wingtra

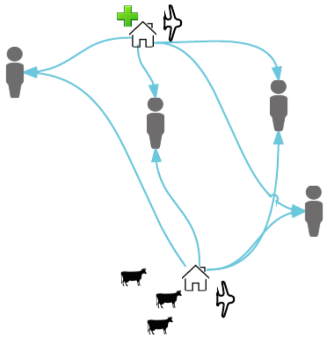
Sebastian Verling

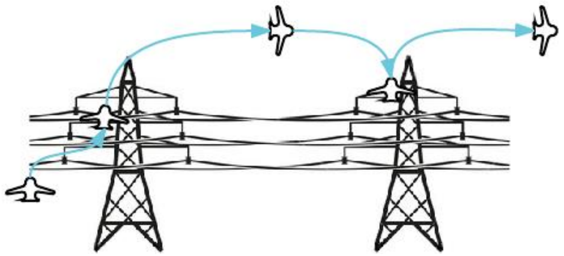
What is Wingtra

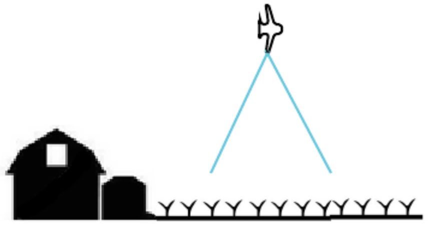
- Started as Studentproject at ETH
- Spin Off Company
- Provide an efficient VTOL Platform
  - Aerial imaging
  - Agriculture
  - Mapping

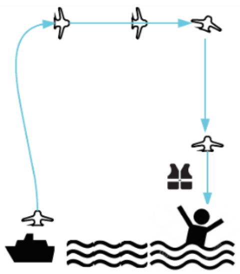
The Vision

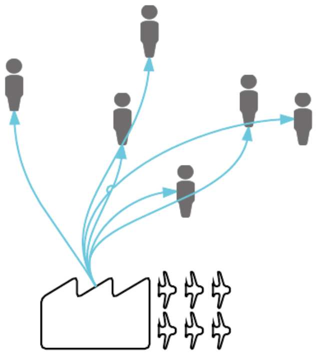
Combined maneuverability and forward flight efficiency make new applications possible



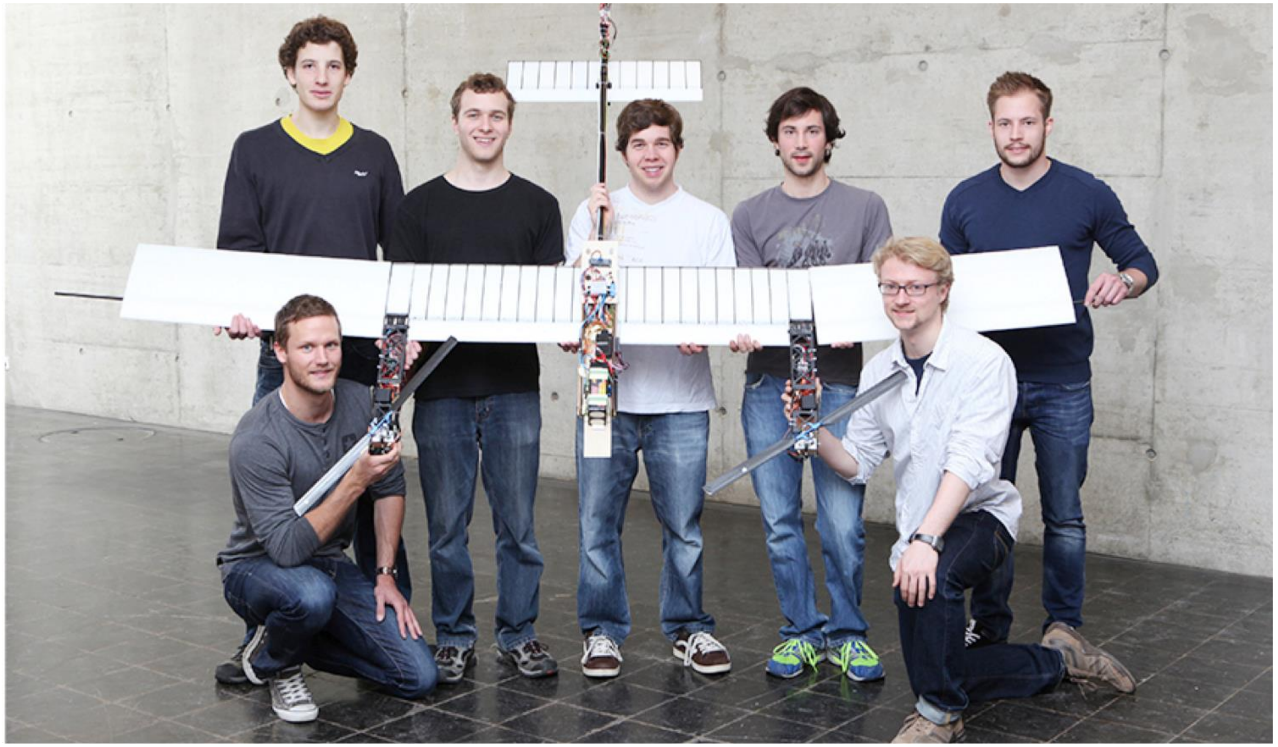








The Focus Project



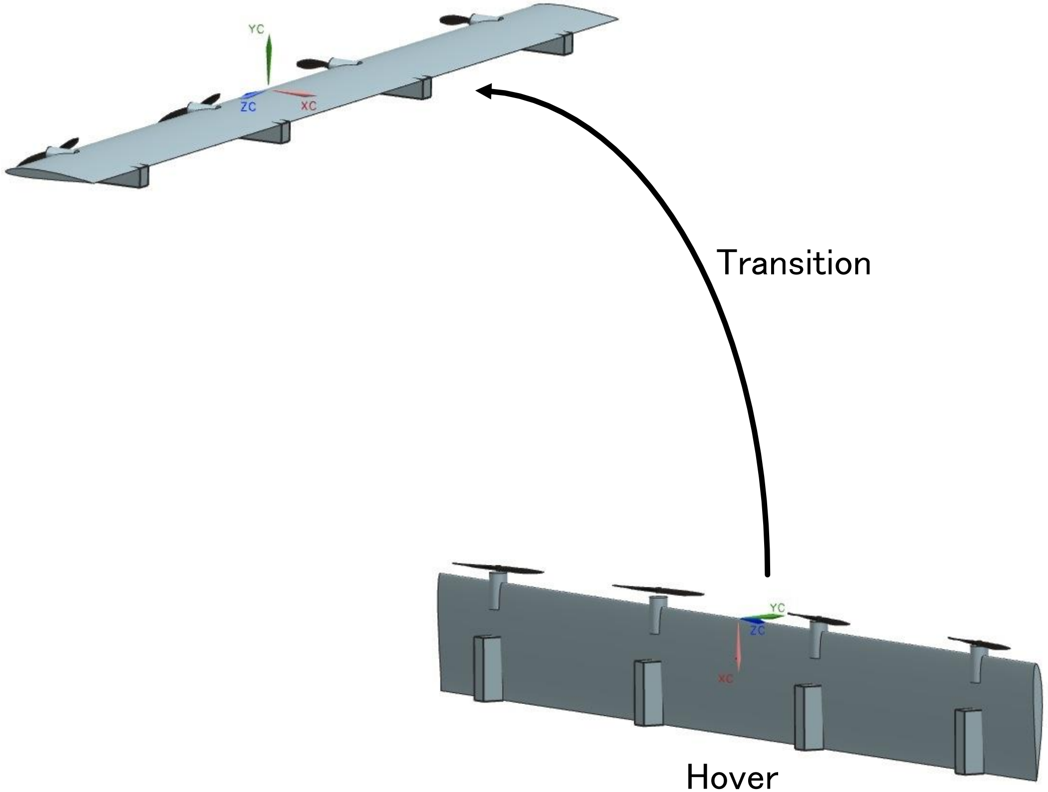
Cruise Flight

Problems with the Design

- Fragile
- 10 actuators
- Complex
- No redundancy
- Expensive Manufacturing

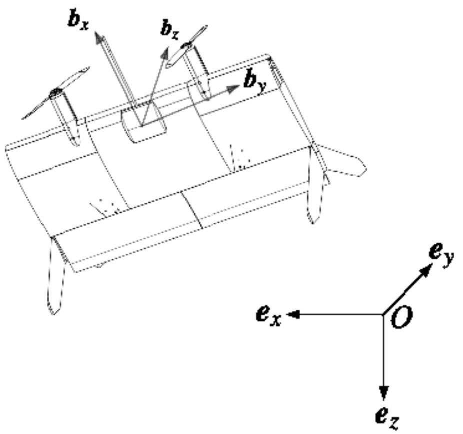
Alternative Design

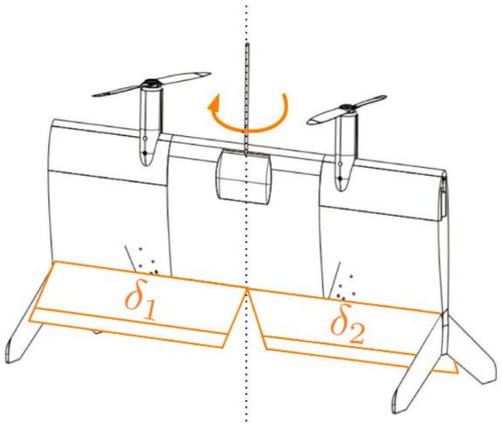
- Lowered Complexity
- Cheap manufacturing
- Robust
- Easy scaling

