Multidisciplinary Optimization of an Electric Quadrotor Urban Air Mobility Aircraft

Eliot Aretskin-Hariton, Eric Hendricks, Daniel Ingraham, Justin Gray, Sydney Schnulo, Jeffrey Chin, Robert Falck, Dustin Hall

NASA Glenn Research Center

Goals

- Demonstrate ability of multidisciplinary analysis tools to perform coupled analysis in the preliminary design phase

Overview

- Quadrotor and Mission
- Optimization Environment
- Coupling Subsystems
- Subsystem Details
- Results
- Conclusions

Quadrotor and Mission

Baseline Mission:

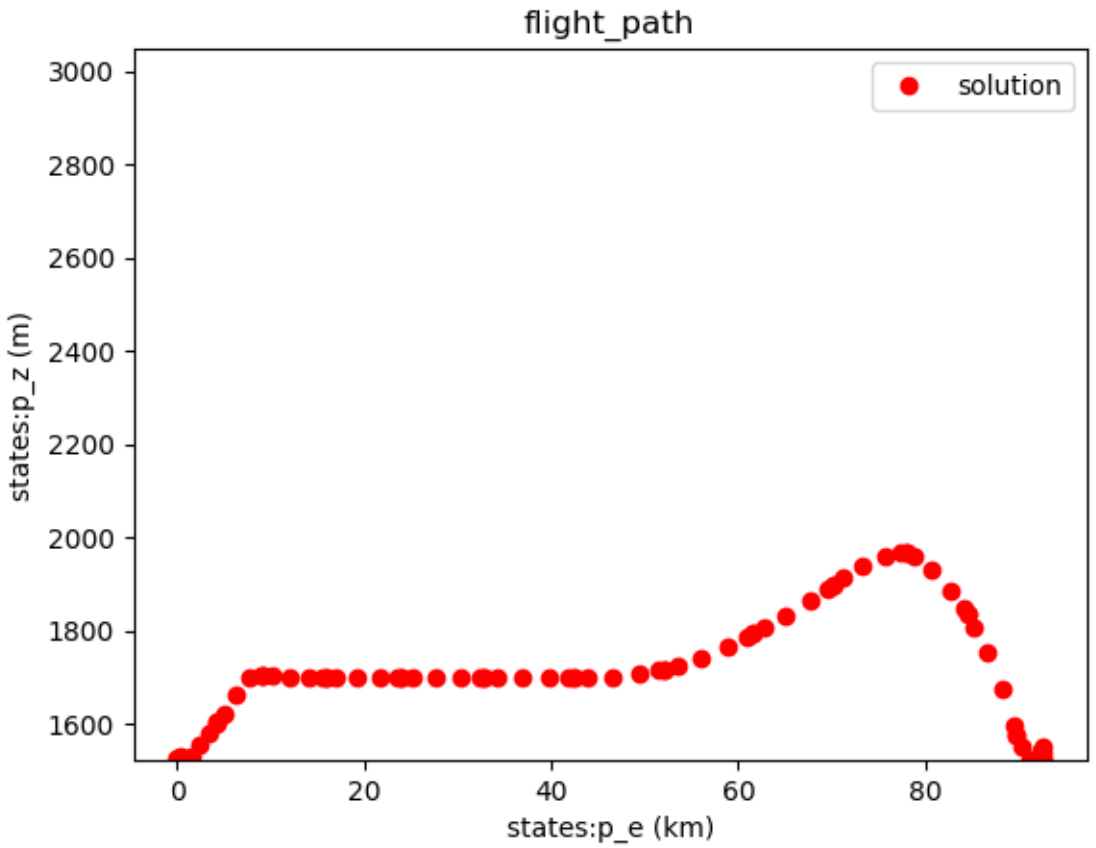
- Single Passenger
- All-electric
- 92.6 km
- 1.5km altitude ceiling
- 200m minimum cruise altitude
- Subsystems: Propulsion, Thermal, Mass, Aero, Trajectory

Optimization Environment:

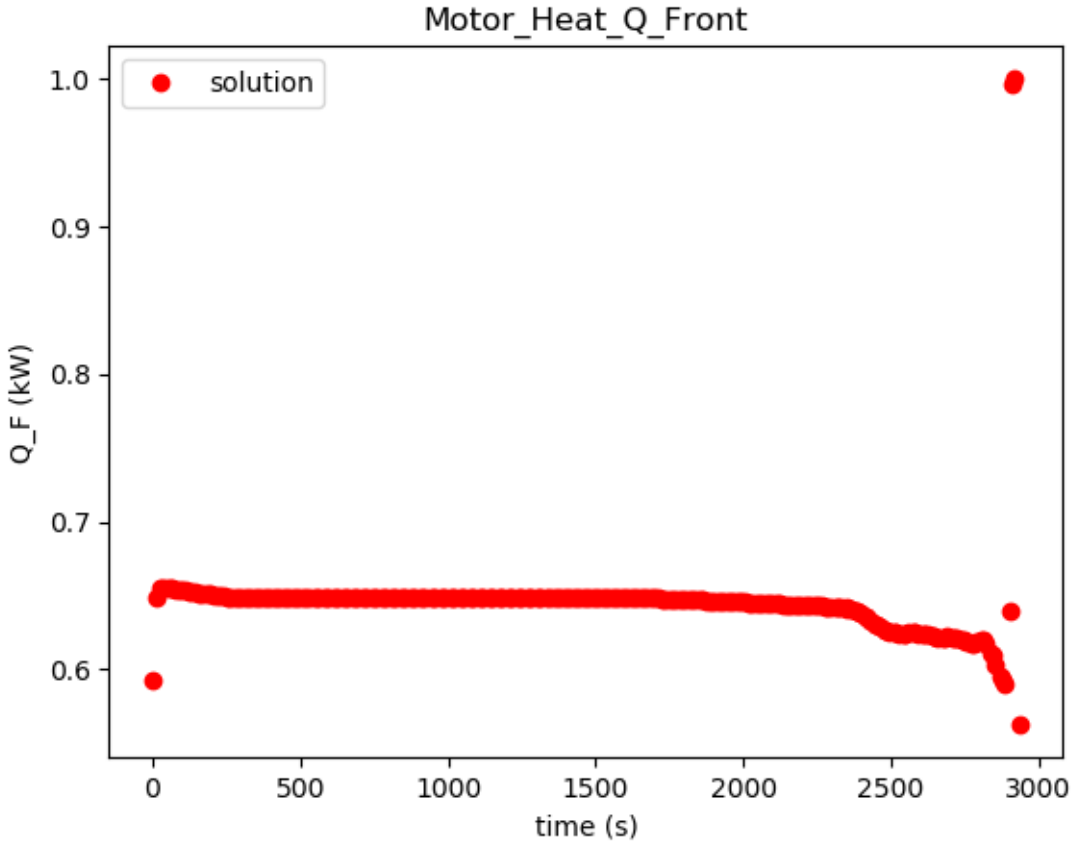
- OpenMDAO
  - Gradient based optimization
  - Analytical derivatives
  - Open Source
- Dymos
  - Allows for time-varying optimal control optimization
  - Pseudospectral methods
  - Varying fidelity phases
  - Open Source

