BADA eVTOL Performance Model for UTM Traffic Simulation and Analysis

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European Global Navigation Satellite Systems Agency
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AIRBUS
EUROCONTROL

Context: DELOREAN project

- "**D**rones and **E**GNSS for **Lo**w ai**r**spac**e** urb**an** mobility"
- Part of EU framework program Horizon 2020
- Main objective: assess and promote the use of EGNOS and Galileo as an enabler to UAM services
- Air Taxi scenario includes a route optimization module, which requires the use of aircraft performance models
- Cooperation between:
  - Airbus UTM: develops UAM eVTOL prototypes
  - EUROCONTROL/BADA: develops aircraft models
- Objective: Generate an aircraft performance model, suitable to be used for research and future UTM automated services

The vehicle: A³ Vahana (eVTOL for UAM)

Vahana was a single-passenger or cargo, all-electric, fully autonomous eVTOL demonstrator, developed by Acubed – Airbus' Innovation Center, in the Silicon Valley

Main characteristics:

- MTOW: 725kg
- Payload: 100kg
- Cruise speed: 100kt
- Range: 50km

Vertical climb, hover and transition to horizontal cruise successfully tested.

Structure of the APM

Aircraft Performance Model is structured in following topics:

1. Motion Equations
2. Power required for horizontal flight
3. Propulsion
4. Operations

Motion Equations

Motion equations are based on the modelling approach of BADA H, a helicopter performance model recently developed by EUROCONTROL.

Energy equation provides a functional relationship that correlates power required for horizontal flight (P_{req}) with following vehicle state variables:

- Power delivered to the propulsion system (P)
- Acceleration
- Rate of climb or descent (ROCD)

$$P - P_{req} = mv\frac{dv}{dt} + mg\frac{dh}{dt}$$

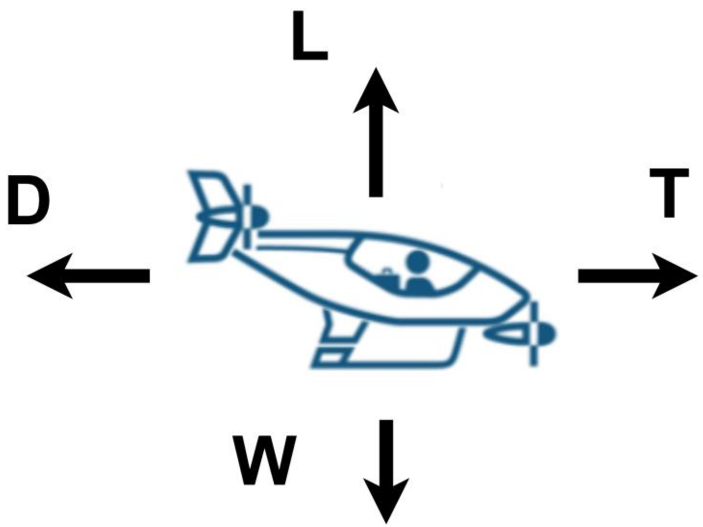
Fuel consumption rate equation is substituted by electric energy consumption rate.

