TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

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Air taxi flight performance modeling and application

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Agenda

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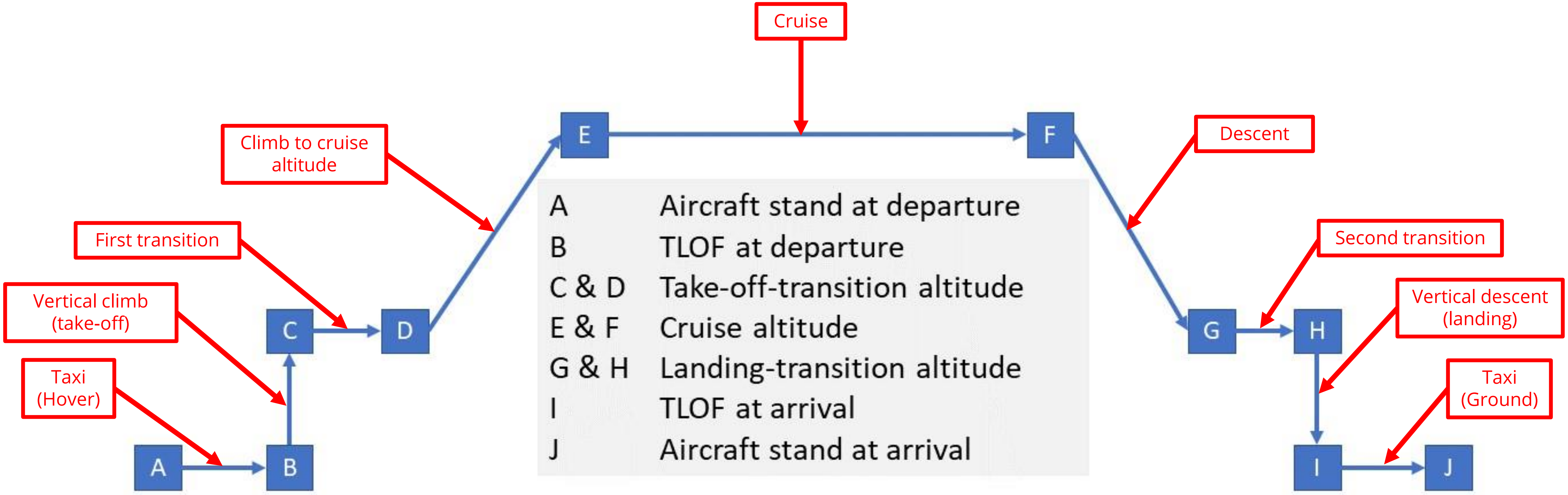
Problem statement

- Various aircraft concepts for flying electrical → different behaviour concerning flight performance
- Battery is the central element → most limiting factor in terms of flight range and endurance of electric vertical take-off and landing aircraft (eVTOL)
- No real world range data available since there are only prototypes → range data published by eVTOL manufacturers
- For later network design, the range is one of the most important capabilities of eVTOLs
- **Central problem: manufacturers data vs. real world conditions**

Does published range data express future reality of air taxi services?

Operational background

Operational background
a) UAM flight mission profile



A	Aircraft stand at departure
B	TLOF at departure
C & D	Take-off-transition altitude
E & F	Cruise altitude
G & H	Landing-transition altitude
I	TLOF at arrival
J	Aircraft stand at arrival

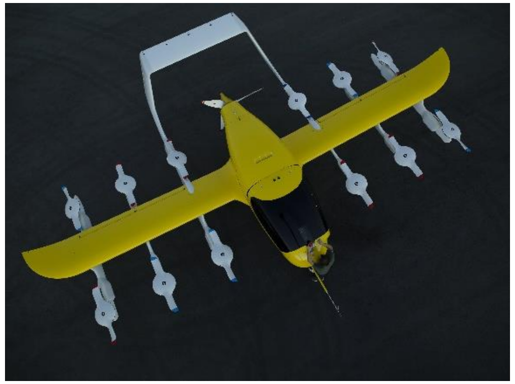
Operational background
b) eVTOL aircraft concepts

