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Department of M3
School of Aerospace

Multidisciplinary Design and Optimization of a Distributed Electric Propulsion UAV with Hybrid-Electric Power Architecture

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Background

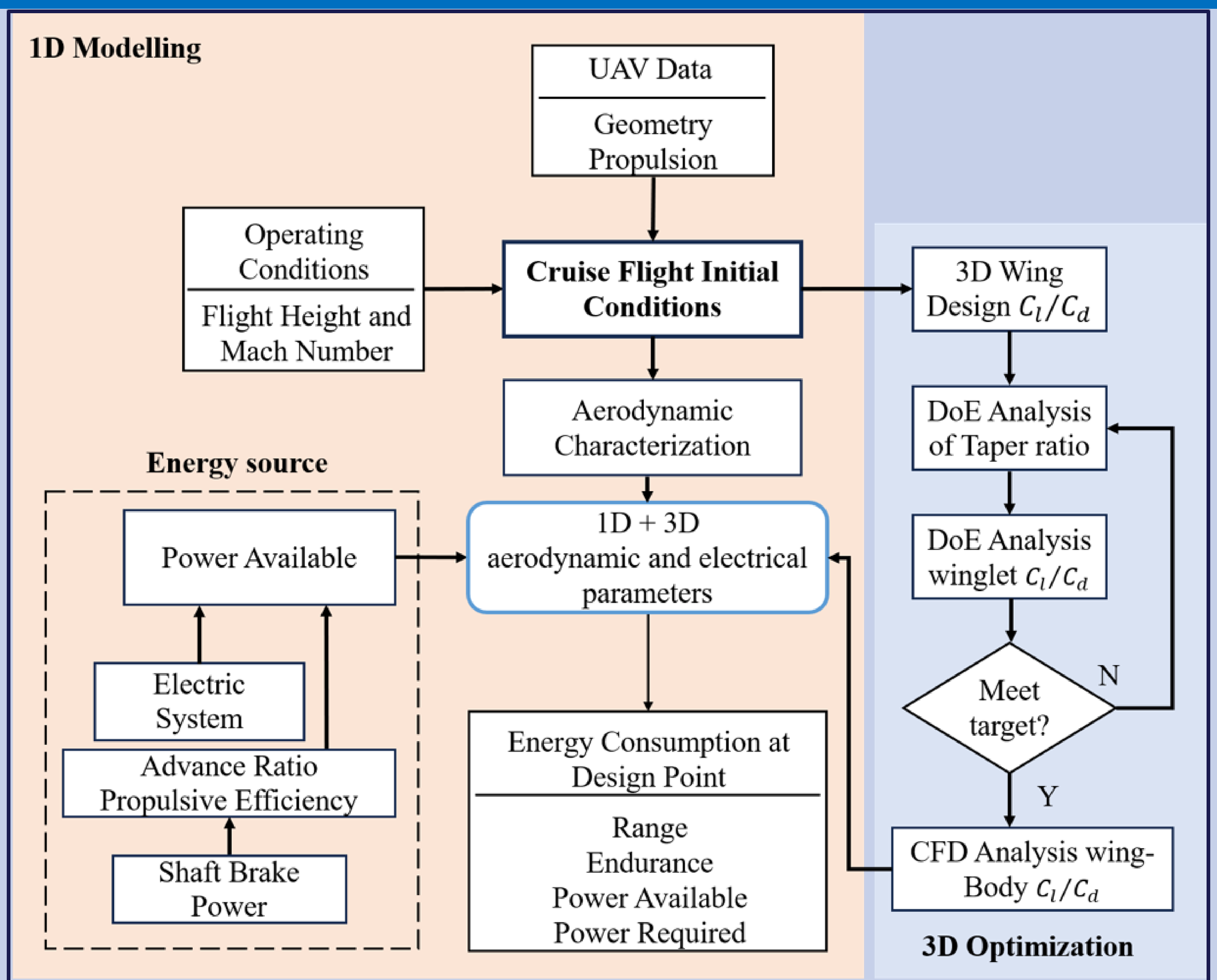
In order to meet the key target of zero-emission aviation for cleaner and environmentally sustainable air transport, there is an increasing demand for novel propulsion architectures. For electric propulsion systems, one key challenge is the long endurance of flights. This project focuses on 3 key target;