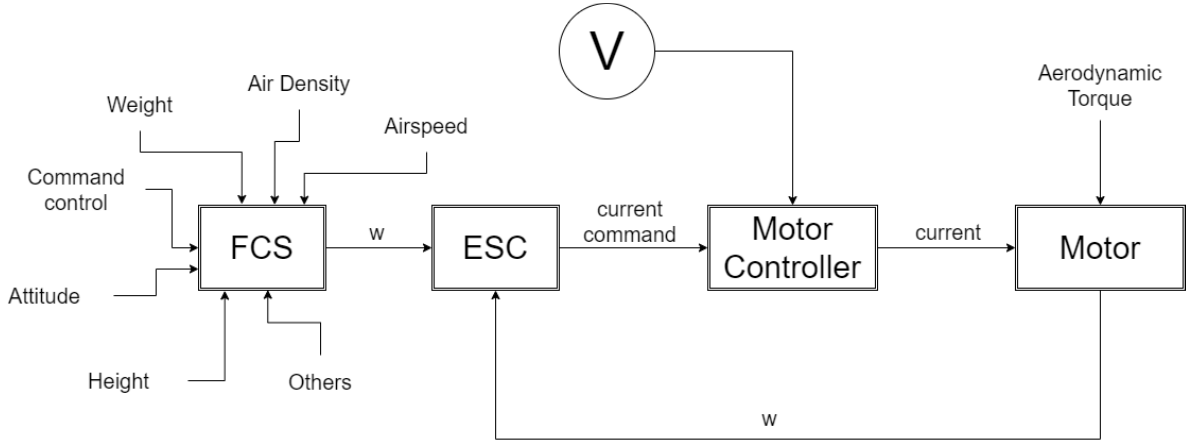
$$\frac{dB}{dt} = -E$$

Aircraft Performance Model

Objective of the Aircraft Performance Model is:

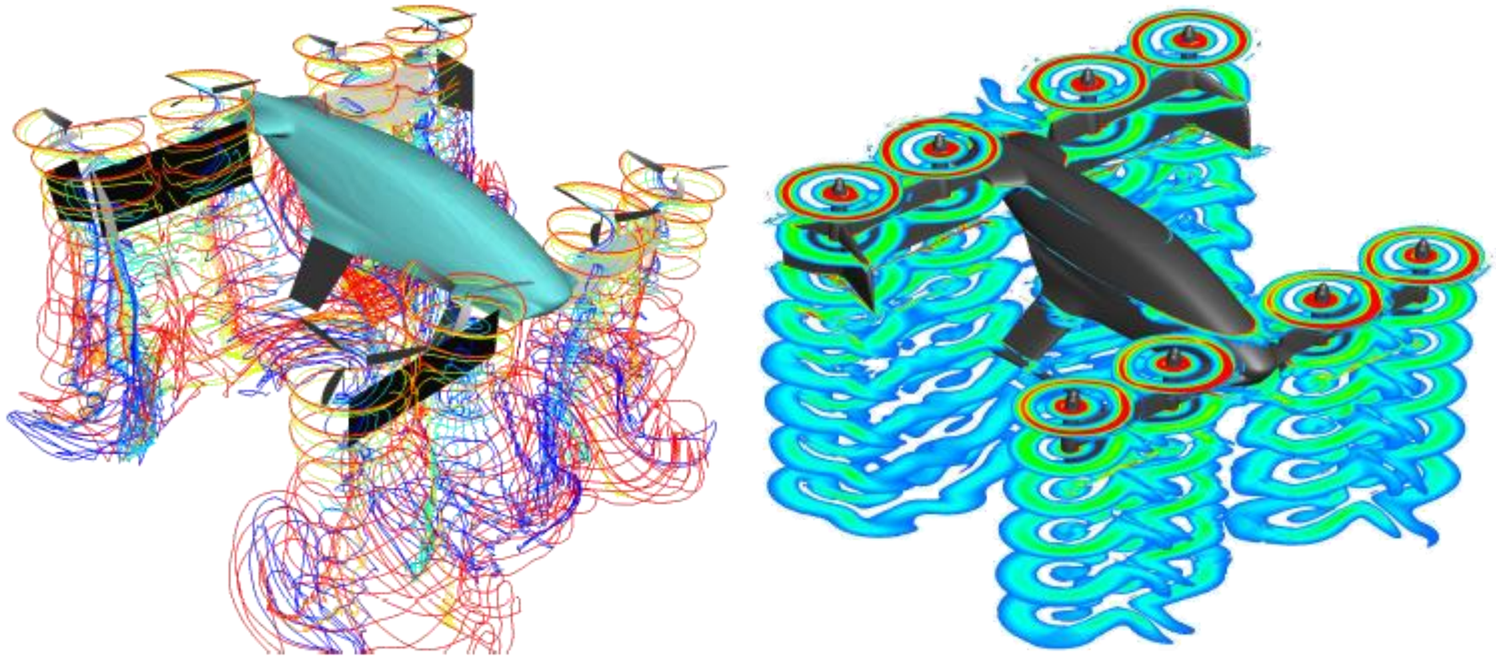
- Provide power required for horizontal flight (P_{req}) as function of the vehicle state variables
- Provide electric energy consumption rate as a function of Power delivered to the propulsion system.