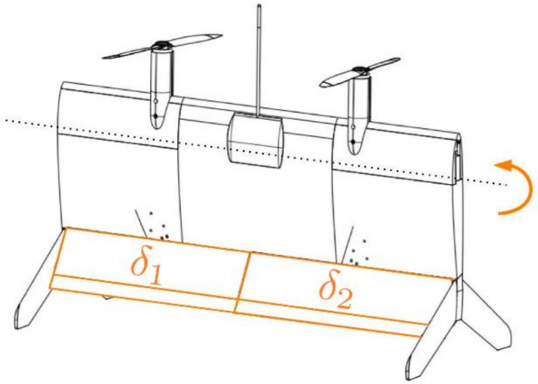


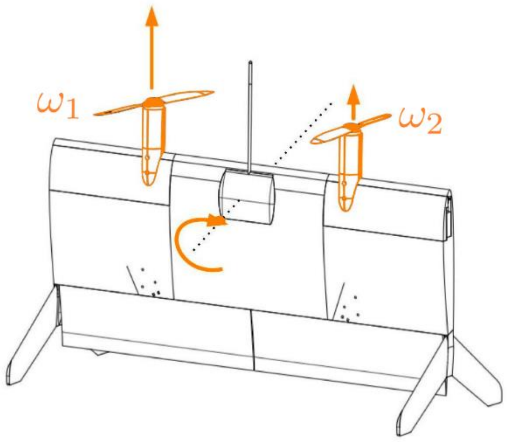
Simple Model for Hover Control

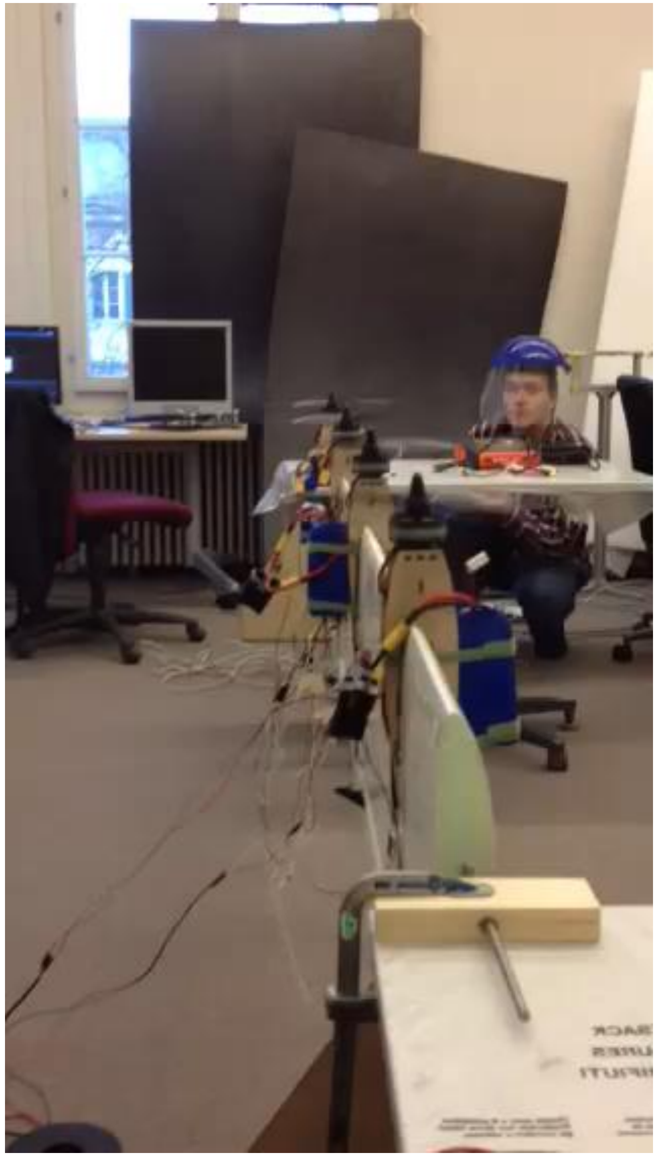
$$M_x = k_x(\delta_1 - \delta_2)$$
$$M_y = -k_y(\delta_1 + \delta_2)$$
$$M_z = k_z(\omega_1^2 - \omega_2^2)$$









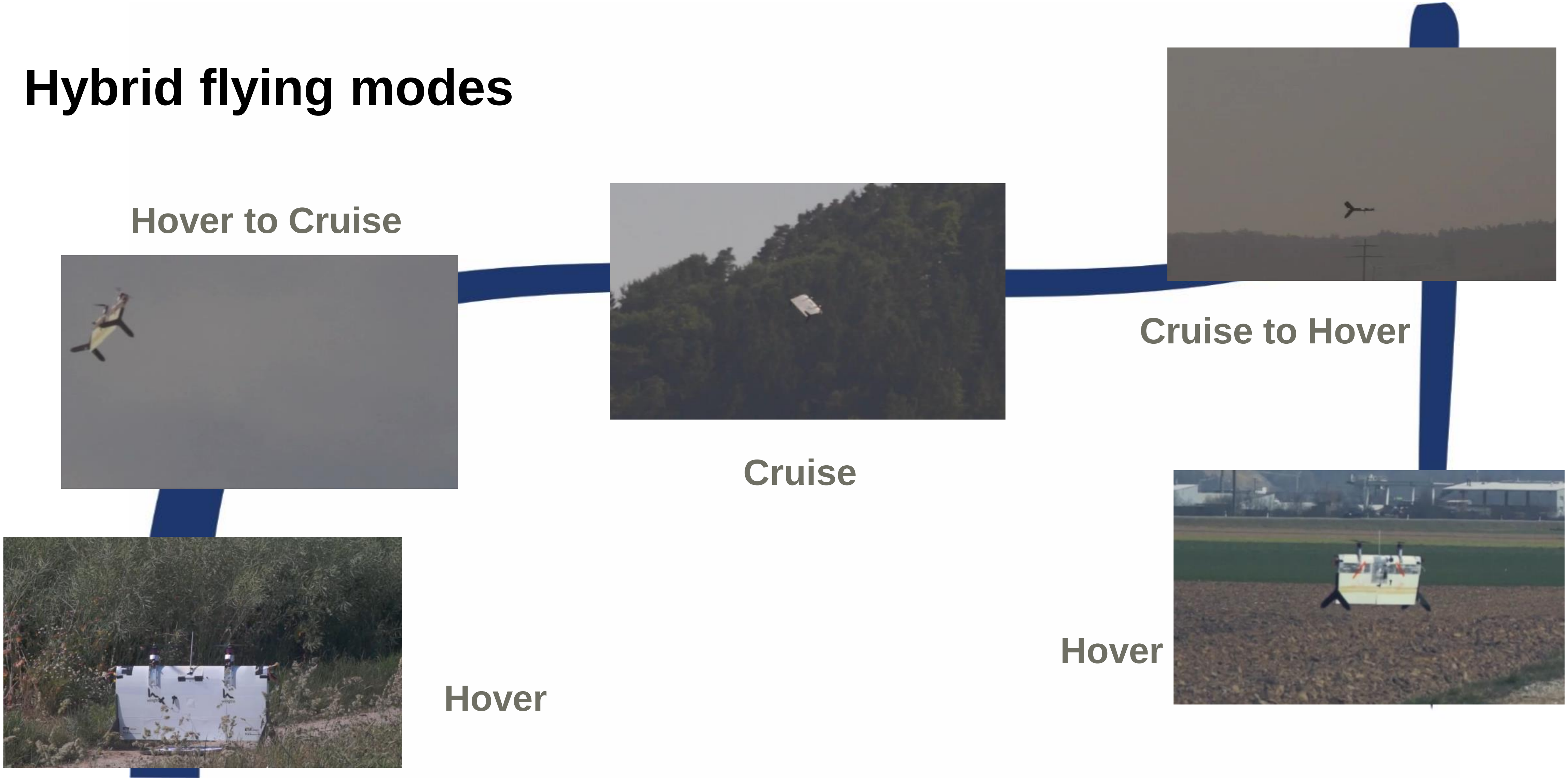


Hover

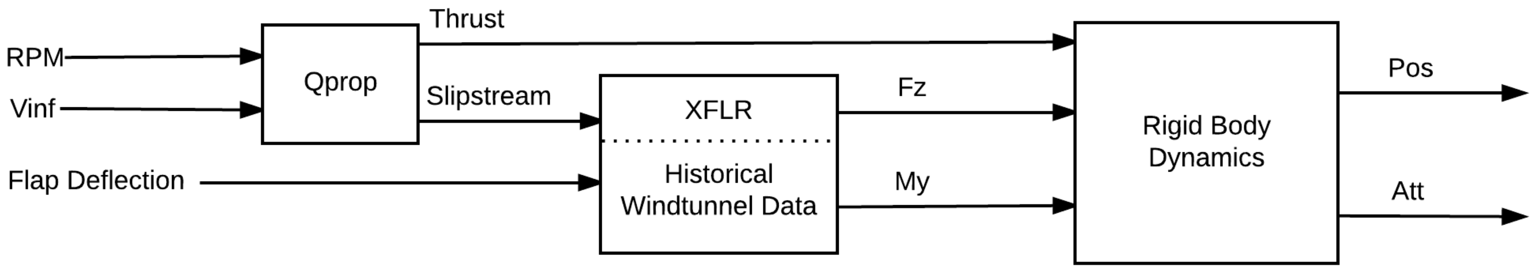
Attitude controller; attitude reference set by human pilot