1. Design and implement a **distributed-electric propulsion (DEP)** system for high C_l/C_d value.

2. Develop a mathematical model for estimating the performance of DEP using **hybrid-electric architecture**.

3. Optimize the **endurance** of the UAV using the mathematical model and CFD results

Methodology



Aircraft Dynamics

Nonlinear State-Space Model for DEP Aircraft

Aerodynamic Forces

Aerodynamic force coefficients (simplified):

$$C_X = C_{X0} + C_{X_\alpha}\alpha + C_{m_{\delta_e}}\delta_e$$
$$C_Y = C_{Y0} + C_{Y_\beta}\beta + C_{n_{\delta_r}}\delta_r$$
$$C_Z = C_{Z0} + C_{Z_\alpha}\alpha + C_{m_{\delta_e}}\delta_e$$

Forces:

$$F_x^{\text{aero}} = \bar{q}_{\text{avg}} S C_X, \quad F_y^{\text{aero}} = \bar{q}_{\text{avg}} S C_Y, \quad F_z^{\text{aero}} = \bar{q}_{\text{avg}} S C_Z$$

Kinematics

$$V = \sqrt{u^2 + v^2 + w^2}$$
$$\alpha = \tan^{-1}\left(\frac{w}{u}\right)$$
$$\beta = \sin^{-1}\left(\frac{v}{V}\right)$$

Aerodynamic Moments

Moment coefficients:

$$C_l = C_{l0} + C_{l_\beta}\beta + C_{l_p}\frac{pb}{2V} + C_{l_{\delta_a}}\delta_a$$
$$C_m = C_{m0} + C_{m_\alpha}\alpha + C_{m_q}\frac{q\bar{c}}{2V} + C_{m_{\delta_e}}\delta_e$$
$$C_n = C_{n0} + C_{n_\beta}\beta + C_{n_r}\frac{rb}{2V} + C_{n_{\delta_r}}\delta_r$$

Moments:

$$L^{\text{aero}} = \bar{q}_{\text{avg}} S b C_l, \quad M^{\text{aero}} = \bar{q}_{\text{avg}} S \bar{c} C_m, \quad N^{\text{aero}} = \bar{q}_{\text{avg}} S b C_n$$

Motor Dynamics

For each motor $j = 1, \ldots, n$:

$$\dot{i}_j = \frac{-Ri_j - k_e\omega_j + V_j}{L}$$
$$\dot{\omega}_j = \frac{k_t i_j - (damping + k_Q|\omega_j|)\omega_j}{J}$$

Battery Model

$$P_b = g(P_c), \quad = \frac{U^2}{2R}\left(1 - \sqrt{1 - \frac{4R}{U^2}P_c}\right)$$