Power Required for Horizontal Flight (I)

Rotorcraft have more complex aerodynamics than airplanes
Multi-rotor aircraft are more complex than single-rotor
Tilt-wing aircraft are even more complex
Vahana has eight rotors on tilt-wings!



Power Required for Horizontal Flight (II)

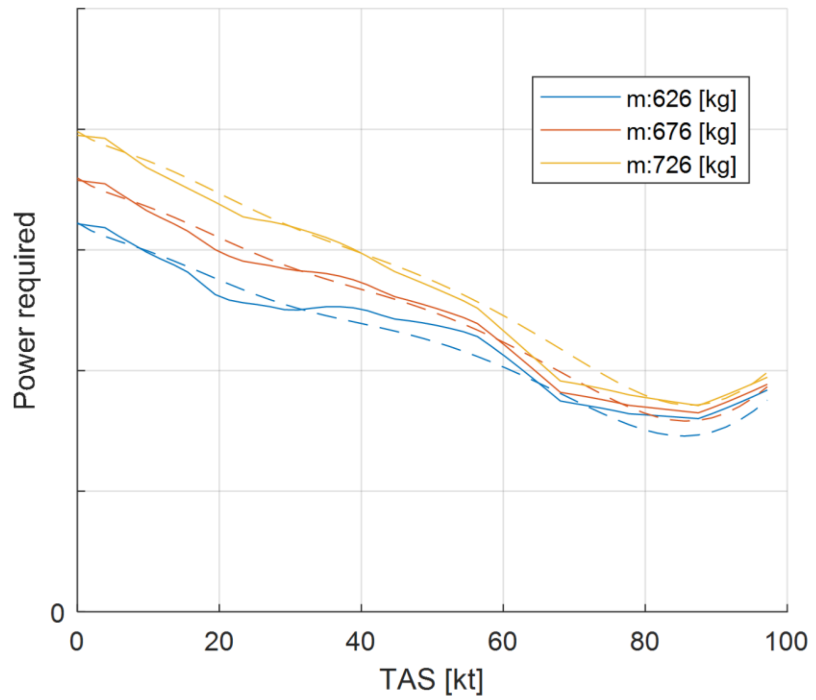
Exiusting BADA Helicopter model formulas are tuned to reproduce the main aspects of Vahana aerodynamics

Rotor angular speed is modelled as a 5th degree polynomial of speed.

$$P_{req} = \rho \pi R^2 (\Omega R)^3 C_{Preq}$$

$$C_{Preq} = C_{pr,1} + C_{pr,2}\mu^2 + C_{pr,3} C_T \sqrt{\sqrt{\mu^4 + C_T^2} - \mu^2}\, C_{pr,4}\mu^3 + C_{pr,5} C_T^2 \mu^3$$

$$C_T = \frac{mg}{\rho \pi R^2 (\Omega R)^2 \cos(\phi)} \qquad \mu = \frac{v}{\Omega R}$$



Propulsion (I)

Electric engines are actually simpler to model than jet or piston:

- Constant efficiency
- No impact of altitude or temperature on power output

Batteries are much more complex to model than fuel:

- Power output depends on state of charge (SOC), temperature…
- Capacity depends on state of health (SOH)

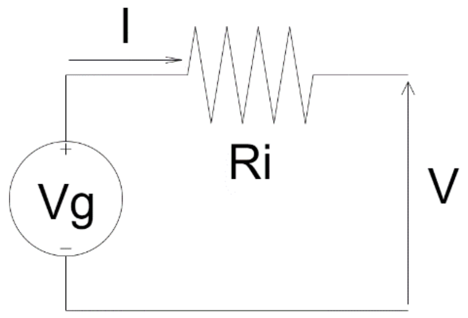
Battery model objectives for the APM are:

- Calculate power losses due to heat dissipation in the battery
- Calculate limitations in power that battery is able to deliver

Propulsion (II)

Power losses are obtained by simulating battery as an ideal electric circuit voltage generator plus resistor.