Tandem Flight Phases

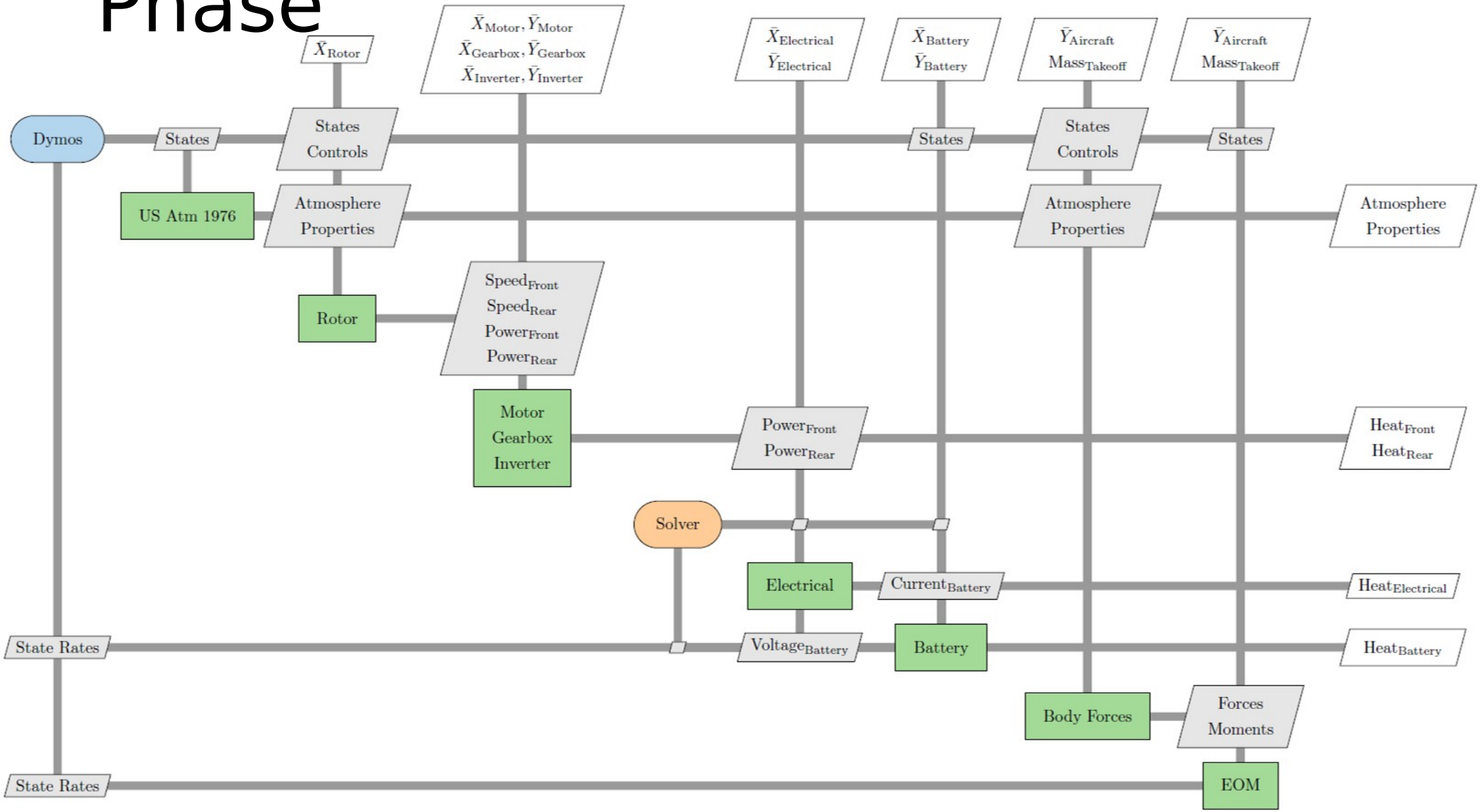
- Main Phase – Lower Fidelity



- Thermal Phase – Higher Fidelity

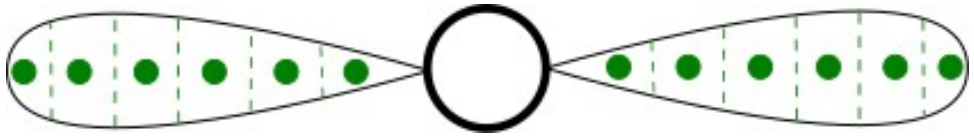


Coupling Subsystems – xDSM Main Phase



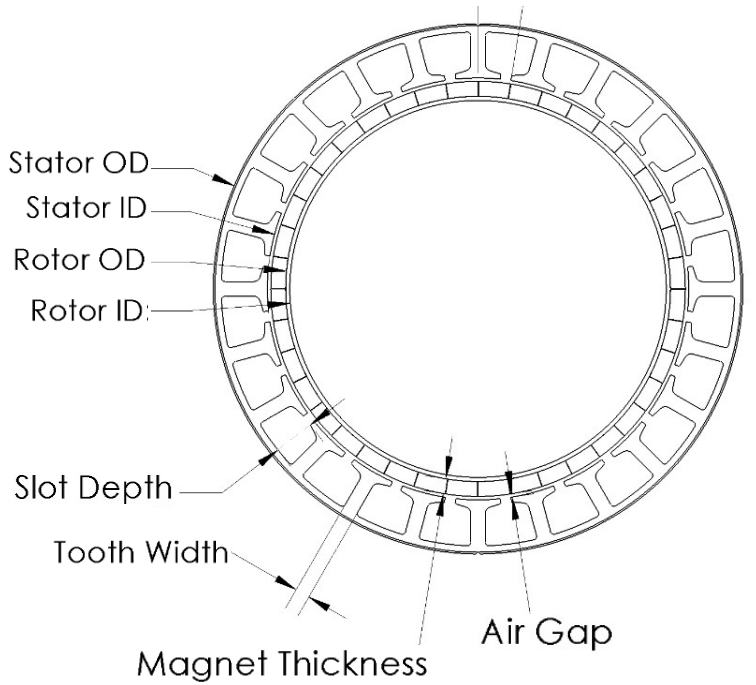
Subsystems: Rotor

- CCBlade.jl combines momentum theory and blade element theory (BEMT) library created by Andrew Ning
- Breaks the blades up into sections or blade elements
- Thrust input results in rotation rate output
- Fixed pitch propeller
- Optimizer Controls: Blade Twist



Subsystems: Motor, Gearbox, Converter

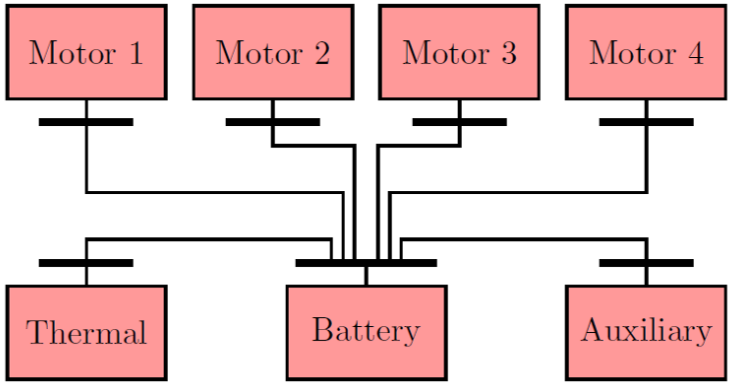
- Motor is a simple efficiency curve
  - 2000 rpm at max efficiency 97%
- Gearbox has a fixed efficiency 99%
- Converter has a fixed efficiency 98%
- Heat load sent to thermal system
- Optimizer Controls:
  - Maximum Rotor Power,
  - Optimal Rotor RPM (gearbox ratio)



Future Work:
Mid-Fidelity Motor Model

Subsystems: Electrical Power

- Zappy load flow model for electrical power distribution is typical of terrestrial power grids
- Balances power output by the battery with power demand generated by the motor and line losses
- Creates heat load on the thermal system