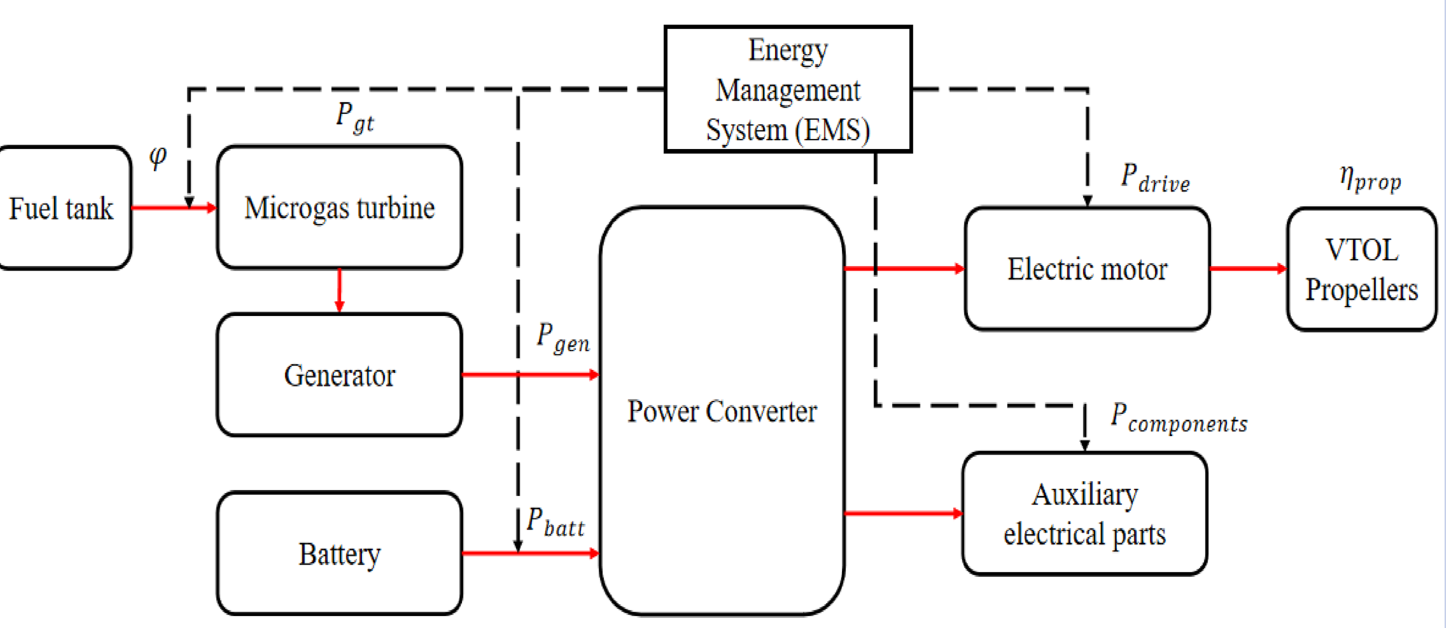
Electric Generator

$$P_{gt} = h_{gen}(P_{gen}(t), \omega_{gen}(t)), \quad = \nu_2(\omega_{gen})P_{gen}^2 + \nu_1(\omega_{gen})P_{gen} + \nu_0(\omega_{gen})$$

Gas Turbine

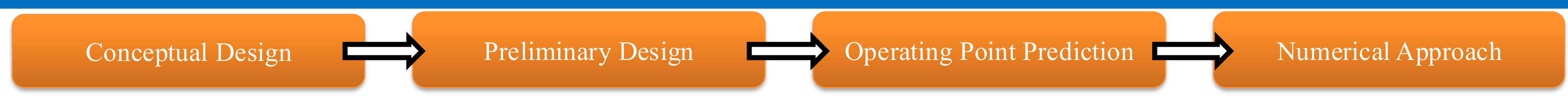
$$\dot{m} = -\varphi = -f(P_{gt}(t), \omega_{gt}(t))$$

