Fuel Consumption Optimization for Hybrid Fuel-Electric Propulsion System of Unmanned Aerial Vehicles

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Outline

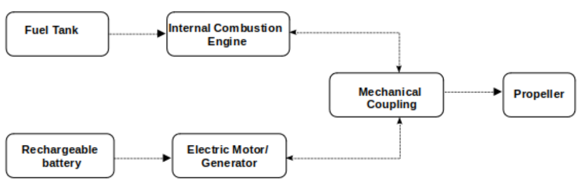
Background

Motivation

- Conventional propulsion systems are either fully fuel-based or fully electric, each with limitations.
- Hybrid systems combine fuel engines and electric motors to enhance endurance, reliability, and efficiency.
- Improved fuel economy and reduced emissions are key motivations.
- Essential for long-endurance UAVs, especially with VTOL capability.

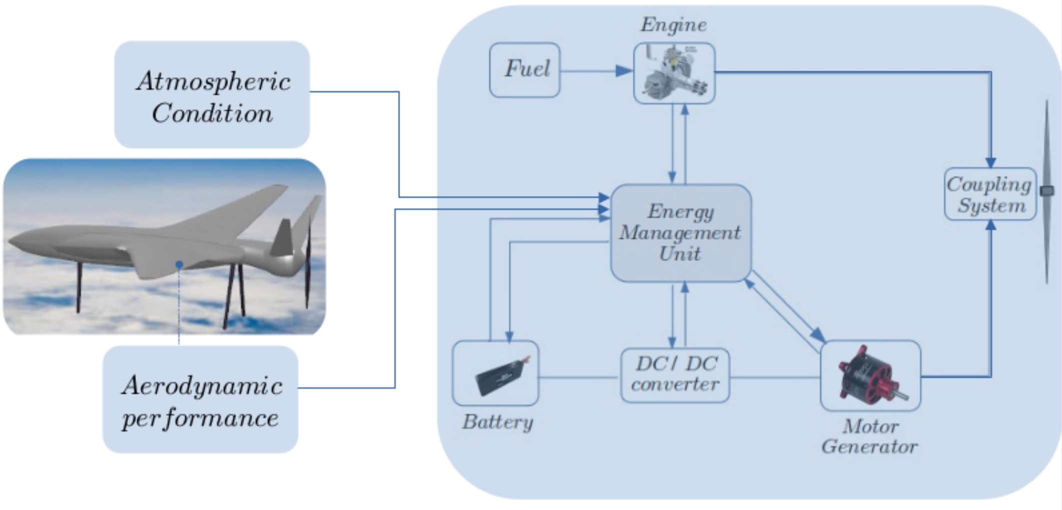
Hybrid Types

- Series Hybrid: Engine drives generator → powers electric motor.
- Parallel Hybrid: Engine and electric motor both drive the propeller.
- Series-Parallel Hybrid: Combines flexibility of both architectures.
- For UAVs, parallel hybrid is most suitable for efficiency and redundancy.



Parallel Hybrid Propulsion System

High-level overview

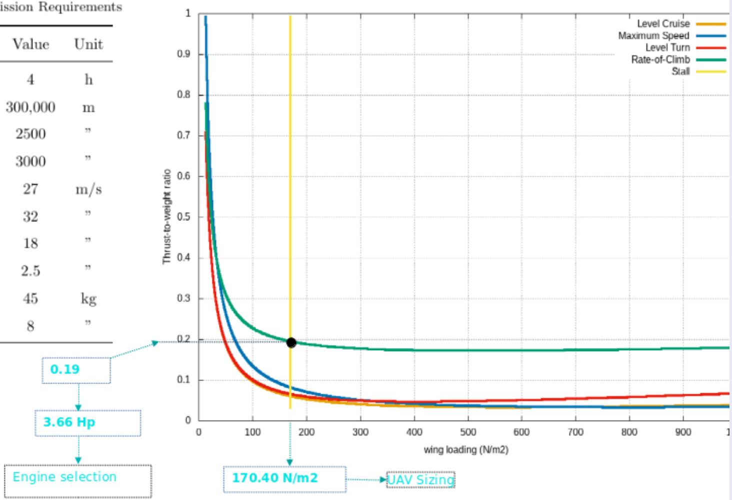


Mission Requirements and Constraints

Constraints

Table 1: Hypothetical Mission Requirements

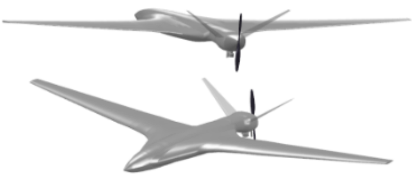
Parameter	Value	Unit
Endurance	4	h
Range	300,000	m
Cruise altitude	2500	"
Service ceiling	3000	"
Cruise speed	27	m/s
Max speed	32	"
Stall speed	18	"
Climb rate	2.5	"
Max. takeoff mass	45	kg
Payload mass	8	"