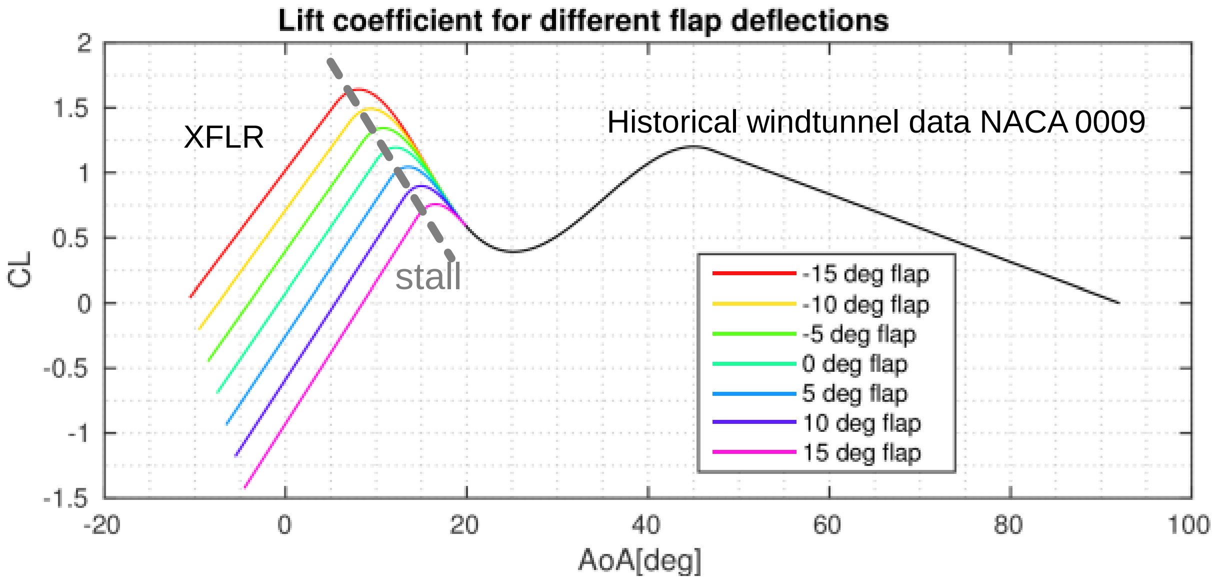
The Team grows

Hybrid flying modes



Cruise model is needed





$$L = \frac{1}{2}\rho A c_L(\alpha) v^2$$

$$D = \frac{1}{2}\rho A c_D(\alpha) v^2$$

$$M = \frac{1}{2}\rho A c_M \bar{c}(\alpha) v^2$$

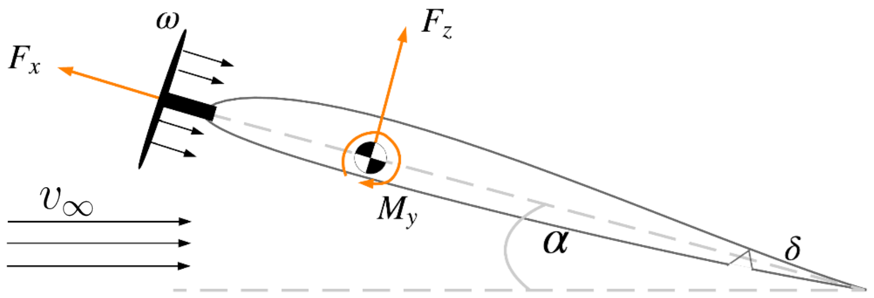
Better Model is needed

Design Iterations

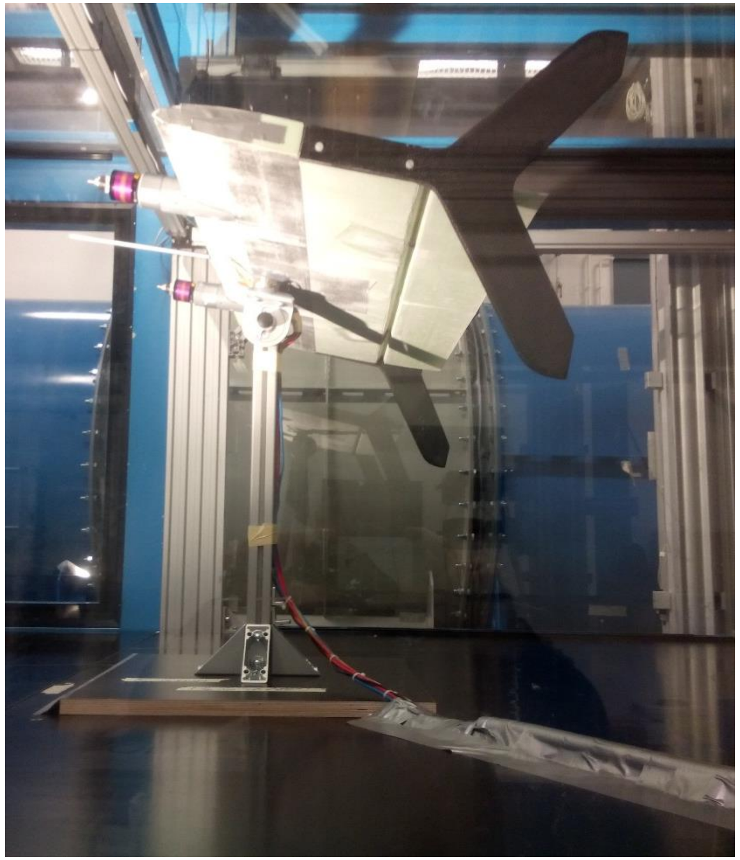
Wind Tunnel Experiment

Simulation Weaknesses

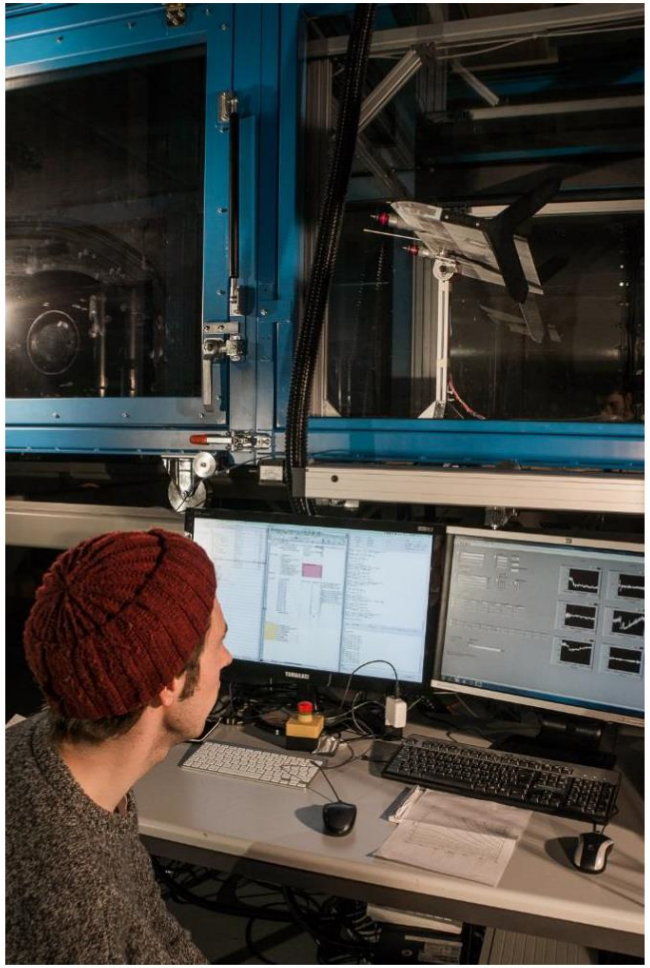
- Propeller Wing Interaction
- High AoA
- Propeller Slipstream

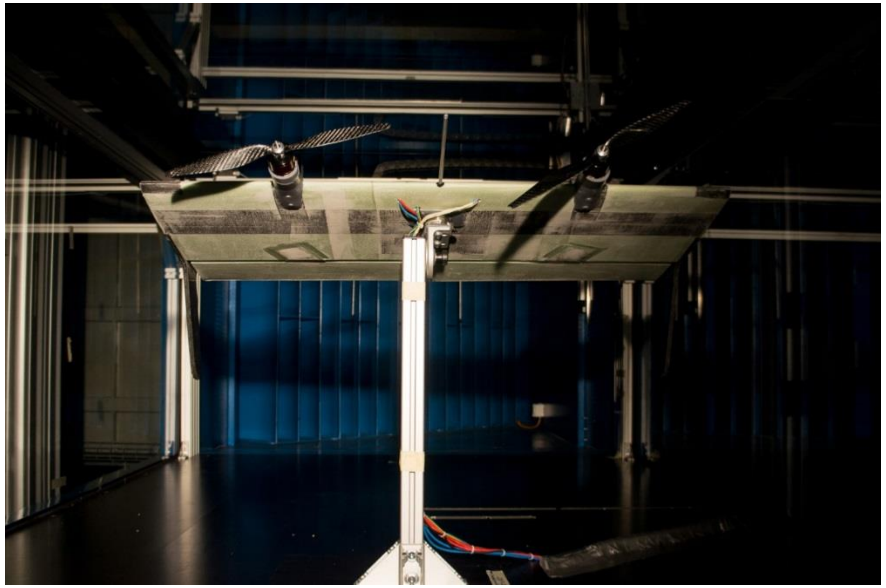


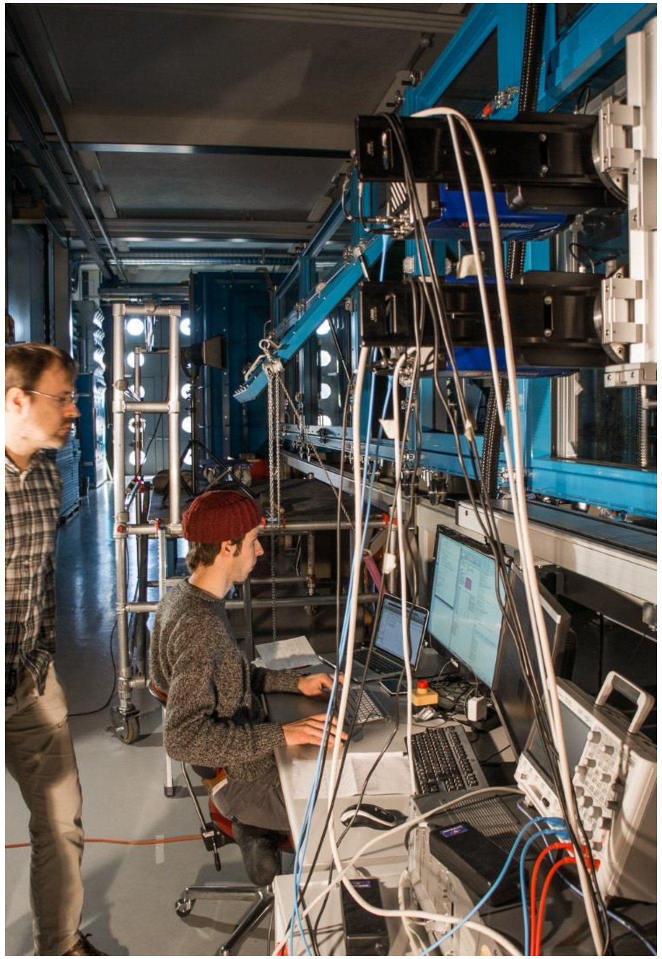
$$\boldsymbol{M} = f(\boldsymbol{\omega}, \boldsymbol{\delta}, \alpha, v_\infty)$$
$$\boldsymbol{F} = f(\boldsymbol{\omega}, \boldsymbol{\delta}, \alpha, v_\infty)$$