Vectored thrust

Source: https://newatlas.com/aircraft/joby-aviation-evtol-video/

- Use of any propulsion unit for vertical and horizontal segments
- Tilting elements to adjust propulsion vector
- Behavior like a fixed-wing aircraft during cruise
- More efficient during cruise; less during vertical segments
- Higher range and speed capabilities

Lift & cruise



Source: https://twitter.com/WiskAero/status/973711770853535744?s=20

- Independent propulsion units for vertical and horizontal segments
- No tilting elements
- Behavior like a fixed-wing aircraft during cruise
- More efficient during cruise; less during vertical segments
- Higher range and speed capabilities

Multicopter

Source: https://www.volocopter.com/solutions/volocity/

- Multiple horizontally mounted rotors
- Comparable to conventional helicopters (rotary-wing aircraft)
- Higher efficiency during vertical segments
- Limited range and speed capabilities

Methodology

Methodology
a) Power & energy requirements (1)

Power requirements per flight segment:

- (Hover)Taxi: $$P_{ht} = \frac{W}{\eta_{hover}} \cdot \sqrt{\frac{DL}{2\rho}} \quad (1)$$
- Vertical climb (take-off): $$P_{to} = P_h \cdot \left[\frac{RoC_{to}}{2v_h} + \sqrt{\left(\frac{RoC_{to}}{2v_h}\right)^2 + 1} \right] \quad (2)$$
- First transition: $$P_{trans} = P_{induced} + P_{drag,rotor} + P_{drag,aircraft} \quad (3)$$

$$P_{induced} = \frac{W}{\eta_{trans} \cdot \sin\theta_{tilt}} \cdot \sqrt{-\frac{V_\infty^2}{2} + \sqrt{\left(\frac{V_\infty^2}{2}\right)^2 + \left(\frac{W}{\sin\theta_{tilt} \cdot 2\rho A}\right)^2}} \quad (4)$$

$$P_{drag,rotor} = \rho A V_{tip}^3 \cdot \left(\frac{\sigma C_d}{8} \cdot (1 + 4.6\mu^2)\right) \quad (5)$$

$$P_{drag,aircraft} = 0.5 \rho V_\infty^3 C_D S \quad (6)$$

DL	Disc loading
RoC_{to}	Rate of climb take-off
v_h	Velocity hover
V_∞	Induced velocity rotor disc plane
V_{tip}	Blade tip velocity
σ	solidity
C_d	Drag coefficent blade
θ_{tilt}	Tilt angle
C_D	Drag coefficient aircraft
S	Wing surface
μ	Velocity ratio at rotor disc plane
A	Total disc area

Methodology
a) Power & energy requirements (2)

V_{climb}	Climb out speed
RoC_{cl}	Rate of climb during climb segment
$\frac{L}{D}$	Lift to drag ratio (during climb and cruise)
V_d	Horizontal descent speed

- Climb to cruise altitude: $$P_{climb} = \frac{W}{\eta_{climb}}\left(RoC_{cl} + \frac{V_{climb}}{\left(\frac{L}{D}\right)_{climb}}\right) \quad (7)$$
- Cruise and descent: $$P_{cruise} = \frac{W \cdot V_{cruise}}{\left(\frac{L}{D}\right)_{cruise} \cdot \eta_{cruise}} \quad (8)$$
- Second transition: $$P_{trans,2} = P_{induced,2} + P_{drag,rotor} + P_{drag,aircraft,2} \quad (9)$$

$$P_{induced,2} = \frac{W}{\eta_{trans} \cdot \sin\theta_{tilt}} \cdot \sqrt{-\frac{V_d^2}{2} + \sqrt{\left(\frac{V_d^2}{2}\right)^2 + \left(\frac{W}{\sin\theta_{tilt} \cdot 2\rho A}\right)^2}} \quad (10)$$

$$P_{drag,rotor} = \rho A V_{tip}^3 \cdot \left(\frac{\sigma C_d}{8} \cdot (1 + 4.6\mu^2)\right) \quad (5)$$

$$P_{drag,aircraft,2} = 0.5\rho V_d^3 C_D S \quad (11)$$

Methodology
a) Power & energy requirements (3)

v_i	Induced velocity during vertical segments
RoC_{ld}	Rate of climb vertical descent
E^*	Specific energy
$m_{battery}$	Battery mass
$m_{aircraf}$	Aircraft mass

