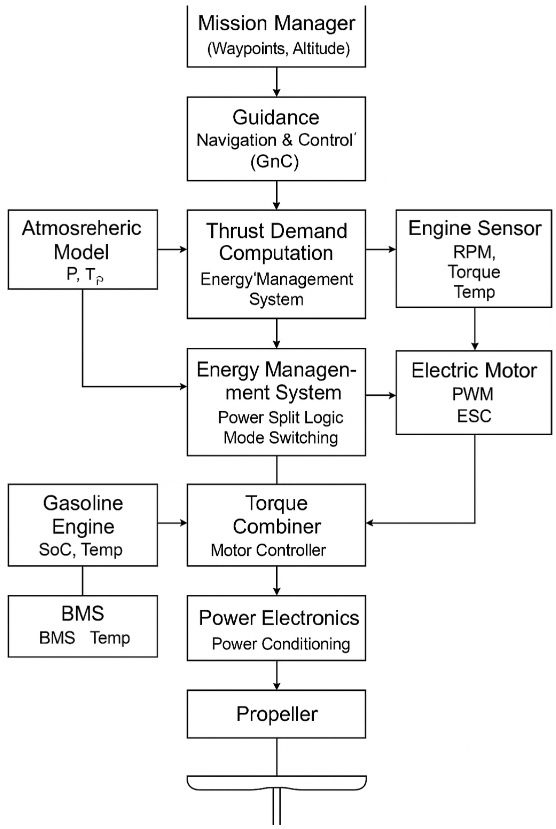


Figure 8: Energy management system design

The flowchart given in Fig. 8 displays detailed architecture of the designed propulsive system. Based on these input, the system computes the amount of thrusts that the motor and engine are required to produce. Thrust demand computation was done base on a mathematical model of UAV's dynamics. This mathematical model is not displayed here to save space.

5. Results and Discussions

The energy management: specifically fuel consumption optimization module was developed and tested in a software-in-the-loop (SITL) simulation environment. PX4 Autopilot and Gazebo three-dimensional environment simulator are used as simulation tools. The designed VTOL UAV model is incorporated to the PX4 Autopilot SITL and commanded to navigation in Gazebo simulation environment. A pre-planned trajectory, according to the aforementioned mission profile, was uploaded to the UAV through QGroundControl station software that is already integrated to both PX4 Autopilot and Gazebo.

The core approach in the energy management system designed is first to obtain the engine efficiency metrics. Based on the performance shown Fig. 4, these metrics are obtained and plotted in Fig. 9. Engine efficiency