Wind Tunnel Experiment







Wind Tunnel Experiment

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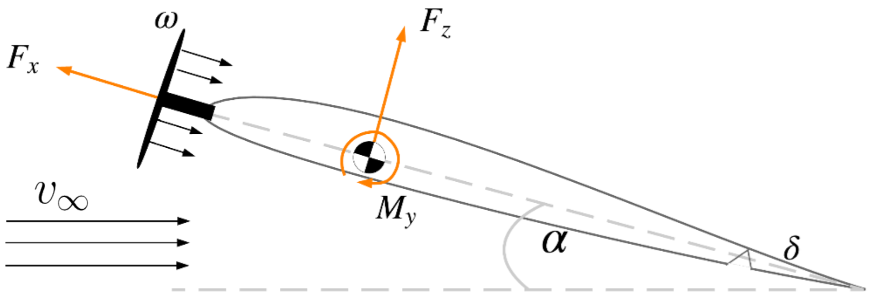
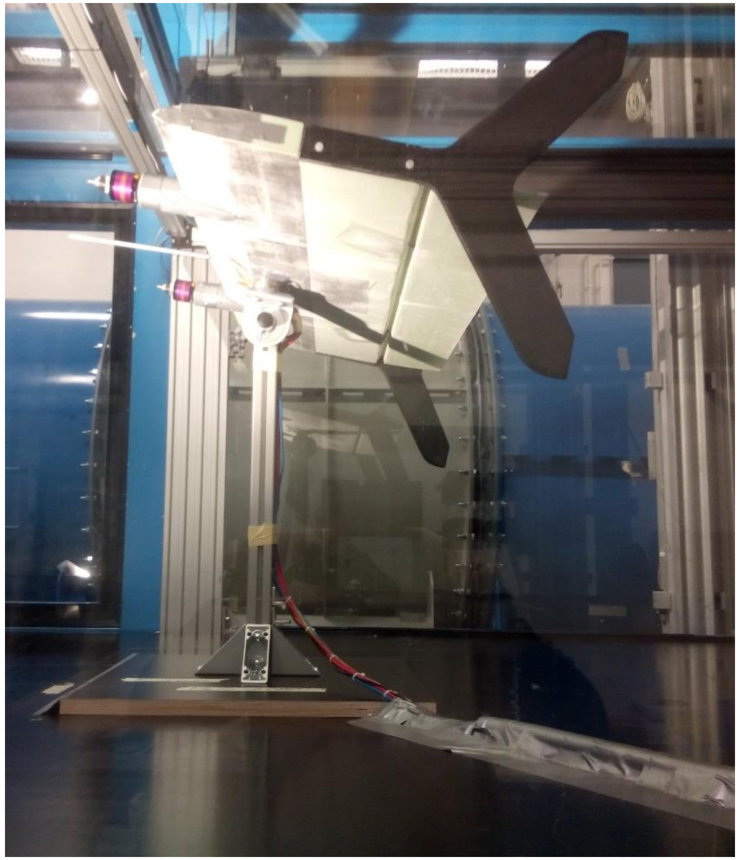


$$\boldsymbol{M} = f(\boldsymbol{\omega}, \boldsymbol{\delta}, \alpha = 5^\circ, v_\infty)$$
$$\boldsymbol{F} = f(\boldsymbol{\omega}, \boldsymbol{\delta}, \alpha = 5^\circ, v_\infty)$$



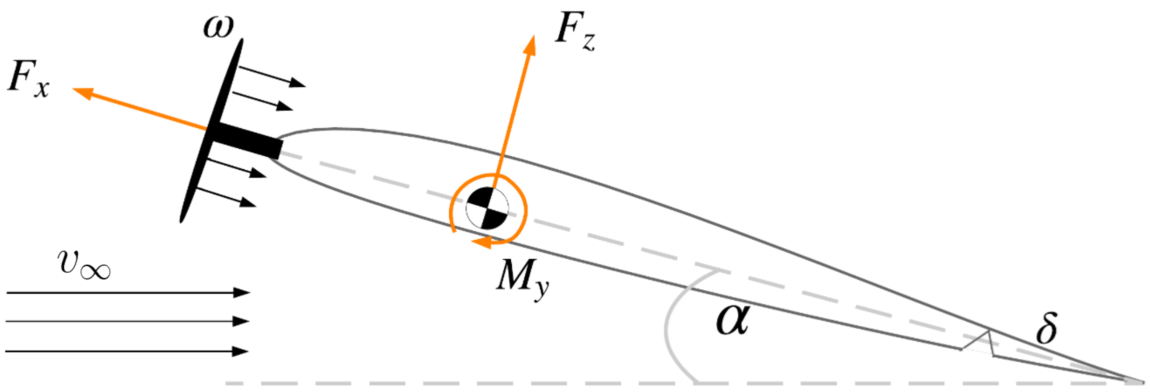
Better Model (constant AoA)

$$F_x = \boldsymbol{c}_{F_{x0}}^\top \begin{pmatrix} 1 \\ |\boldsymbol{v}_\infty| \\ |\boldsymbol{v}_\infty|^2 \end{pmatrix} + \boldsymbol{c}_{F_{x2}}^\top \begin{pmatrix} 1 \\ |\boldsymbol{v}_\infty| \end{pmatrix} \omega^2$$

$$M_y = \boldsymbol{c}_{M_{y0}}^\top \begin{pmatrix} 1 \\ \omega|\boldsymbol{v}_\infty| \end{pmatrix} + \boldsymbol{c}_{M_{y1}}^\top \begin{pmatrix} \omega \\ |\boldsymbol{v}_\infty|^2 \\ \omega^2 \\ \omega|\boldsymbol{v}_\infty| \end{pmatrix} \delta$$

$$F_z = \boldsymbol{c}_{F_{z0}}^\top \begin{pmatrix} 1 \\ |\boldsymbol{v}_\infty|^2 \\ \omega^2 \\ \omega \\ \omega|\boldsymbol{v}_\infty| \end{pmatrix} + \boldsymbol{c}_{F_{z1}}^\top \begin{pmatrix} \omega \\ |\boldsymbol{v}_\infty|^2 \\ \omega^2 \\ \omega|\boldsymbol{v}_\infty| \end{pmatrix} \delta$$

Remark: Polynomial model based on intuition and manual fitting



Better Controller

- Newly designed attitude controller
  - No switching
  - No singularities
  - Easy integration with high level controllers
  - Computationally lightweight

$$\boldsymbol{e}_R = \boldsymbol{R}^T \left(\frac{-\boldsymbol{e}_z \times \boldsymbol{\tau}}{1 - \boldsymbol{e}_z \boldsymbol{\tau}} \right)$$

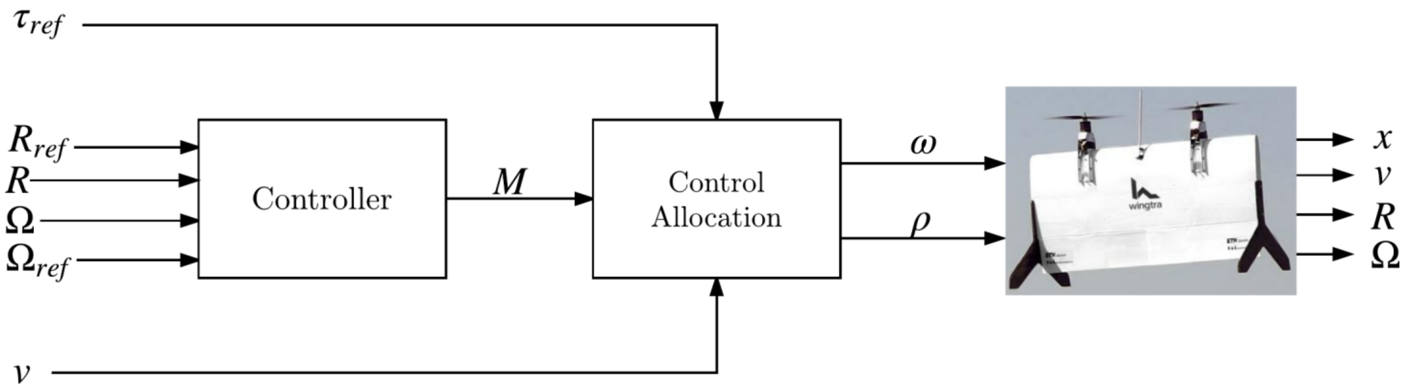
$$\boldsymbol{\tau} = \boldsymbol{R}\boldsymbol{R}_{ref}^T(-\boldsymbol{e}_z)$$

$$\boldsymbol{\Omega} = \boldsymbol{\Omega} - \boldsymbol{\Omega}_{ref}$$

$$\boldsymbol{M} = -\boldsymbol{k}_R \boldsymbol{e}_R - k_\Omega \boldsymbol{e}_\Omega + \boldsymbol{\Omega} \times \boldsymbol{J}\boldsymbol{\Omega}$$

- Control allocation

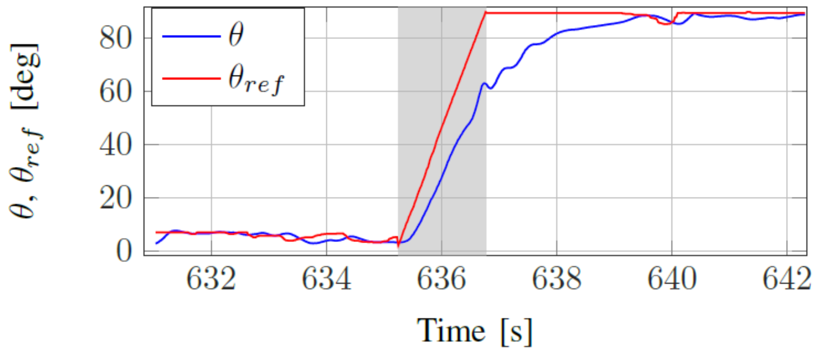
  Based on windtunnel data



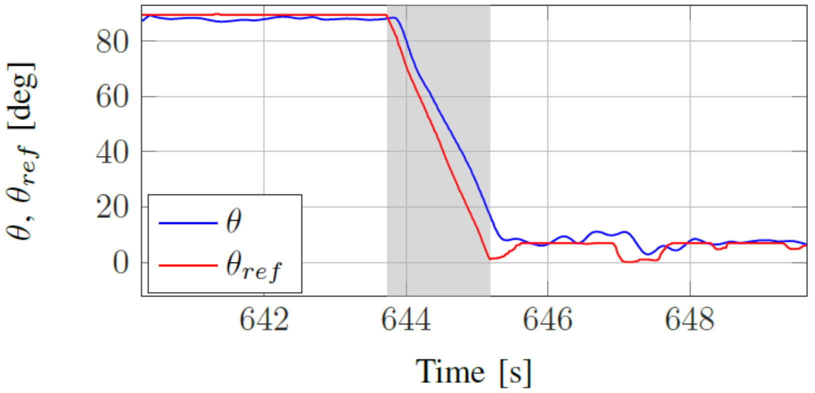
S. Verling et al, "Full Attitude Control of a VTOL Tailsitter UAV", in *International Conference in Robotics and Automation*, Stockholm, Sweden, May 2016

Results: Pitch angle tracking during transition

Cruise to Hover



Hover to Cruise



It works -> Make it usable

- Real applications require payload
- New hardware iteration
- **Make it easy to use**