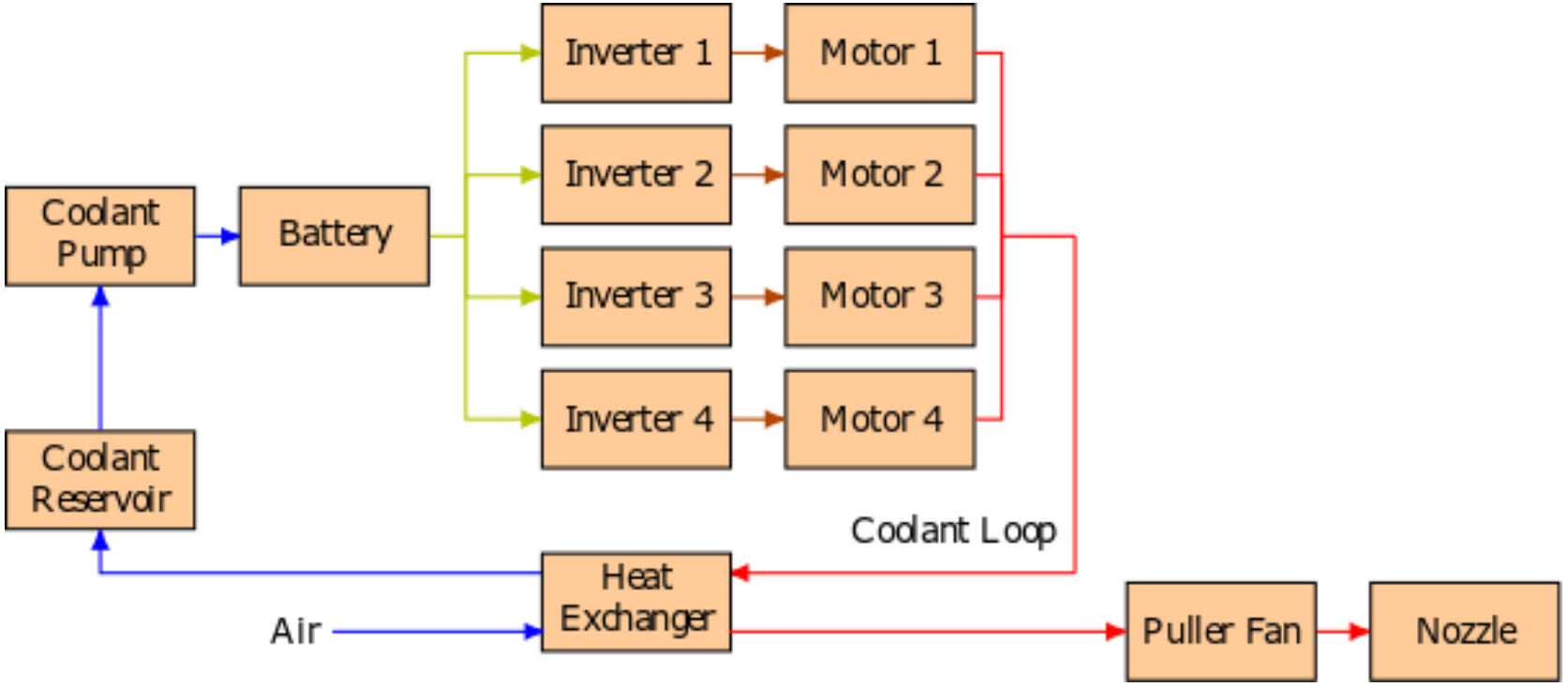


Subsystems: Battery

- Battery model uses battery temperature and state of charge to calculate voltage output.
- State of Charge (SOC) starts at 95% charge and is allowed to sink to 20% but the end is just a lower constraint
- Creates heat load for thermal system
- Optimizer Controls: Total available power (kWh) , Maximum energy draw (amps)

Subsystems: Thermal

- Thermal system tracks battery, coolant, forward motor, and aft motor temperatures
- Optimizer Controls: Heat Exchanger size, Throat Area