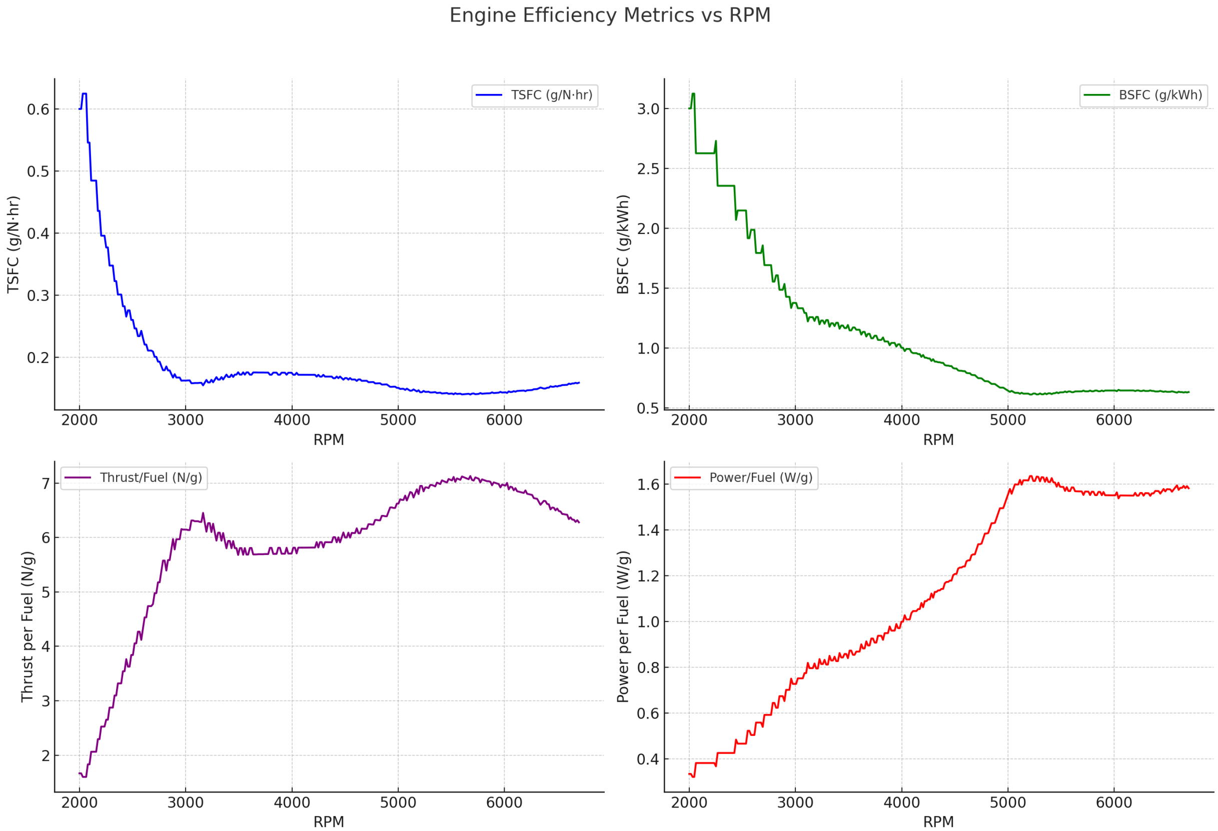


Figure 9: Engine efficiency

Utilizing the engine efficiency plots given in Fig. 9, the engine's ideal operating point (IOP) was identified. This IOP corresponds to engine's RPM of 5206 and engine shaft power of 1.52 kW, as shown Fig. 10.

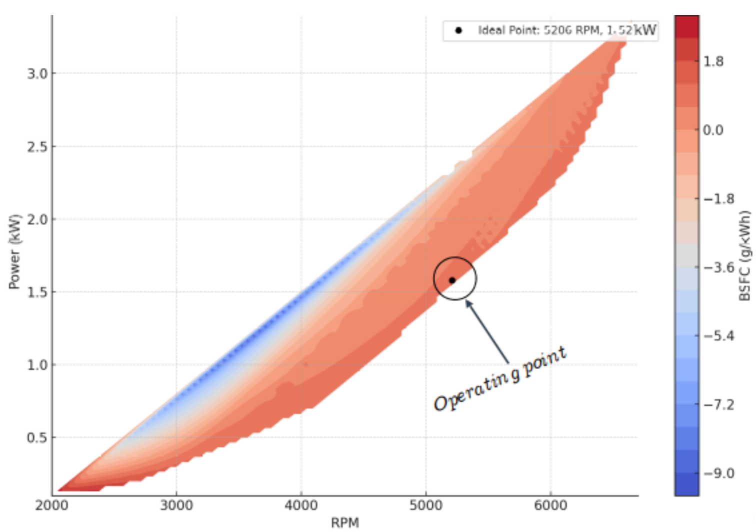


Figure 10: Engine Ideal Operating Point

The energy management system tries to keep the engine to operate at its IOP. If excess power is required, the battery supplies it through the integrated motor whereas if the required power is less than 1.52 kW, the battery is set to charging mode.

The UAV was commanded to navigate along the trajectory under two different propulsion system: fully engine and hybrid. The comparison of fuel consumptions, shown in Table 4 indicates that there is significant difference.

Table 4: Fuel consumption comparison.

Configuration	Endurance (hrs)	Fuel Used (L)	Remarks
Fully ICE	2.2	4.5	Heavy at takeoff
Fully Electric	0.8	0	Limited by battery
Hybrid (proposed)	2.5	4.14	Optimized balance

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