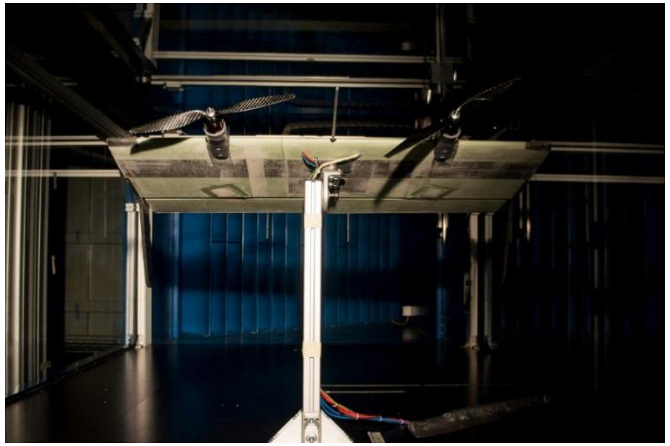
Another Design iteration

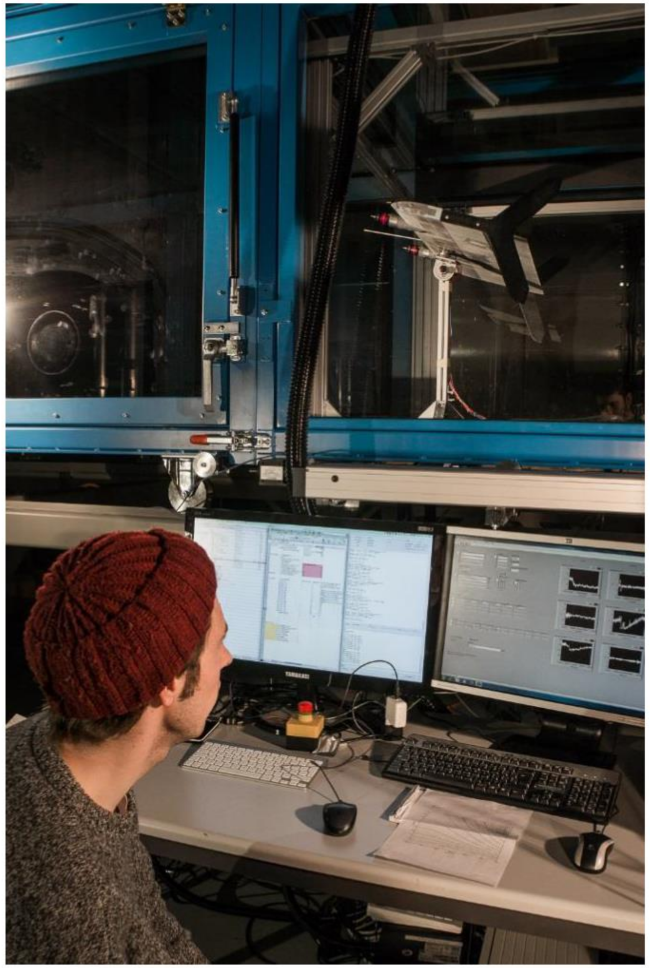
- Aerodynamically optimized

wingtra

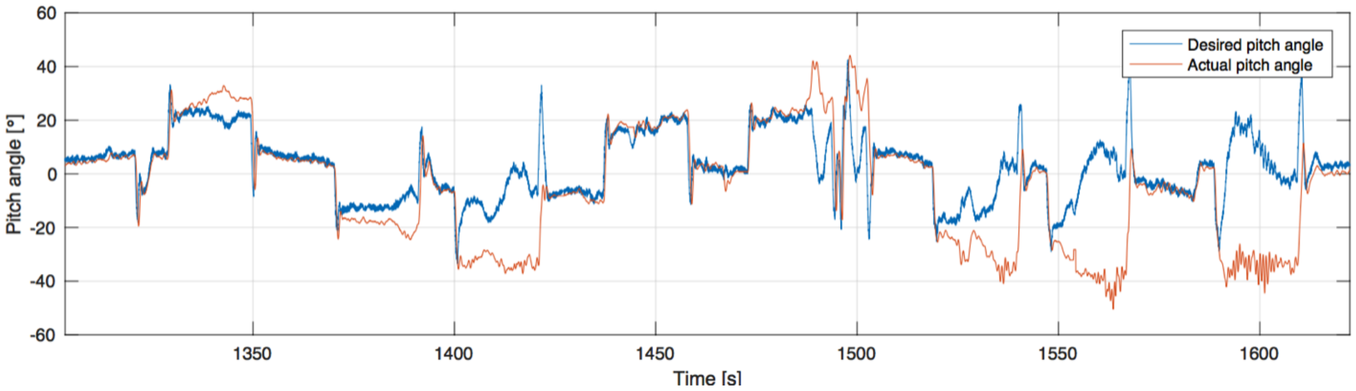
Wind Tunnel Limitations

- Due to size of windtunnel not all AoA could be tested
- Results up to 55°

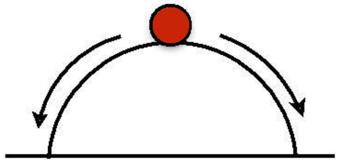


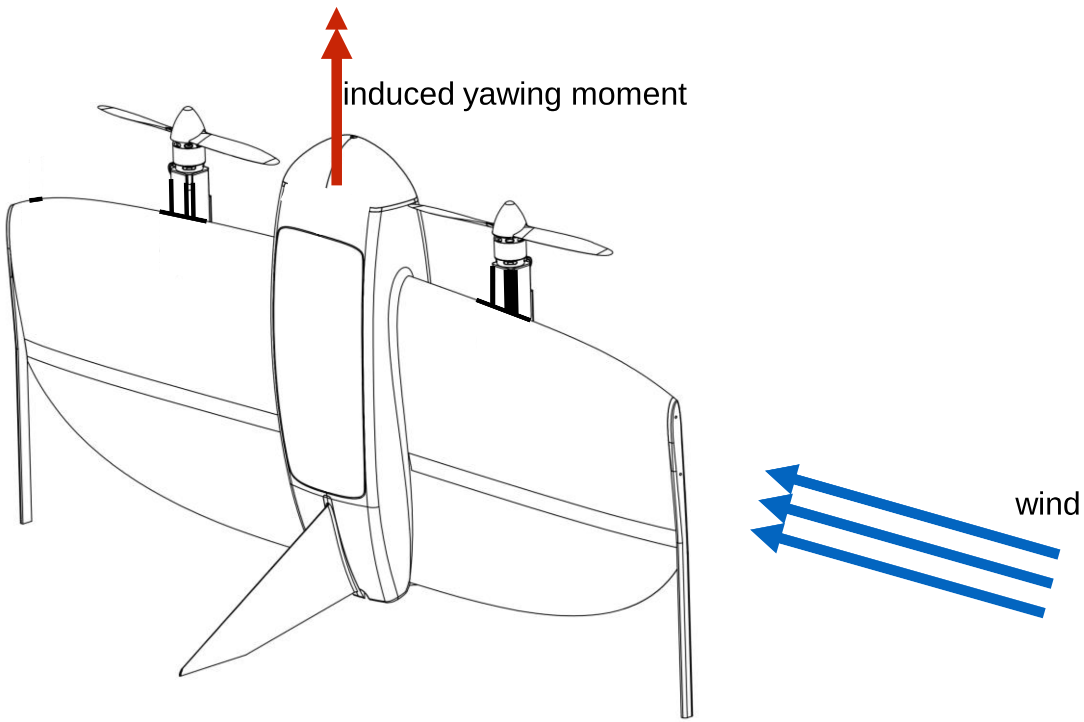


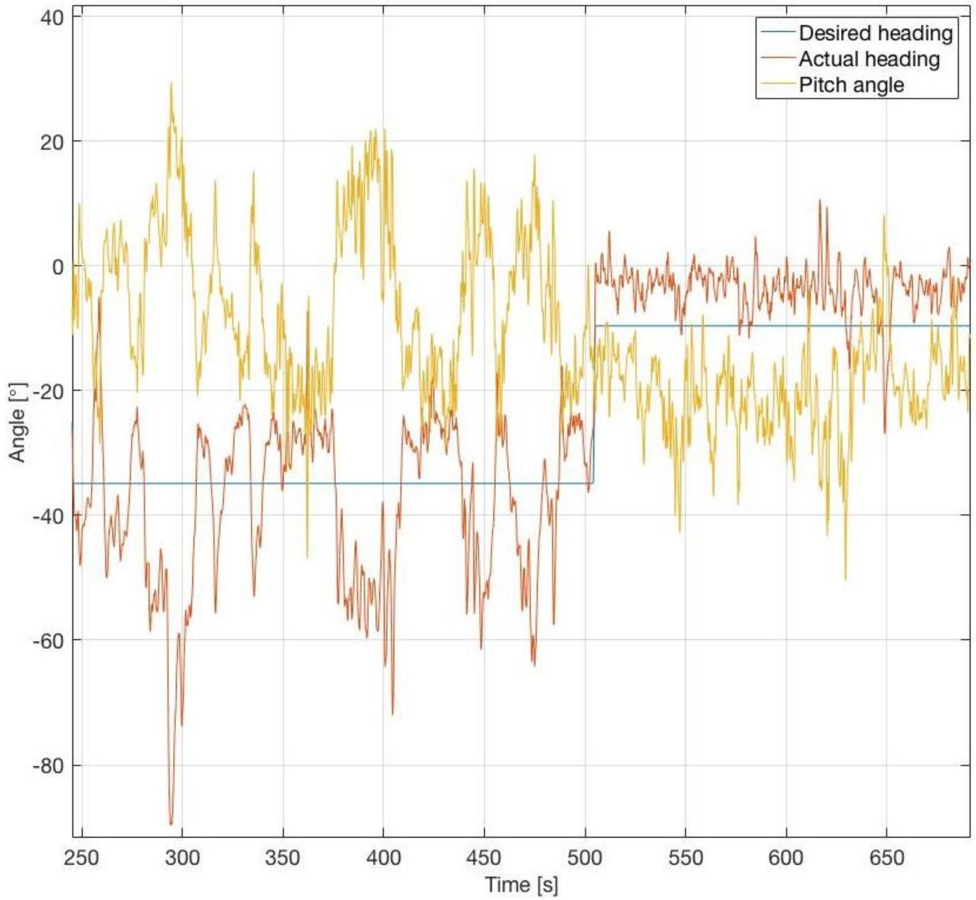
Flying in Wind (very high AoA)