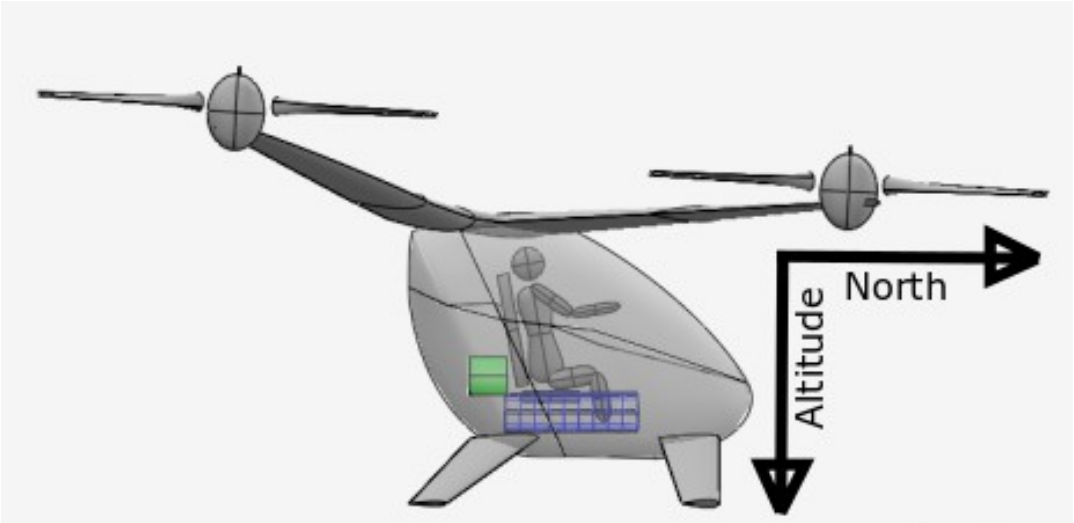


Subsystems: Aerodynamics & Mass

- Simple drag with spherical vehicle
- Weights for all components
- Calculates Masses for:
  - Fuselage
  - Landing gear
  - instrumentation

Subsystems: Trajectory

- Equations of Motion (EOM) track vehicle translational position and velocity and rotational position and velocity
- Uses thrust to calculate translational and angular acceleration based on axi-symmetric inertia matrix
- Optimizer Controls: Thrust produced by forward and aft rotors

