

Simulation Studies for an Urban Air Mobility Aircraft using Hardware-In-Loop Experiments

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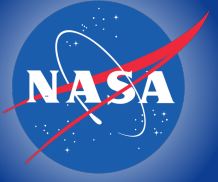
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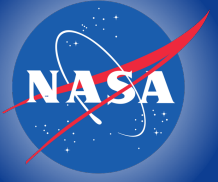
NASA Ames Research Center, Moffett Field, CA





Outline

- **Motivation**
- **Power Demand Simulation**
- **Hardware-in-loop Experiments**
- **Parametric Study and Results**
- **Summary and Future Work**



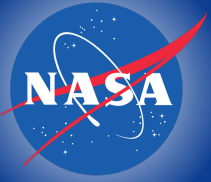
Motivation

- Urban Air Mobility (UAM) will be enabled using Lithium-ion polymer (Li-Po) battery powered electric vertical takeoff and landing (eVTOL) aircraft
- Current battery technology imposes constraints on flight duration and range of eVTOLs because of:
 - low specific energy (energy/mass)*
 - nonlinear discharge behavior**
- Planning and flying minimum-energy trajectories are important from safety and efficiency perspective

*https://www.energytech.org/wp-content/uploads/2017/11/Energytech_MISRA_presentation-rev2.pdf

**Daigle, Matthew J., and Chetan Shrikant Kulkarni. "Electrochemistry-based battery modeling for prognostics." Annual Conference of the Prognostics and Health Management Society (PHM 2013)

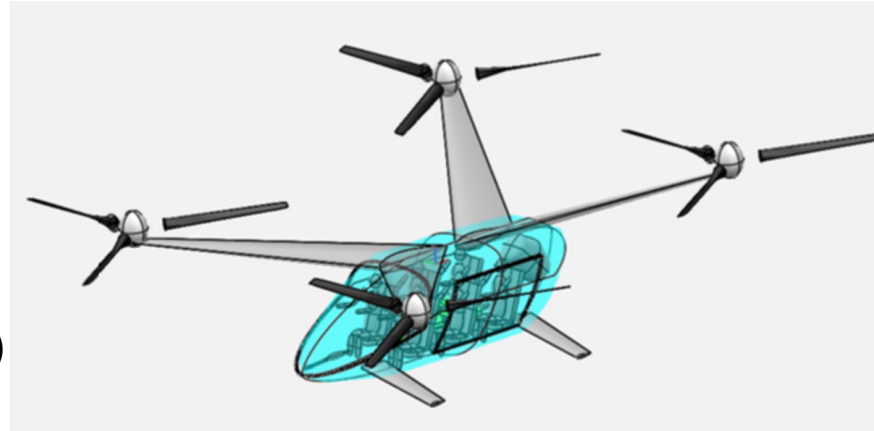




NASA's Conceptual eVTOL Model*

State Variables:

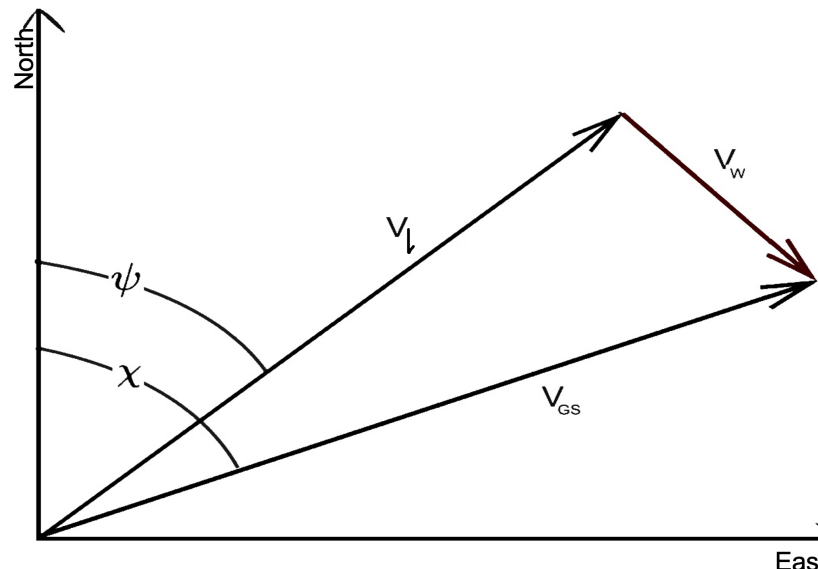
- λ (Latitude)
- τ (Longitude)
- h (Altitude above MSL)
- Ψ (Heading Angle)
- V_l (Lateral Component of True Airspeed)
- V_v (Vertical Component of True Airspeed)