Alignment with wind







exactly parallel to wind
30 degrees off wind direction

Lift/Drag – Force Model

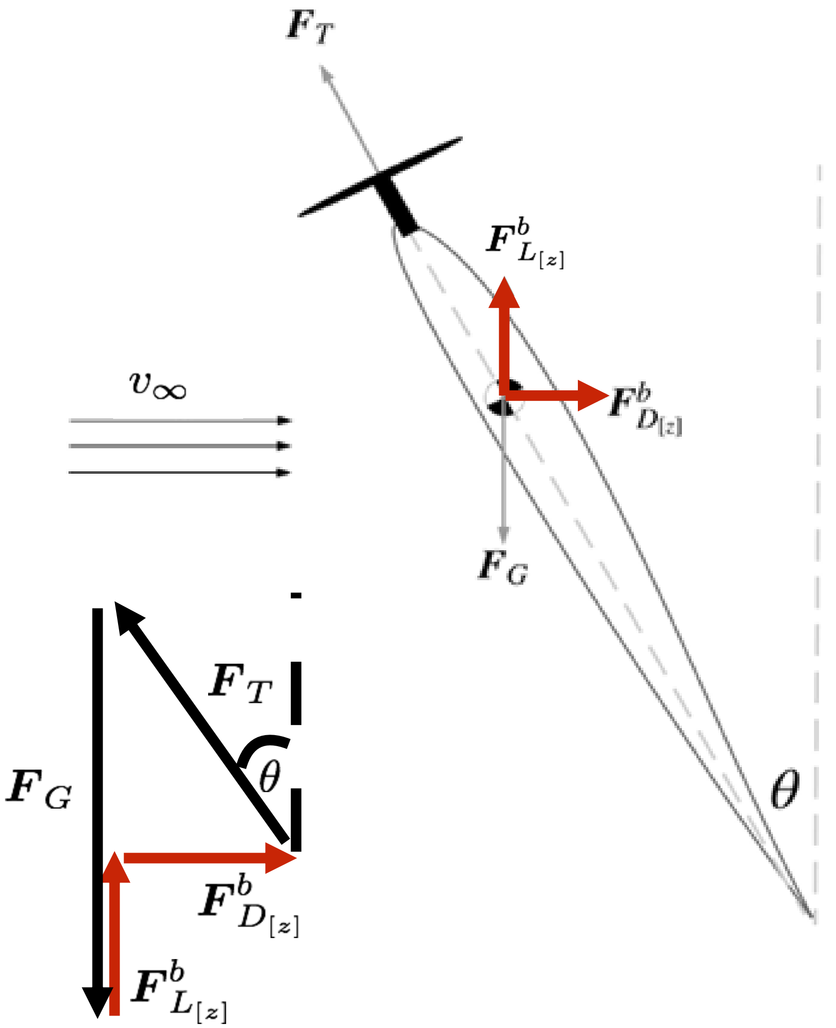
- Steady-state lift/drag force model derived from flat plate theory.
- Assumes constant altitude.

$$F_G = mg$$

$$F^b_{D[z]} = \frac{1}{2} c_D \rho A \cos^2(\theta) v_\infty^2 \qquad \text{(aerodynamic drag)}$$

$$F^b_{L[z]} = \frac{1}{2} c_L \rho A \sin(\theta)\cos(\theta) v_\infty^2 \qquad \text{(aerodynamic lift)}$$

$$\boxed{v_\infty = \sqrt{\frac{2mg\tan(\theta)}{c_D \rho A}} = k\sqrt{\tan(\theta)}} \qquad \text{(freestream velocity)}$$



Y. Demitri, S. Verling et al, “Model-based Wind Estimation for a Hovering VTOL Tailsitter UAV”, in *International Conference in Robotics and Automation*, Singapore, June 2017

Model-based wind estimation approach

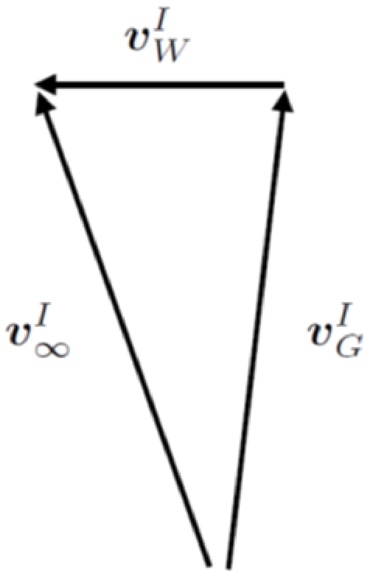
Wind Triangle

Windspeed = Freestream - Groundspeed

$$\tilde{\boldsymbol{v}}_W^I = \boldsymbol{v}_\infty^I - \boldsymbol{v}_G^I$$

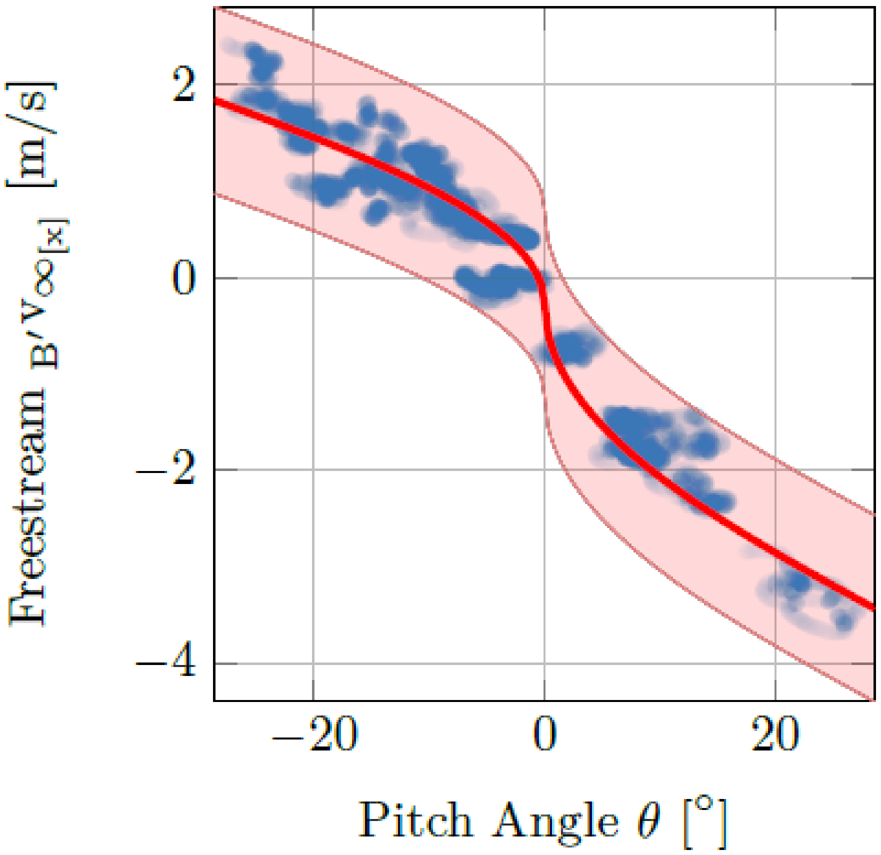
$$\tilde{\boldsymbol{v}}_W^I = \boldsymbol{R}_\psi \begin{pmatrix} k_z\sqrt{\tan(\theta)} \\ k_y\sqrt{\tan(\phi)} \end{pmatrix} - \begin{pmatrix} v_{G[N]}^I \\ v_{G[E]}^I \end{pmatrix}$$

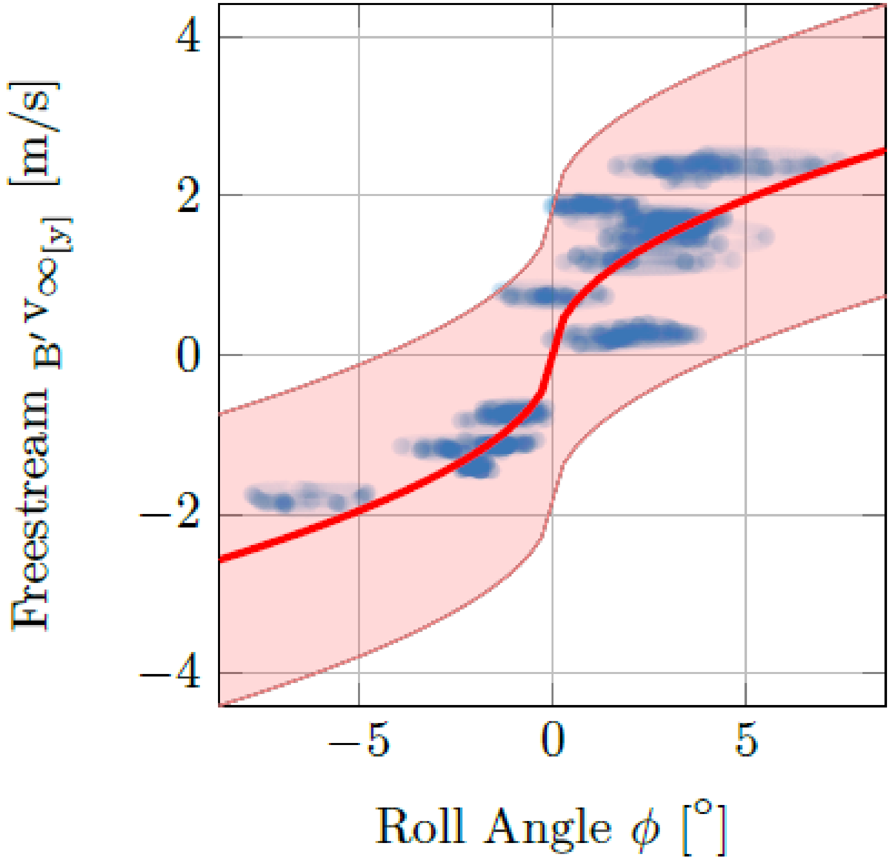
$$\boxed{\tilde{\boldsymbol{v}}_W^I = \begin{pmatrix} \cos(\psi) & -\sin(\psi) \\ \sin(\psi) & \cos(\psi) \end{pmatrix} \begin{pmatrix} k_z\sqrt{\tan(\theta)} \\ k_y\sqrt{\tan(\phi)} \end{pmatrix} - \begin{pmatrix} v_{G[N]}^I \\ v_{G[E]}^I \end{pmatrix}}$$