- Vertical descent (landing): $P_{vd} = P_h \cdot \left[\frac{RoD_{ld}}{v_h} + \frac{v_i}{v_h}\right]$ (12)
- (Ground)Taxi: $P_{gt} = 0.1 \cdot P_{cruise}$ (13)

<u>Energy demand E per flight segment i:</u>

- General expressed by product of power P_i and time t_i: $E_i = P_i \cdot t_i$ (14)
- With n segments the total Energy E_{tot} becomes: $E_{tot} = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} P_i \cdot t_i$ (15)

<u>Range estimation:</u>

- range equation for electric flight: $R = E^* \cdot \eta_{tot} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \frac{m_{battery}}{m_{aircraft}}$ (16)

Methodology
b) Model application – assumptions

Battery parameters

	Vectored Thrust	Lift & Cruise	Multicopter
$E^* \left[\frac{Wh}{kg}\right]$	150	180	180
$P^* \left[\frac{W}{kg}\right]$	2,100	1,600	1,100
$\eta_{tot}[-]$	0.95	0.95	0.95
$DoD\ [-]$	0.8	0.8	0.8
$m_{battery}[kg]$	730	400	300
$E_{use}[kWh]$	83	55	41
$P_{use}[kW]$	1,165	486	251

General assumptions

- Consideration of additional power requirements due to losses of the propulsion system by introducing several efficiency values
- Cruise speed chosen according to 80% of maximum speed published by manufacturers
- Calculation and results based on the maximum take-off mass (MTOM) of each eVTOL
- Range estimation based on specific energy for cruise and descent segment (E^*_{cruise})

Flight mission time

Segment	Time [s]
First taxi	30
Take-off	45
First transition	45
Climb	60
Cruise & descent	1,500
Second tranition	45
Landing	45
Second taxi	30
Σ	**1,800**

Results

Results

Power Requirements

- Transition segments = peak power demanding segments for vectored thrust and lift & cruise eVTOL, whereas it is the climb for multicopter
- The power demand during transition of vectored thrust eVTOL exceeds P_{use} by 22.8% and 41.7% for lift & cruise
- Power demand for all other segments is lower than P_{use}
- Power demand for multicopter in all segments is lower than P_{use}

Energy demand

- Excess of energy demand compared to E_{use}:
  - vectored thrust by 37% and
  - multicopter by 11%
- Lift & cruise eVTOL has reserve of 11% after assumed mission
- Multicopter would be able to perform flight mission when using total energy (16% reserve in that case)

Range estimation

- Estimation is only based on the time of cruise and descent segment (corresponding E^*_{cruise})
- Only theoretical, because eVTOL would not be able to perform the assumend mission according to results of power and energy requirements
- Vectored thrust: 115 km *(vs. 240 km)*
- Lift & Cruise: 70 km *(vs. 40 km)*
- Multicopter: 50 km *(vs. 35 km)*

Conclusion

Conclusion

- Expectation that vertical segments / transition = peak power / energy demanding segments is proven (the chosen values for specific power and energy are not sufficient)
- Simplification of using ρ at MSL:
  - Influences of altitude and temperature are neglected within our framework
- Battery parameters = central factor
  - Value of specific power affects and limits performing capability of vertical segments
  - Value of specific energy influences achievable range
- To increase range → maximizing of:
  - Battery mass ratio (increasing battery mass by a constant aircraft mass)
  - Lift over drag ratio
  - Total system efficiency
  - Energy density → values of 450 Wh/kg expected in future → possible ranges:
    - Vectored thrust: 260 km
    - Lift & cruise: 190 km
    - Multicopter: 120 km

Thank you for your attention!

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