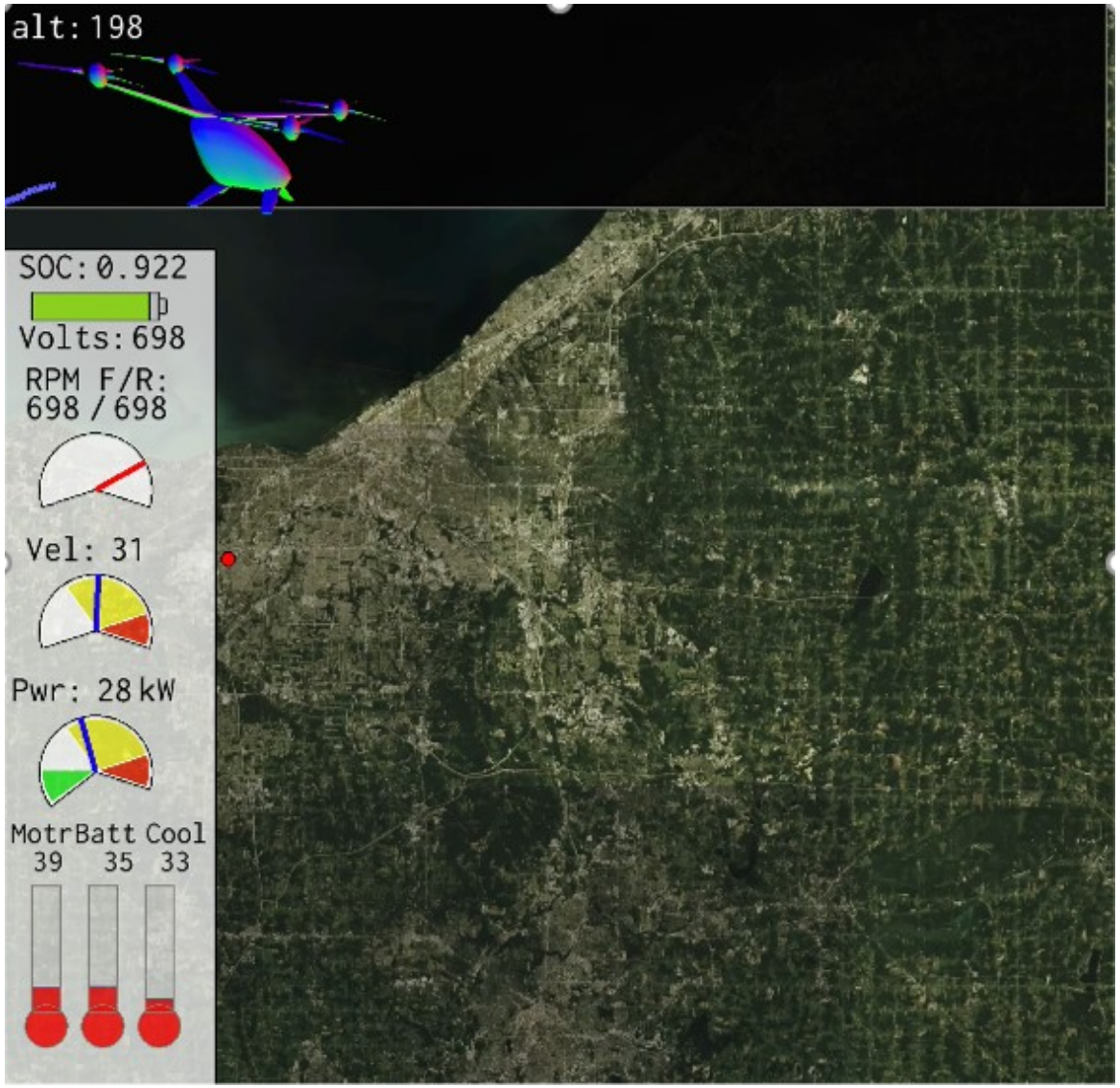


Summary of Problem

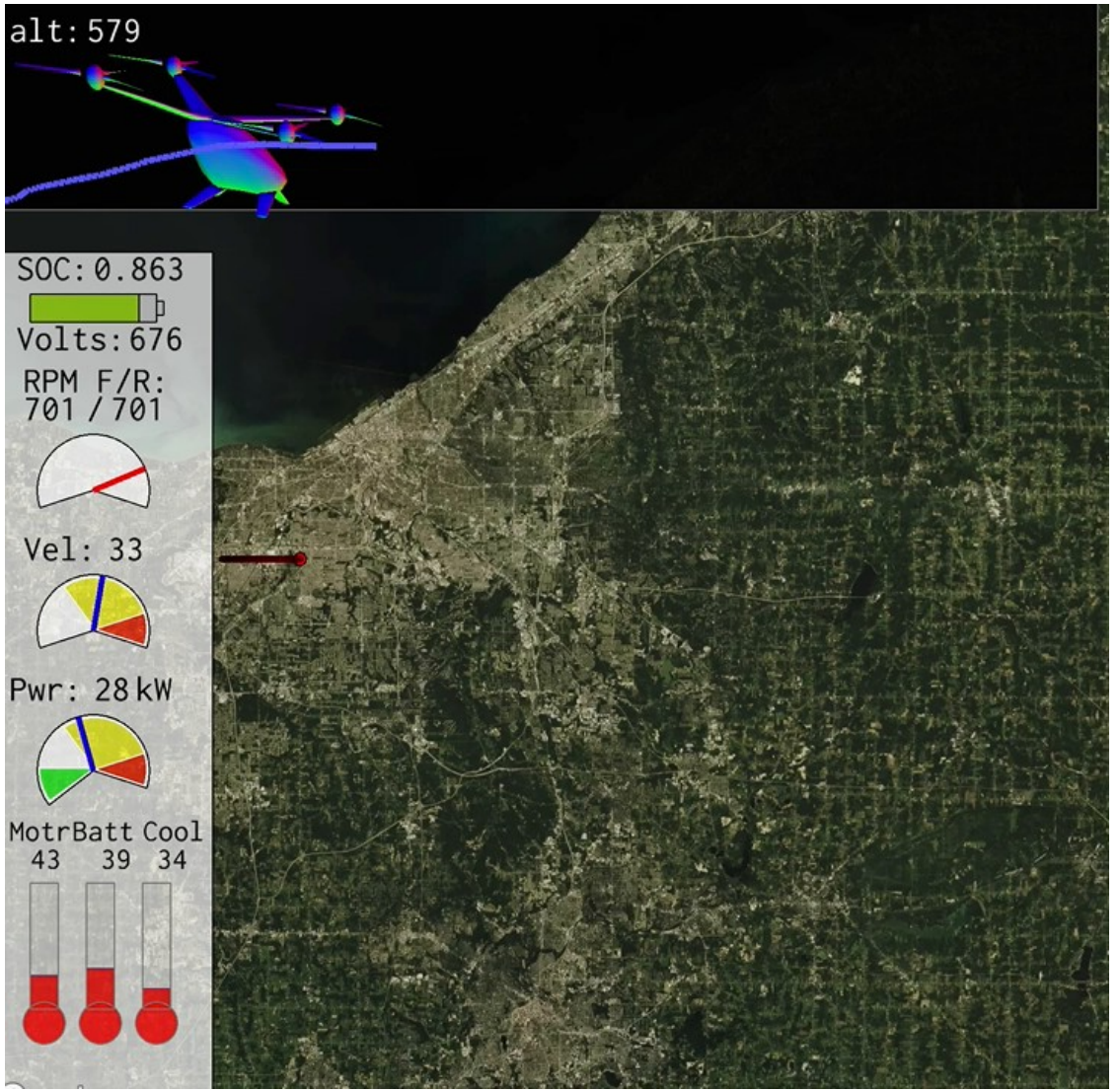
	Variable/Function	Size
minimize	Takeoff mass, or	
	Energy consumption	
with respect to	Total battery energy	1
	Discharge rate	1
	Blade twist distribution	6
	Design rotor power	1
	Coolant flow rate	1
	Heat exchanger width	1
	Heat exchanger height (Coolant)	1
	Heat exchanger height (Air)	1
	Heat exchanger throat area	1
	Takeoff mass (slack)	1
	Rotor shaft speed (slack)	1
	Battery temperature (slack)	75
	TMS power (slack)	75
	Rotor thrust (front and aft)	90

subject to	Time duration	4
	Body frame velocity rates	4
	Max. rotor power	75
	Aircraft pitch rates	76
	Trajectory constraints	154
	Max. descent rate constraint	75
	Min. cruise altitude	45
	Min. battery state of charge	77
	Min. battery Thevenin voltage	75
	Max. battery temperature	271
	Max. coolant temperature	271
	Max. motor temperatures	272
	Takeoff mass (slack)	1
	Battery design constraint (slack)	1
	TMS power (slack)	75
	Battery temperature (slack)	75
	Pseudospectral constraints	2148