Quadrotor eVTOL Aircraft*

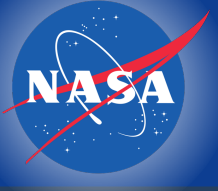
Control Variables:

- T (Thrust)
- Θ (Rotor Tip-Path-Plane Pitch Angle)
- Φ (Rotor Tip-Path-Plan Bank Angle)



Lateral navigation definition

*Silva et al., "VTOL Urban Air Mobility Concept Vehicles for Technology Development," 2018 Aviation Technology, Integration, and Operations Conference, 2018, p. 3847.



Energy Consumption

$$\frac{d\lambda}{dt} = \frac{V_l \cos \psi + W_n}{(R_{\text{Earth}} + h)} = \frac{V_{GS} \cos \chi}{(R_{\text{Earth}} + h)}$$

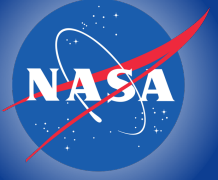
$$\frac{d\tau}{dt} = \frac{V_l \sin \psi + W_e}{(R_{\text{Earth}} + h) \cos \lambda} = \frac{V_{GS} \sin \chi}{(R_{\text{Earth}} + h) \cos \lambda}$$

$$\frac{dh}{dt} = V_v + W_v$$

$$\tan \gamma = \frac{V_v}{V_l}$$

$$T = 4T_{\text{rotor}}$$

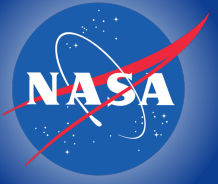
$$D = 1.1984q$$



Power Model

$$P_{\text{required}} = P_{\text{induced}} + P_{\text{parasite}} + P_{\text{climb}} + P_{\text{profile}}$$

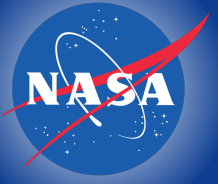
$$P_{\text{required}} = \kappa \sum_{n=1}^4 (T_{\text{rotor}} v_i)_n + TV \sin \alpha + \frac{\rho A_{\text{rotor}} (\omega R)^3 \sigma C_{d \text{ mean}} F_P}{8}$$



Hardware-in-loop Experiments

- Simulation Setup

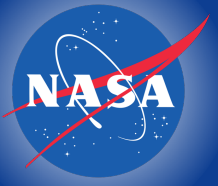
Cruise Altitude (m)	Power Required (kW)					
	Vertical Takeoff	Climb	Cruise	Descent (45 Deg)	Approach (8 Deg)	Vertical Landing
500	264.94	273.53	142.74	Negligible	Negligible	139.45
1000	264.94	272.66	148.10	Negligible	Negligible	139.45
2000	264.94	273.03	154.84	Negligible	Negligible	139.45
3000	264.94	273.13	161.54	Negligible	Negligible	139.45



Hardware-in-loop Experiments

- Simulation Setup

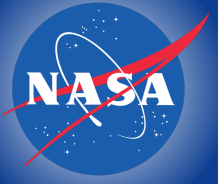
Cruise Altitude (m)	Normalized Power Drawn (W)					
	Vertical Takeoff	Climb	Cruise	Descent (45 Deg)	Approach (8 Deg)	Vertical Landing
500	607.28	628.75	328.12	0	0	320.56
1000	607.52	626.76	340.43	0	0	320.56
2000	607.52	627.61	355.94	0	0	320.56
3000	607.52	627.84	371.32	0	0	320.56



Hardware-in-loop Experiments

- Battery pack is charged at 1C of the rate current
- Discharge the battery pack based on the flight power profile
- This profile is normalized to the ratings of the battery under test.
- Record current, voltage and temperature during the cycles are recorded through the MACCOR test unit.
- For this work, performance of the battery at different cruise C rates is planned at constant temperature. C rating means. what does changing of C rates does to the battery SOC and distance travelled.