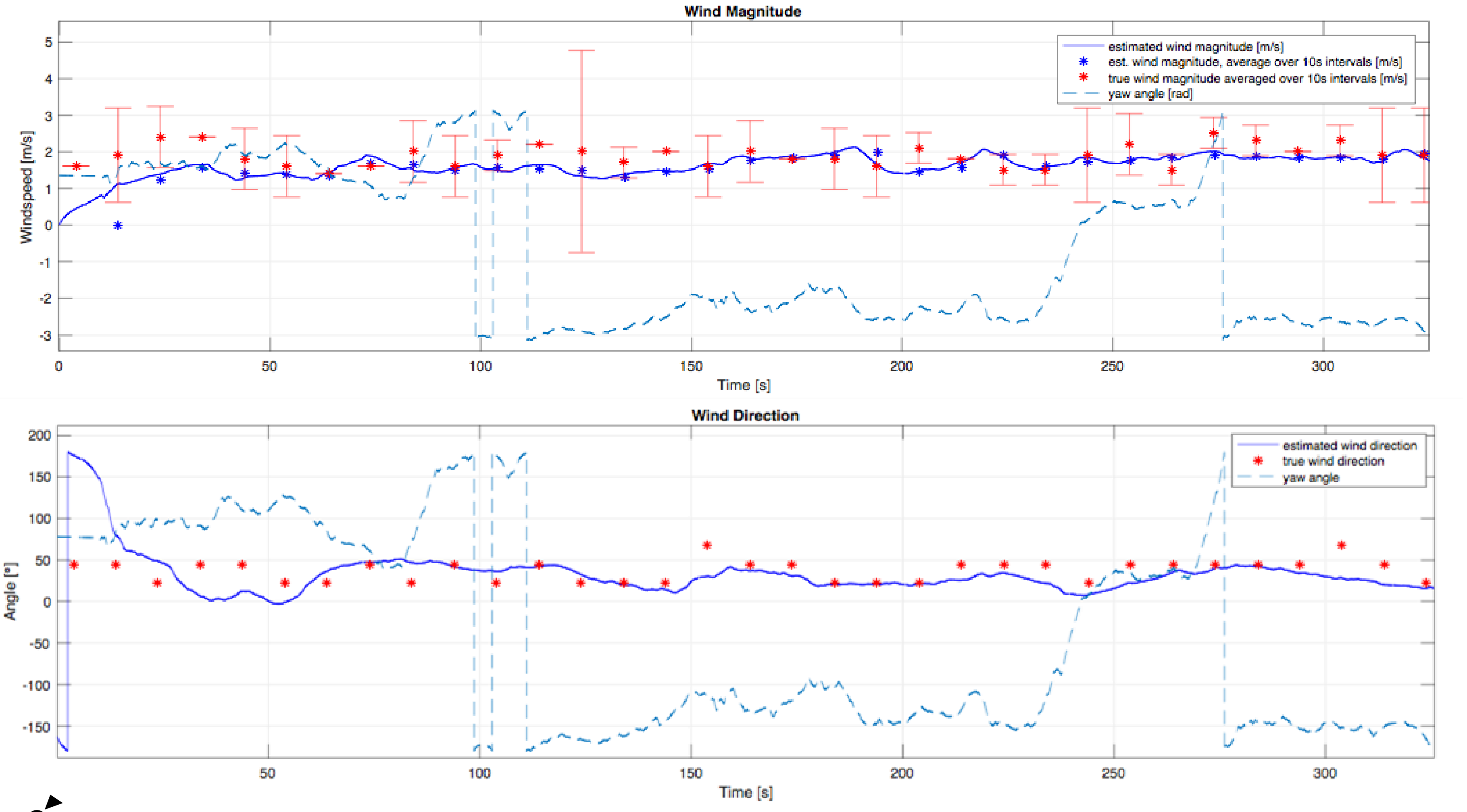
Parameter Identification

Model-based wind estimation approach



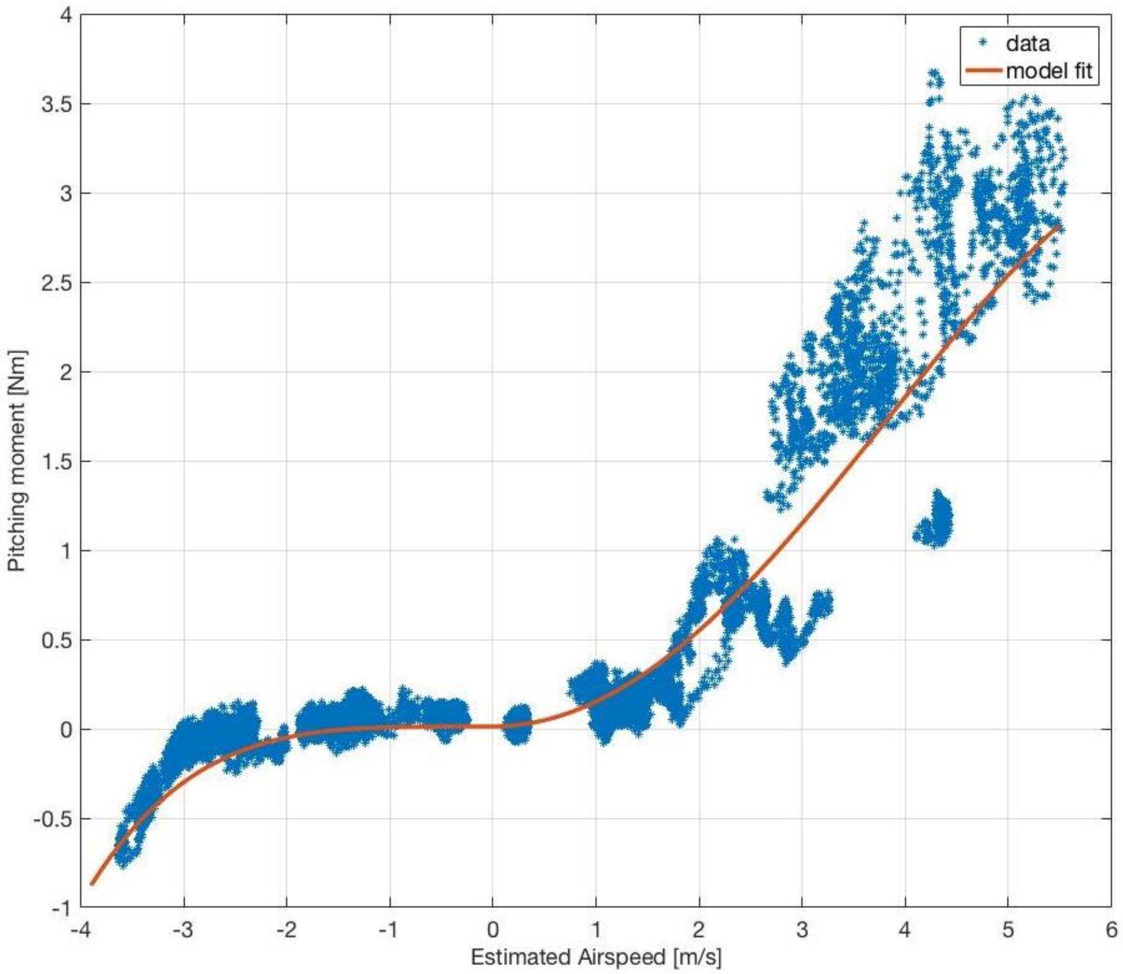


Estimation Results



Moment correction (in high AoA)

- Assuming steady state
- Polynomial fit



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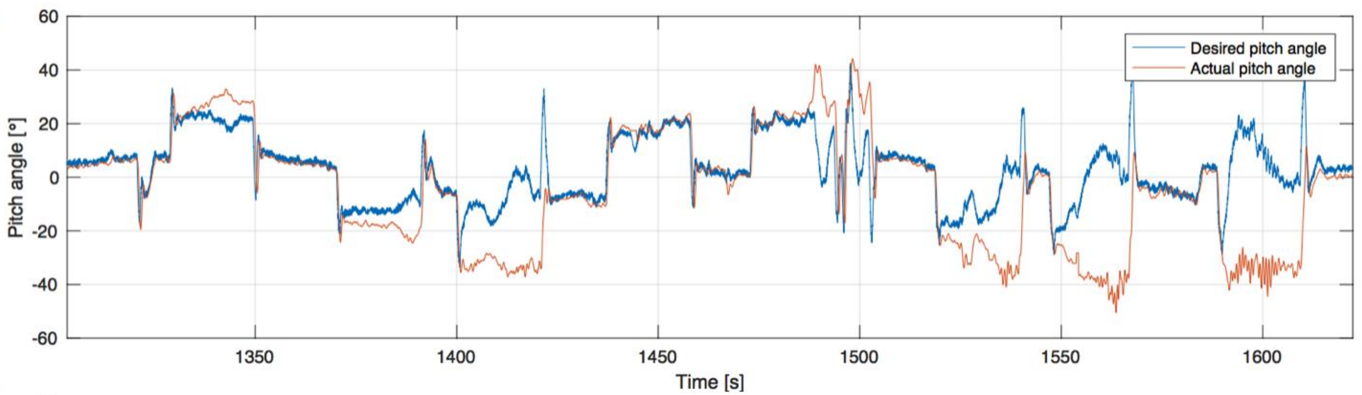
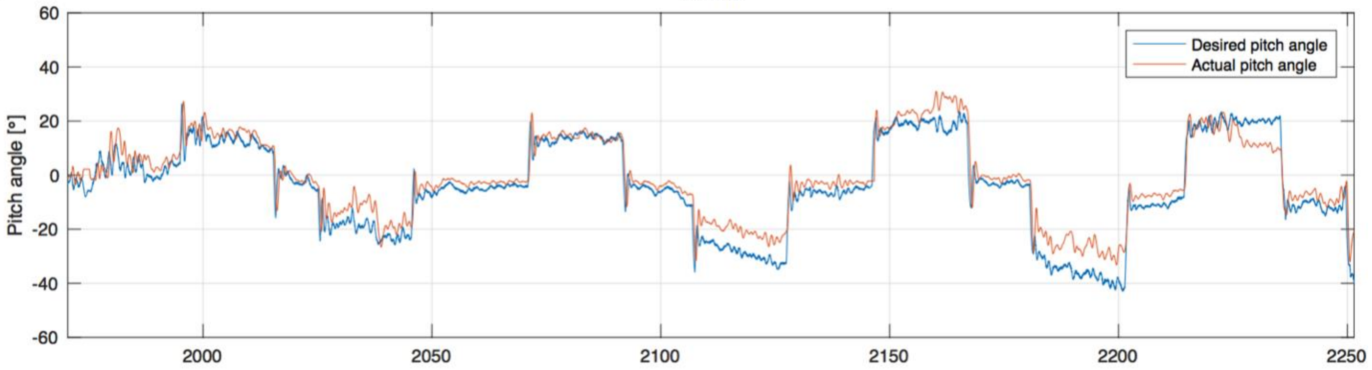
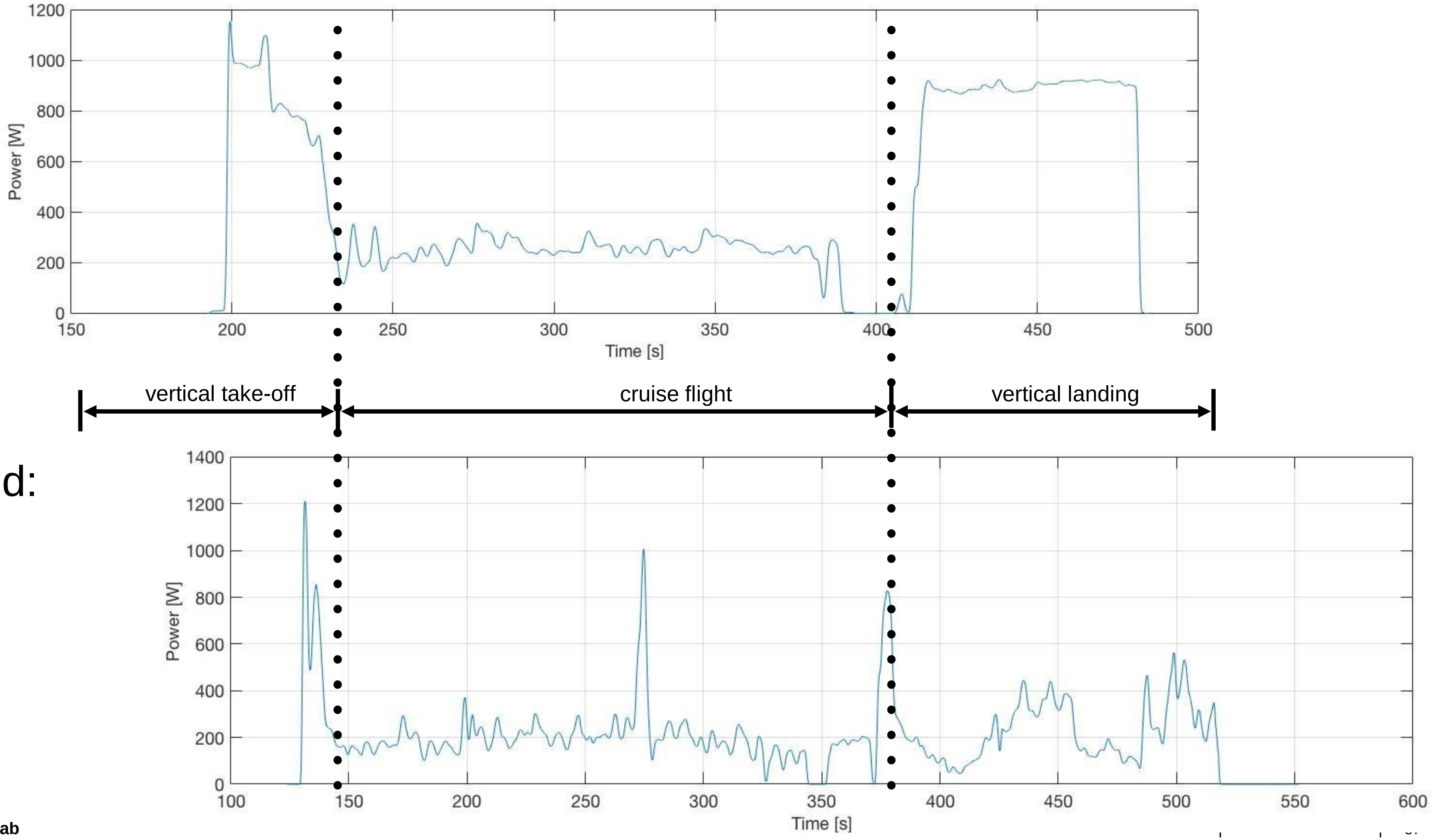