Hybrid-Electric Architecture

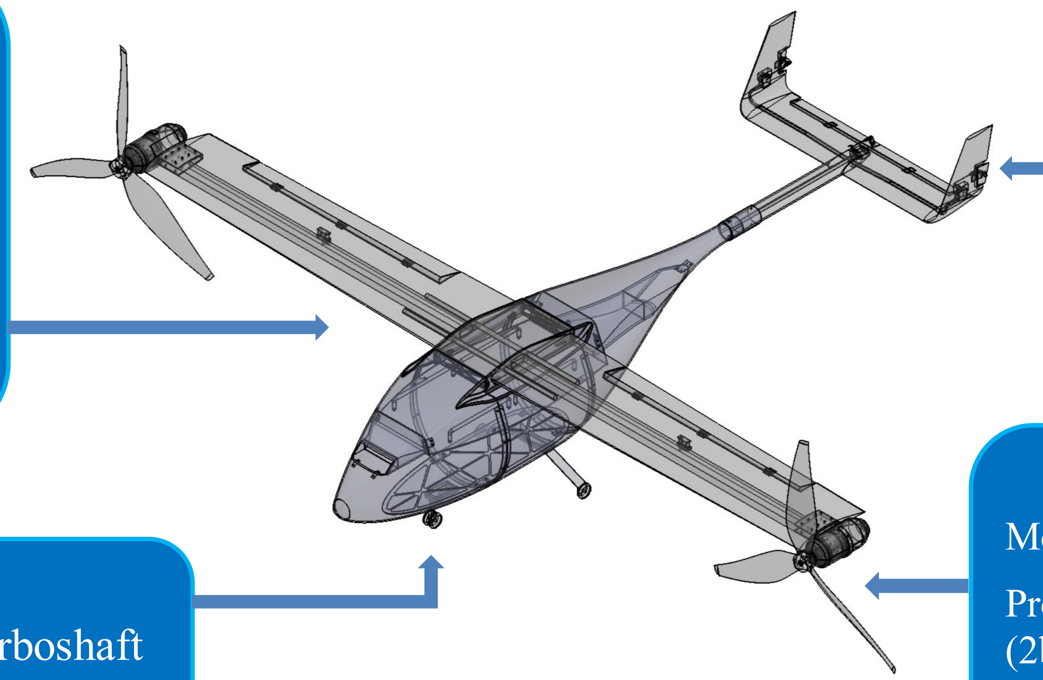


Power balance for series configuration is given as $P_{elec}(t) = P_{batt}(t) + P_{gen}(t)$

Results: Aircraft Design, CFD, and Hybrid-Electric Propulsion



Main Wing:
Span: 2m
Mean chord: 0.2m
Area: 0.45 m^2
Aspect Ratio: 10
Cl_cruise : 0.65
Cd_cruise : 0.04
Taper ratio: 1.25

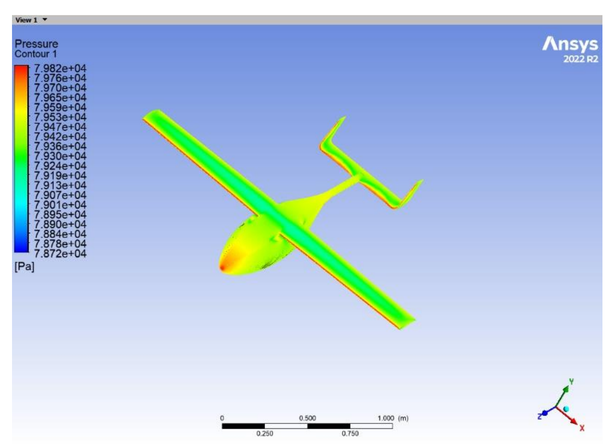


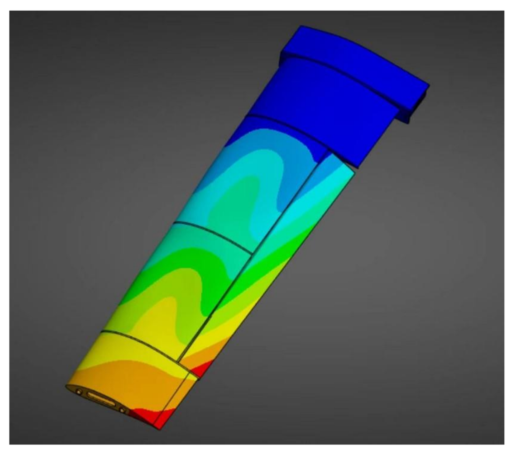
Tail:
Twin-boom tail design
Span: 0.54 m
Chord: 0.14 m
Area: 0.00756 m2