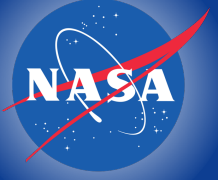




Results and Discussion

- Vertical Take Off
- Climb
- Cruise
- Decent
- Approach
- Vertical Landing

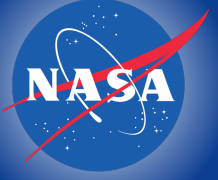
Cruise Altitude (m)	Flight Duration (sec)					
	Vertical Takeoff	Climb	Cruise	Descent (45 Deg)	Approach (8 Deg)	Vertical Landing
500	15.51	85	680.8	0	115	15.5
1000	15.51	180	855.5	11.4	115	15.5
2000	15.51	369	1045.9	32.6	115	15.5
3000	15.51	558	1147.9	52.1	115	15.5



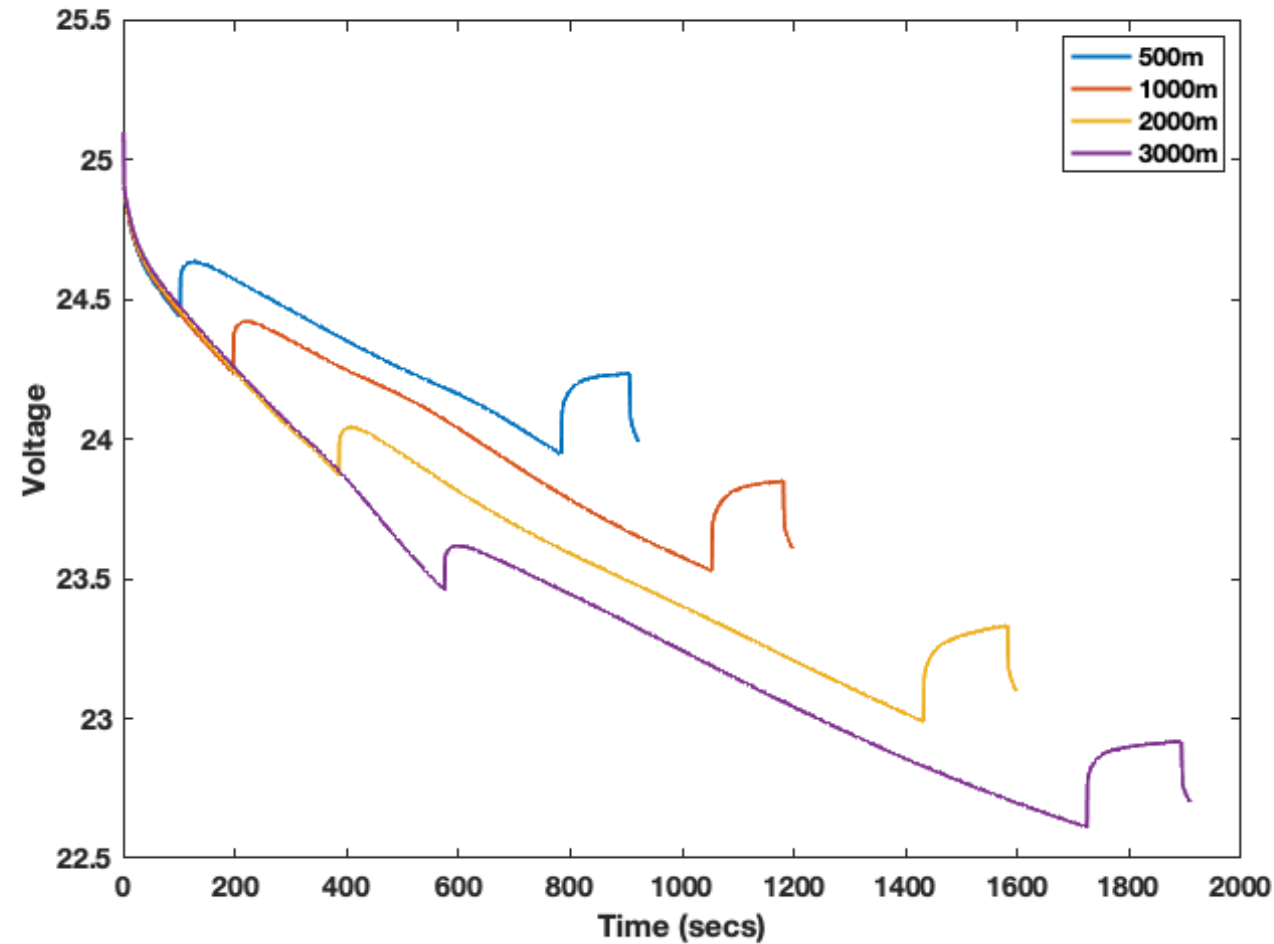
Results and Discussion

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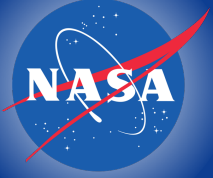
Cruise Altitude (m)	Best-Range Airspeed (m/s)	Power Required (kW)
500	43	142.74
1000	44	148.10
2000	46	154.84
3000	48	161.54



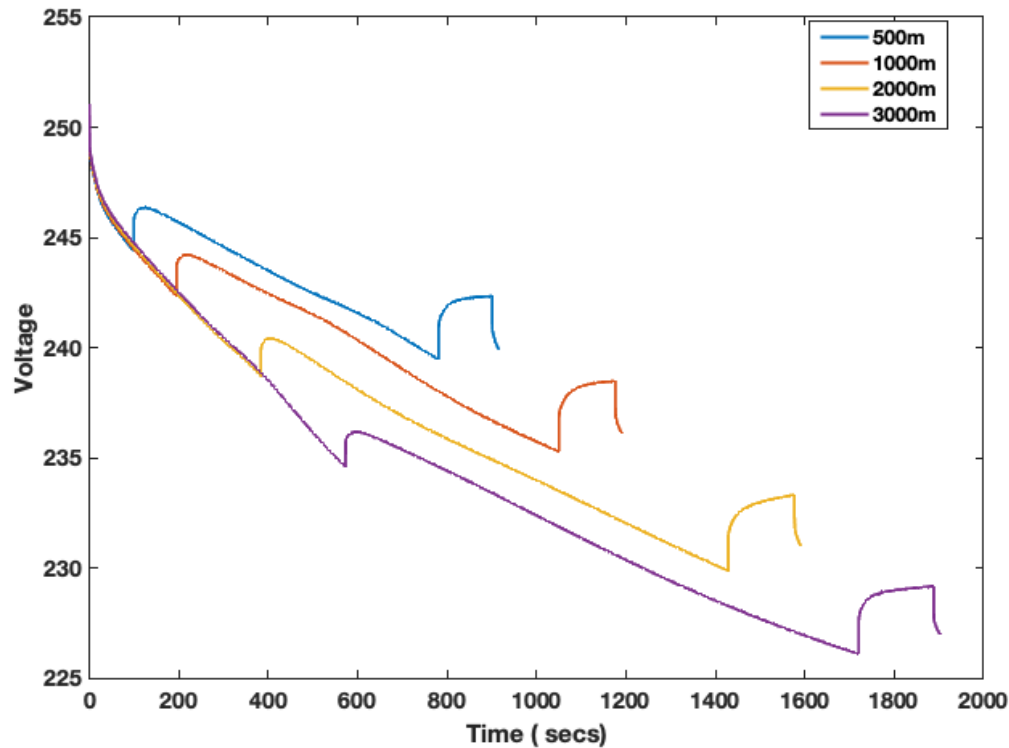
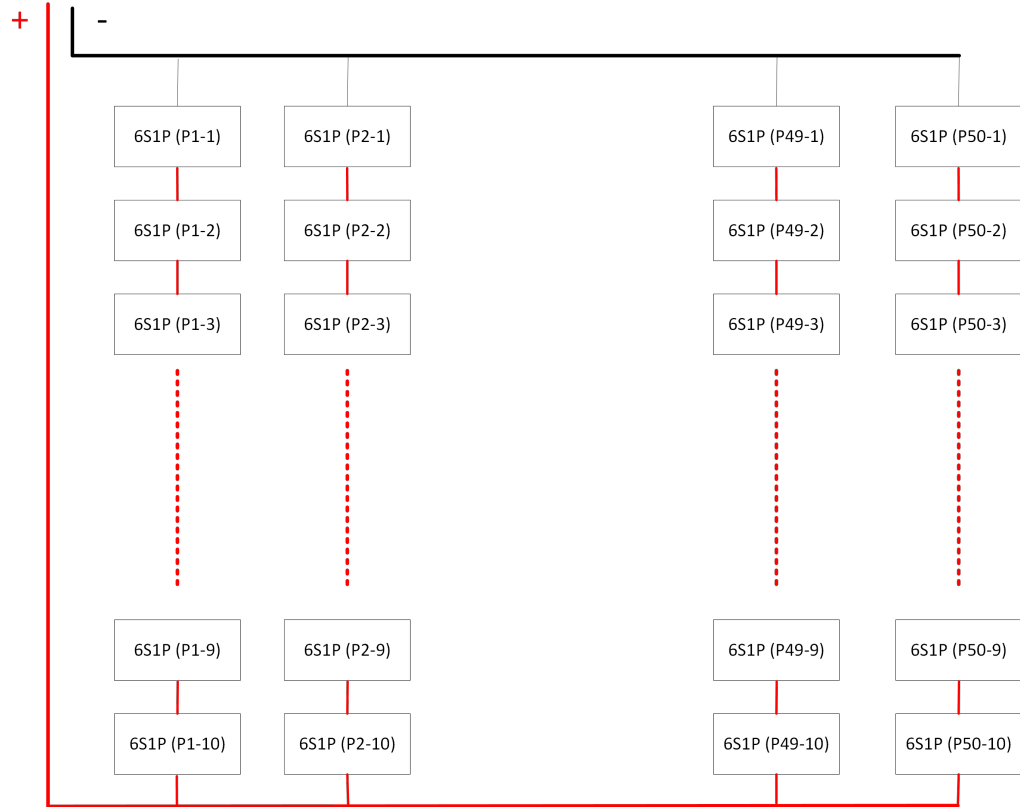
Results and Discussion