Vg and Ri are modelled as functions of the battery State Of Charge (SOC) and current delivered to the system.



$$V_G = V_0 - R_0 \cdot I$$

$$V_0 = v_0 + v_1 \cdot SOC^{v_2} + v_3 \cdot \frac{SOC}{SOC + 0.1} + \frac{v_4}{100.1 - SOC}$$

$$R_0 = r_0 + r_1 \cdot SOC^{r_2} + r_3 \cdot \frac{SOC}{SOC + 0.1} + \frac{r_4}{100.1 - SOC}$$

$$R_i = r_{i0} + r_{i1} \cdot SOC + +r_{i2} \cdot SOC^2$$

$$P_{loss} = R_i \left(\frac{V_0 - \sqrt{V_0^2 - 4 \cdot R_t \cdot P_{bat}}}{2 \cdot R_t} \right)^2$$

Propulsion (III)

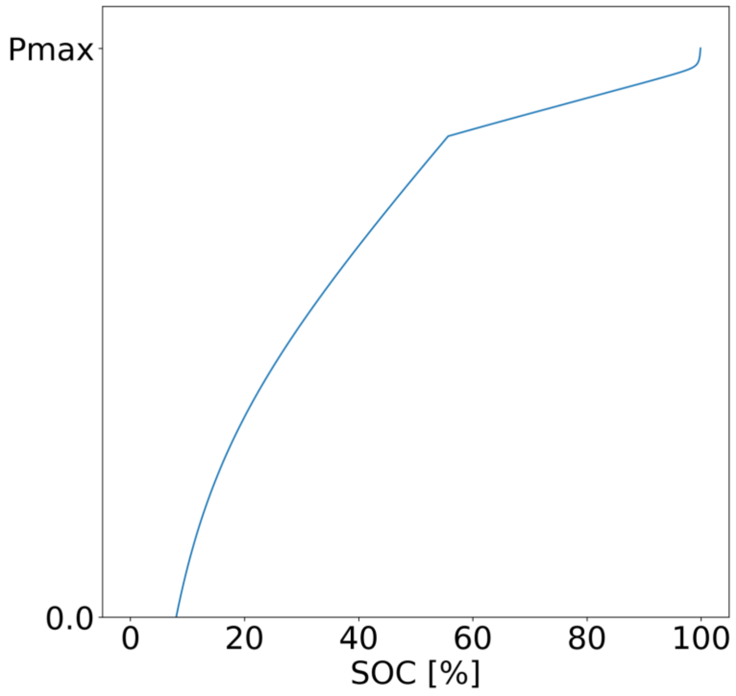
Limitations of maximum power deliverable by battery are also obtained as a function of SOC.

Maximum current battery can produce:

- $P_{\max 1} = V_{min} \frac{V_0 - V_{min}}{R_t}$

Minimum voltage required by system:

- $P_{\max 2} = (V_0 - R_t \cdot I_{max}) \cdot I_{max}$

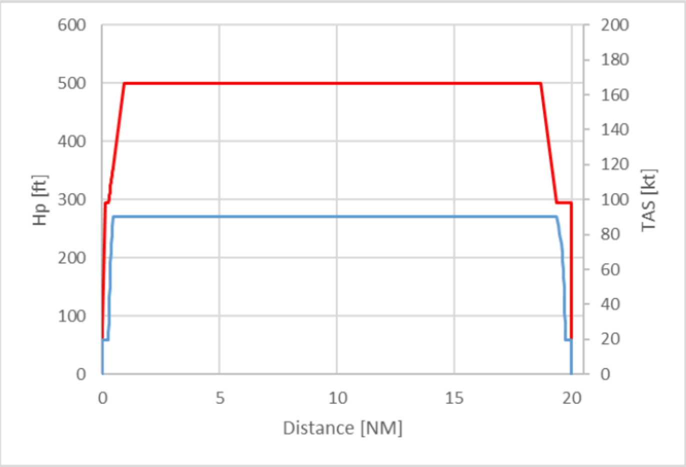


Operations

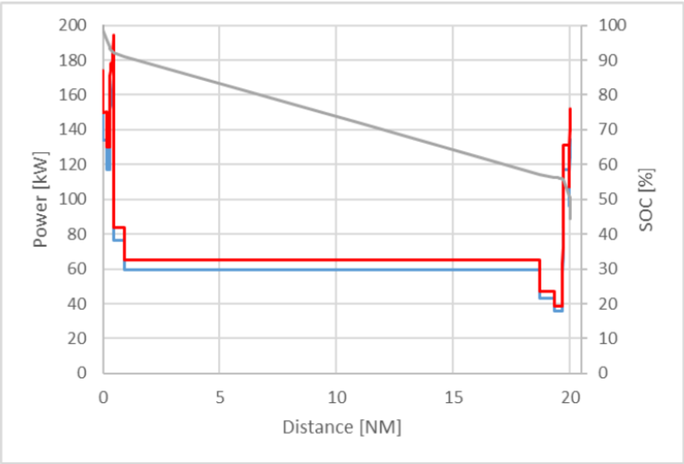
Main obstacle in producing an operations model is that there is no large eVTOL currently operating.

Re-use of what's available (e.g. Uber Elevates mission profiles) and make "educated guesses" to fill in the blanks, until the concepts get more mature

Proposed model allows to calculate a full trajectory, from take-off to landing



Altitude and true airspeed (full trajectory)



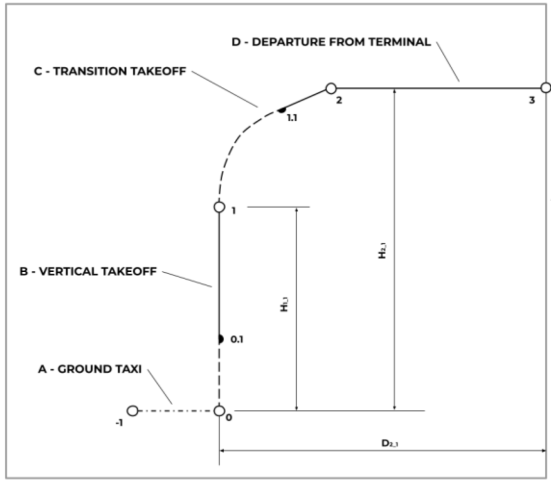
Mechanical and electrical power, SOC (full trajectory)

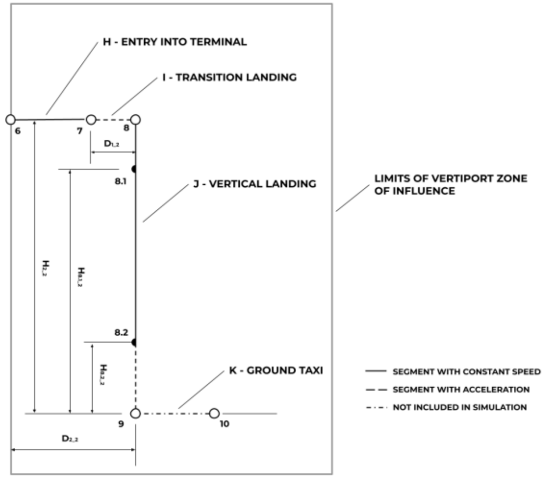
Known Limitations and Future Work

Only one vehicle dataset was used to generate the model: no general goodness of fit can be assessed now for power required or battery.

Model has to be fed with data of other vehicles.

Vehicle operations are the biggest unknown. Only guesses can be made right now. Future research work on this topic will lead to improving the operations model.





Conclusion

Airbus UTM and EUROCONTROL developed a UAM vehicle model based on data from a real flying eVTOL.

Model proposed is based on currently existing APM implementation (BADA), precise enough for traffic management applications.

Even though the physical model needs to be validated with data from other eVTOL, it is a good starting point for future developments.