Fuselage:
Battery: Li-ion
Engine (for HEP) : Jetcat Turboshaft
Landing Gears: Tricycle (1 - 2)
Battery Cooling Path

Rotor/Motors:
Motor Type: TMotor AT5230
Propeller Type: EOLO propeller (2blades), Spit Fire T5147 (3 blades)
DEP Config: 6 - 8 propellers

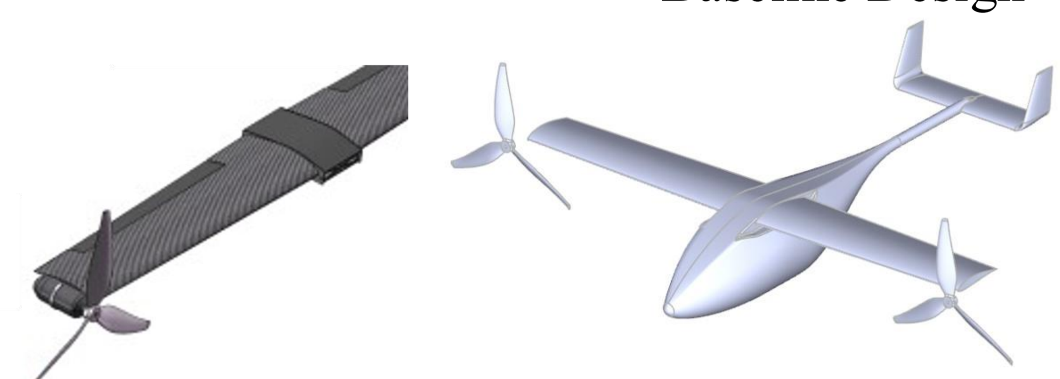
CFD and FEM Analysis of the Experimental Aircraft Design