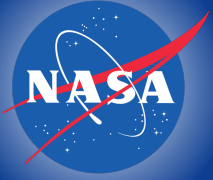
Flight Profile Simulation on a Li-Po 6S Battery Pack at different altitudes for 30 nm range



Results and Discussion

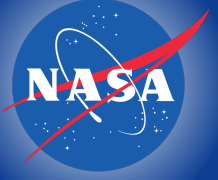


Voltage Discharge Plot : Profile Simulation at vehicle level with for different altitudes for 30nm range

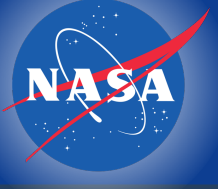


Summary

- The purpose of this research study was to observe and validate as a first step if the battery pack is able to sustain through the simulated flight demonstration and not discharge below a set lower threshold value of 30%
- A NASA-proposed conceptual multirotor eVTOL aircraft flight in the urban environment was
- simulated to estimate power consumption. Using the flight dynamics and kinematics equations energy consumption for the eVTOL vehicle is calculated. The simulated power was calculated for different cruise altitudes i.e 500, 1000, 2000 and 3000m for a range of 30 nm where the cruise speed current draw is assumed to be 0.6C.
- Demonstrated a hardware-in-loop experiment to simulate a battery pack for a 30nm range for different altitudes.
- The results observed through the hardware-in-loop tests on the battery pack show that with change in altitude for a similar range of 30nm the amount of power draw. Subsequently the voltage discharge and state-of-charge is lower indicating the upon completion of the flight the vehicle will have lower SOC available



- Perform hardware-in-loop experiments for estimated power consumption rates at varying C rates for cruise speed
- Observe their effect on the voltage discharge and SOC of the batteries
- Model based prognostics framework will be implemented to estimate state-of-charge as well as predict remaining flying time given a particular flight profile



Please reach out for your questions

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