Results: Baseline Video

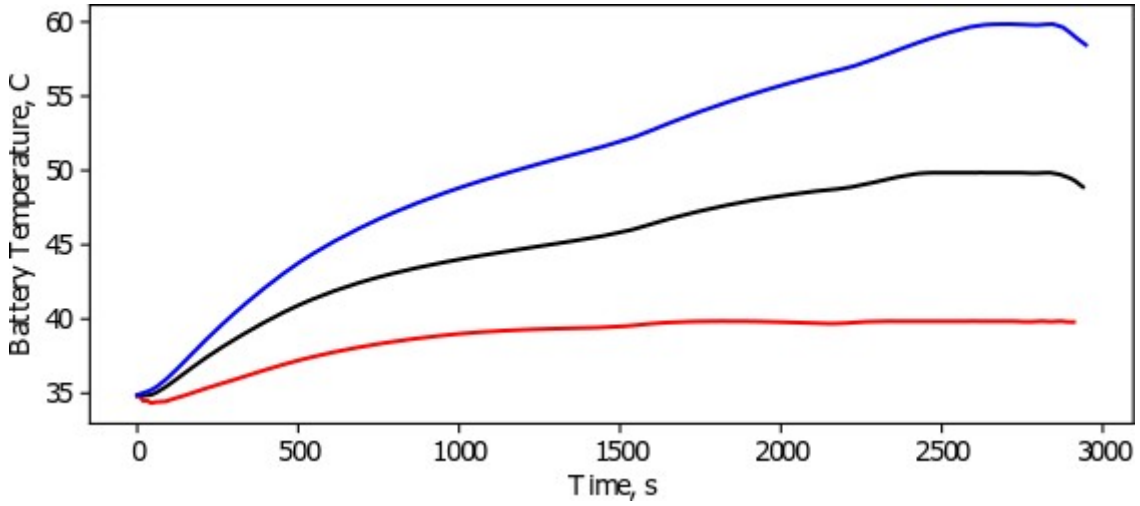


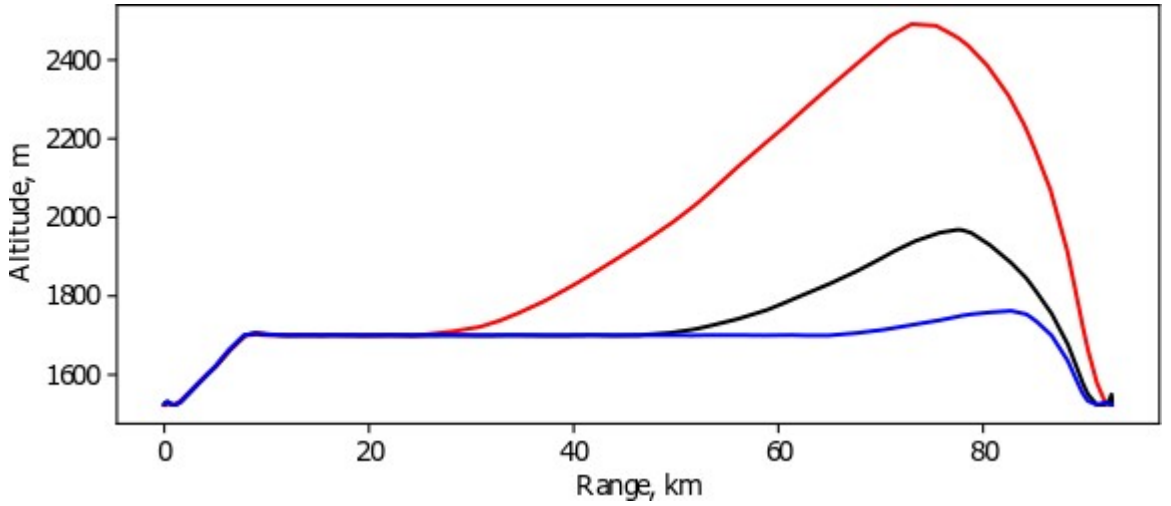
Results: Baseline Video

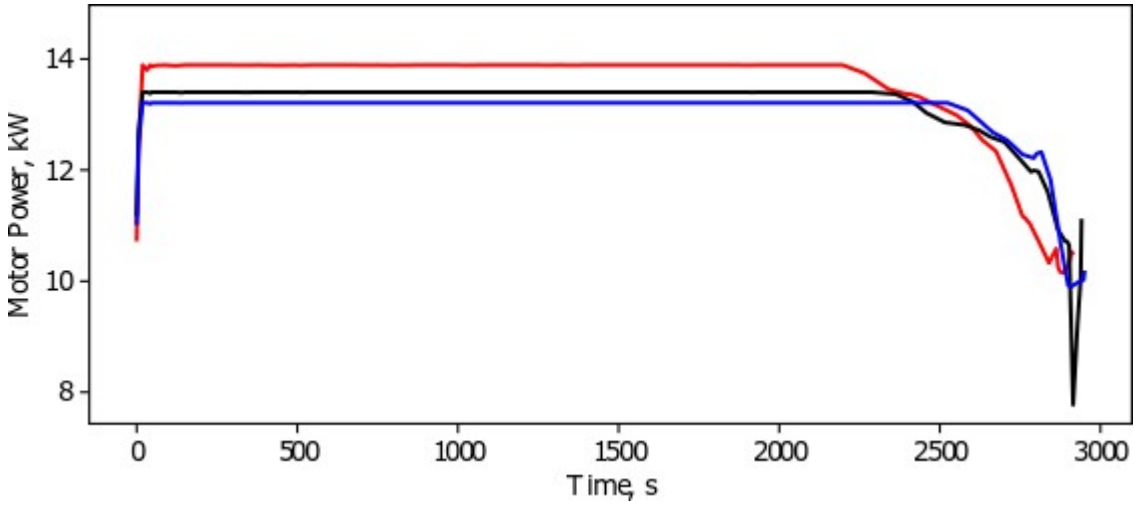


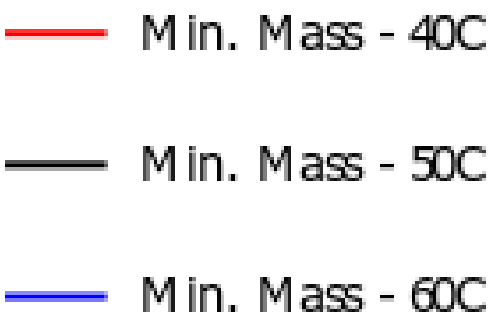
* Altitude (ft)
* Battery Temp (C)

Results: Battery Thermal Sweep



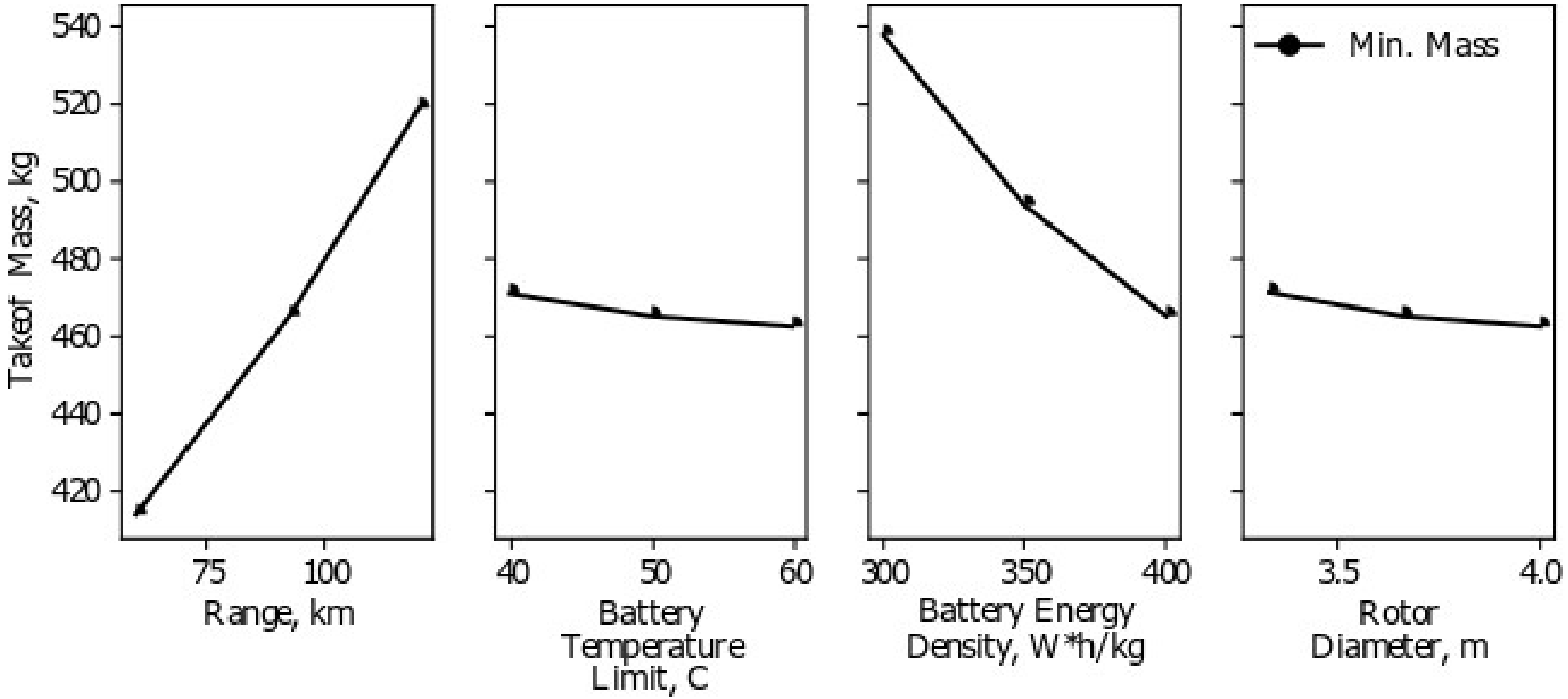






Results: Design Sweeps

- Sweeps of Range, Battery Temp, Energy Density, and Rotor Diameter



Conclusions

- Thermally constrained trajectory
- Battery temp constraints have small effect on system weight
- Changing trajectory can be more effective than increasing thermal management system weight
- Demonstrated tightly coupled optimization

Questions?
earetski@mail.nasa.gc