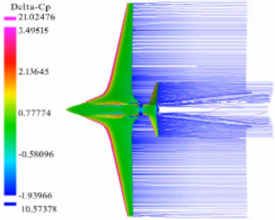


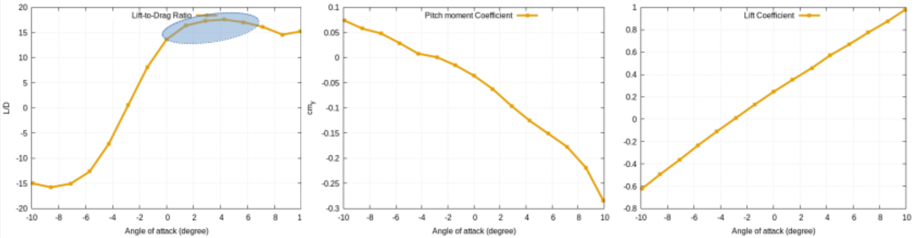
Sizing & Performance

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	- - -







Engine Selection

Engine

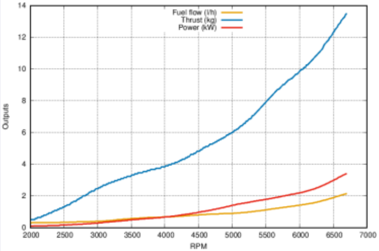
Table 3: Engine type selection

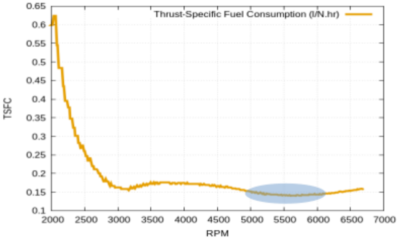
Engine type	horsepower (HP)	weight (kg)	Capacity (cc)
Orbital75	5.2	4.4	75
DLE55	5.5	1.61	55.6
DLA64	7.2	1.87	64
HFE DA70	5.0	1.85	70
HFE DA100	7.4	2.5	100
RCV DF70	5.7	3.0	70

DLA 64 cc Engine

Table 4: Technical data of DLA 64 cc Engine

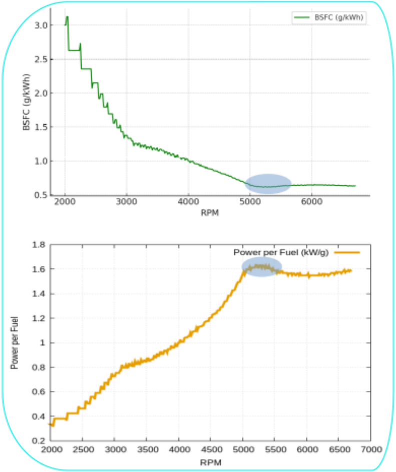
Parameter	Value	Unit
Architecture	2-stroke twin boxer	—
Bore	37	mm
Stroke	30	"
Displacement	64	cm^3
Compression Ratio	7.8:1	—
Fuel Type	gasoline	—
Cooling System	air cool	—
Dimension	$7 \times 5.9 \times 6.89$	inch
Min. BSFC	225	$g/kW \cdot h$

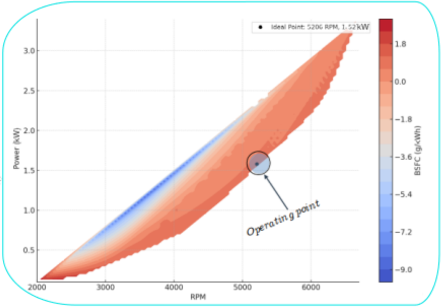




Engine Operating Point

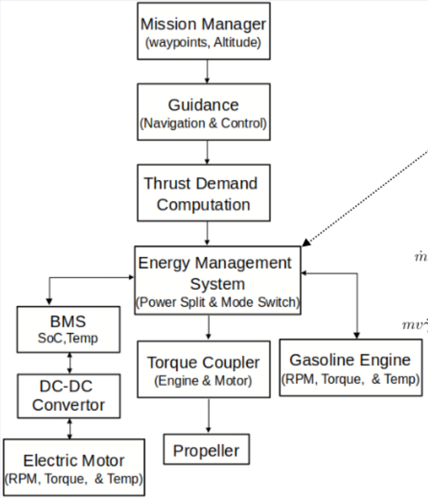
Operating Point

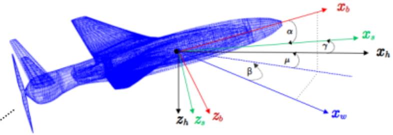




Energy Management System (EMS)

EM





$$\boldsymbol{F}_{net} = \boldsymbol{L} + \boldsymbol{D} + \boldsymbol{T} + \boldsymbol{W} + \boldsymbol{F}_w$$

$$\boldsymbol{F}_{net} = \frac{d}{dt}(m\boldsymbol{V}) = (\dot{m}\boldsymbol{V} + m\dot{\boldsymbol{V}})$$

$$\dot{m}v + m\dot{v} = T\cos(\alpha) - D - W\sin(\gamma) - F_w\cos(\beta)\cos(\mu)$$

$$mv\dot{\lambda} = -F_w\sin(\beta)$$

$$mv\dot{\gamma}\cos(\lambda) = -T\sin(\alpha) - L + W\cos(\gamma) - F_w\cos(\beta)\sin(\mu)$$

$$\boldsymbol{T} = \epsilon\boldsymbol{T}_e + (1-\epsilon)\boldsymbol{T}_m \quad \text{where} \quad 0 \leq \epsilon \leq 1$$

$$\dot{m} = -\dot{m}_{fuel} = -c\boldsymbol{T}_e \quad \text{c is Thrust specific fuel consumption}$$

Energy Management System (EMS)

EMS

- EMS optimizes power distribution between engine and motor.
- Monitors propulsion power demand, engine efficiency map, and battery state.
- Controls engine throttle, generator output, and motor torque.
- Implements RBF-PID controller for adaptive response to flight power demands.