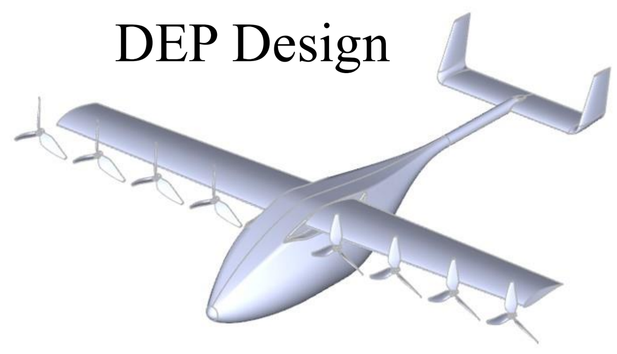


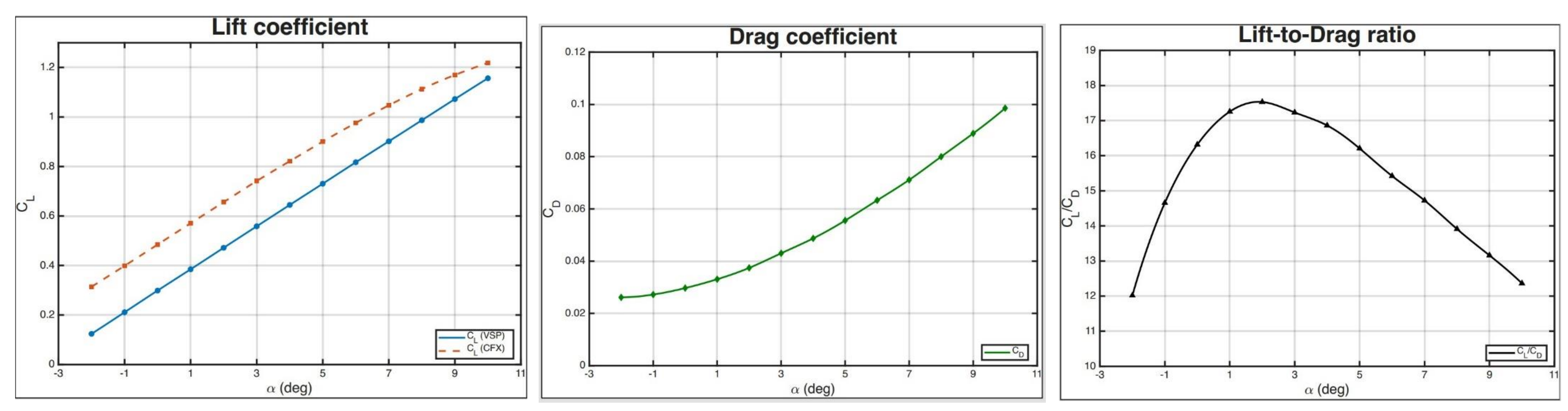
Composite materials

Baseline Design

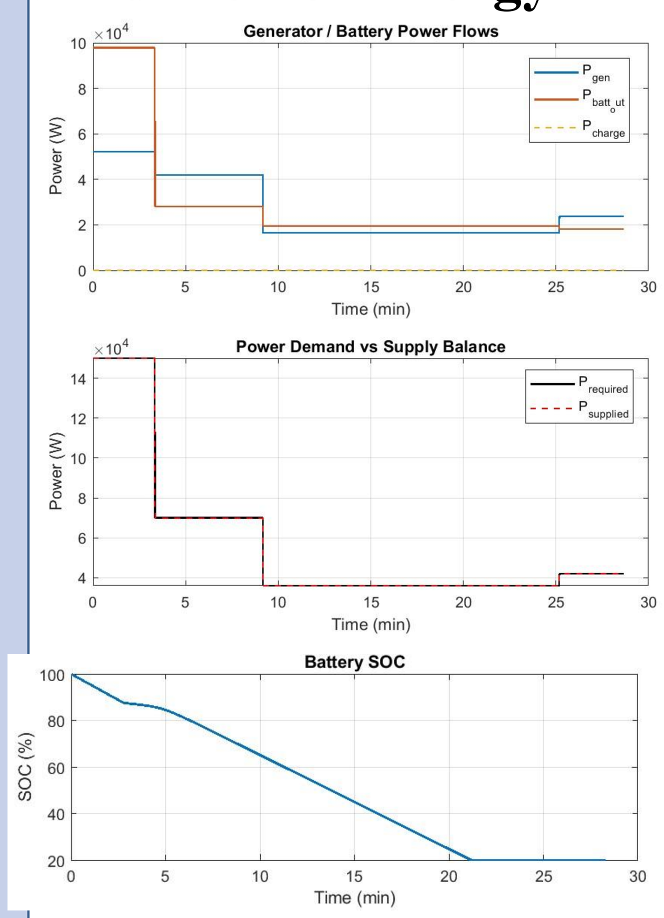


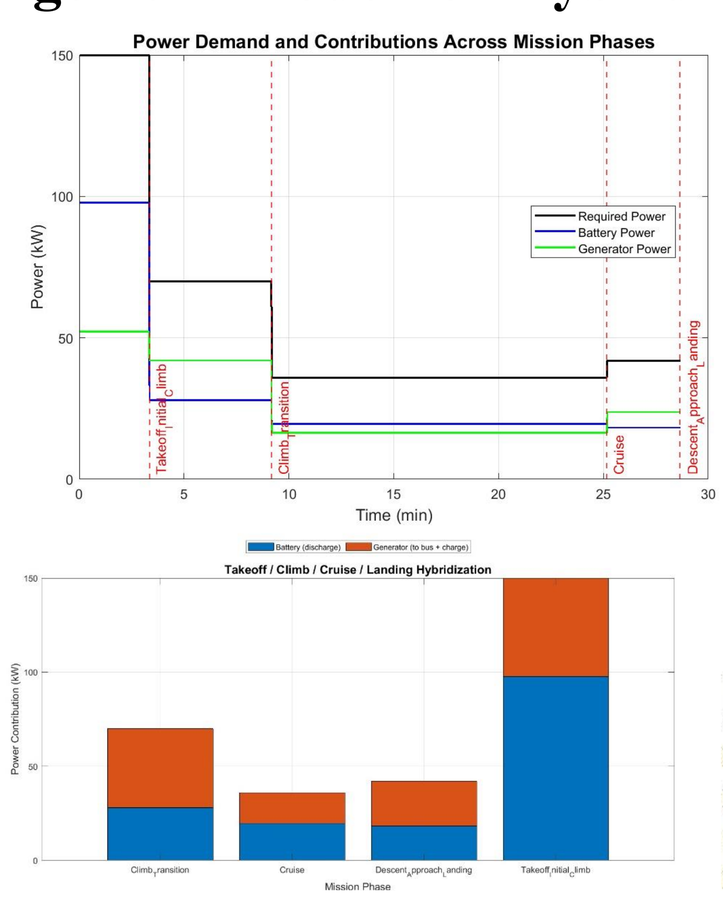
DEP Design

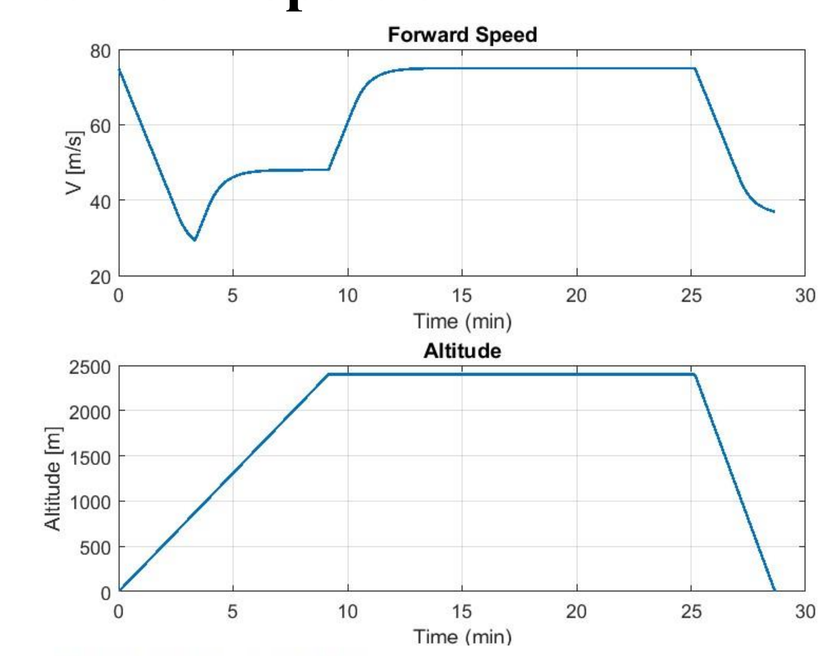




Validation of Energy Management Model for Hybrid-Electric Propulsion





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--- ENDURANCE SUMMARY ---
Time-based Endurance: 0.47 hr
Energy-based Endurance: 0.90 hr
Range: 115.38 km | Energy per km: 1127.49 Wh/km
Fuel used: 7.74 kg | Battery used: 37.60 kWh
Energy split: Battery 28.9% / Fuel 71.1%
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Conclusion and Further Work

- An experimental aircraft for DEP and HEP architecture for long range and endurance has been design and numerically validated. Experimental test will be carried out to compare results.
- An Energy management model using MPC strategy for DEP architecture with HEP has been completed for accurate prediction of range and endurance. Using the NASA Maxwell X-57 for validation, prediction – 0.9hrs, experiments - 1.1hrs.
- By modifying the aerodynamic design, battery/generator capacity and the power distribution, an aircraft with an energy-based endurance of **2.1hrs** increased to **3.8hrs**, thus, about 80% increase.

Supervisor – Dr. Richard Amankwa Adjei