Performance

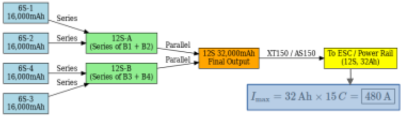
- Optimization goal: minimize fuel consumption while maintaining flight performance.
- RBF-PID adapts to nonlinear dynamics and uncertainties in UAV operation.
- Simulation results show significant improvement in fuel economy ($\sim 9\%$).
- Engine operates near optimal efficiency point using adaptive control.

Avionic

Tattu 22.2 V

Specification

Brand	Tattu
Capacity(mAh)	16000
Voltage(V)	22.2
Discharge Rate (C)	15
Max Burst discharge Rate (C)	30
Configuration	6S1P
Net Weight(±20g)	1932



Potentza KV185

T_{max} = 16.7 kg @:

- I = < 126 A
- Throttle = 60%
- Volt = 38 V
- Prop = Falcon 23x8

T-motor KV160

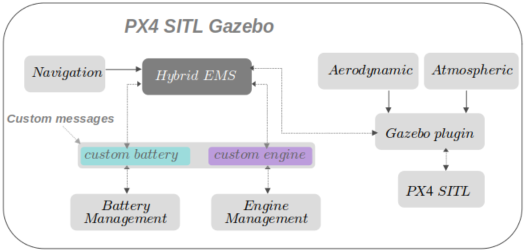
T_{max} = 15 kg @:

- I = < 105 A
- Throttle = 60%
- Volt = 44.4 V
- Prop = Falcon 32x11

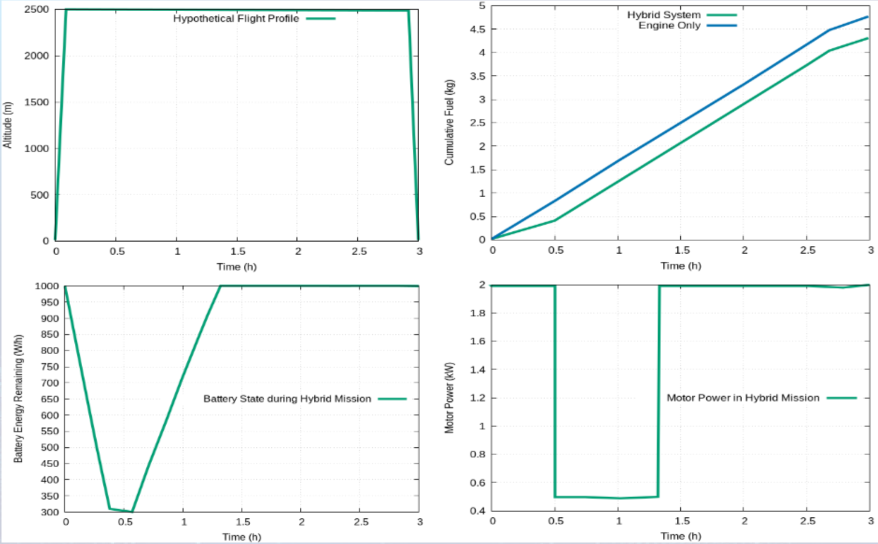
Validation: Simulation

- Hybrid EMS: Manages energy of propulsive system
- Custom battery and custom engine are custom messages
- PX4 SITL: Contains simulated vehicle in Gazebo environment
- Hybrid EMS receives:
  - waypoint information from Navigation module
  - Aerodynamic and atmospheric parameters through Gazebo plugin
  - battery, motor, status through custom battery
  - engine status through custom engine
- Hybrid EMS sends
  - fraction of total required thrust to engine
  - remaining fraction to motor

Platform



Fuel Efficiency Comparison



Fuel Efficiency Comparison

Fuel Efficiency

Table 5: Fuel consumption comparison.

Configuration	Endurance (hrs)	Fuel Used (L)	Consumption (%)
Fully ICE	3.0	4.77	95.4
Fully Electric	0.8	0	—
Hybrid (proposed)	3.0	4.31	86.2
Hybrid efficiency			**9.2**

Conclusion and Future Works

Outlook

- Hybrid propulsion offers the best trade-off between endurance and efficiency.
- Parallel hybrid with RBF-PID controller is effective for UAV energy management.
- Future work: Hardware-in-the-loop validation and real-flight testing.
- Integration with PX4-based UAV systems for autonomous operation.

Thank You