Power consumption: hover consumption down to ⅓

no wind:

8 m/s average windspeed:



Landing in wind

Ground detection based motor cut-off

Distance sensor based motor cut-off

Transition

Altitude Gain

↓

More Hover Time to land

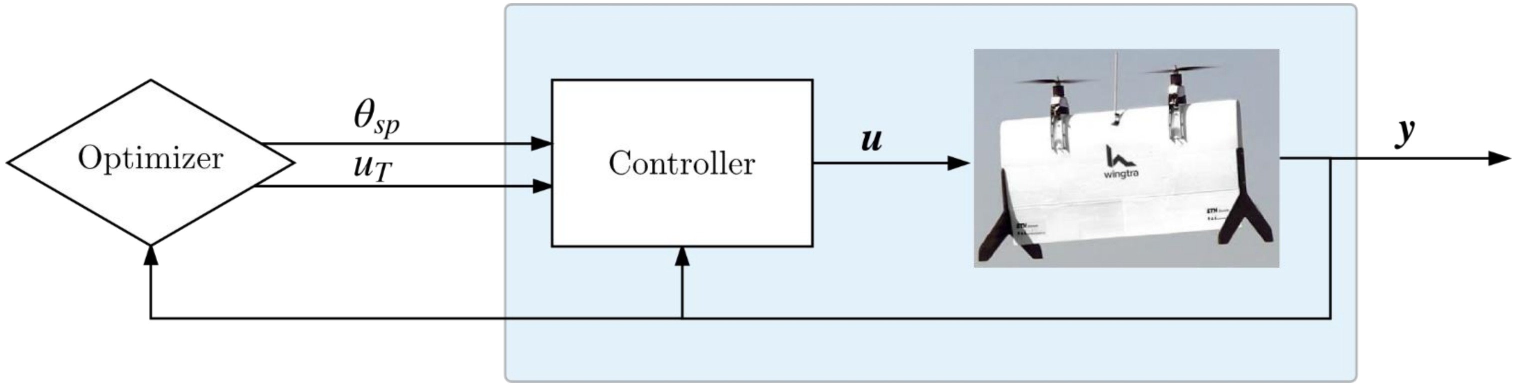
↓

Increased Energy Consumption

↓

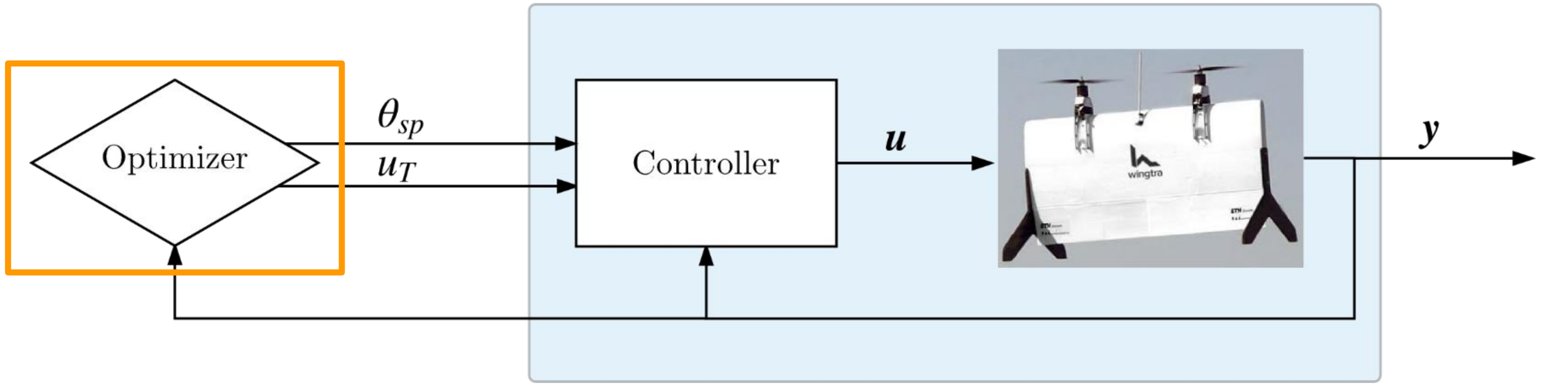
Less Flight Time

Model-Based Optimization



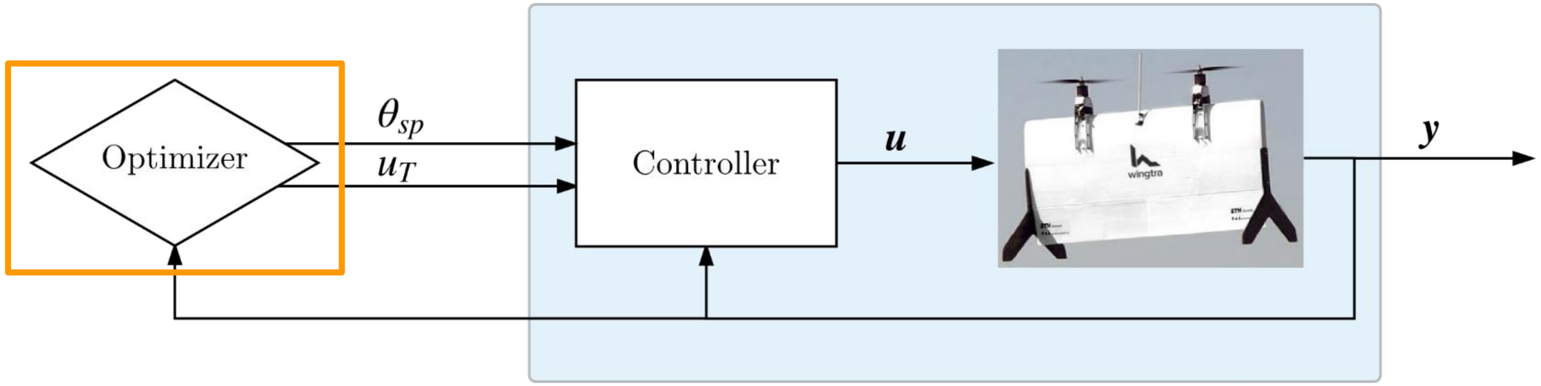
S. Verling et al, "Model-based Transition Optimization for a VTOL Tailsitter UAV", in *International Conference in Robotics and Automation*, Singapore, June 2017

Model-Based Optimization



$$J = \sum_{t=0}^{t_{end}} w_1 (z(t) - z(0))^2 + \boldsymbol{w}_2^T \boldsymbol{v}(t)^2 + w_3 \min \left(\left(\theta(t) - \frac{\pi}{2} \right)^2 \right)$$

Model-Based Optimization



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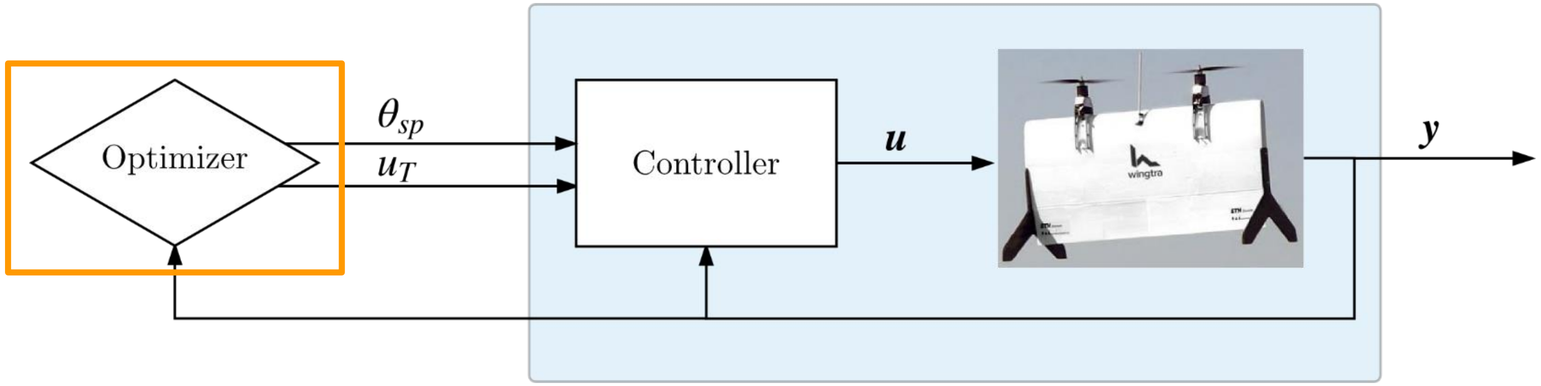

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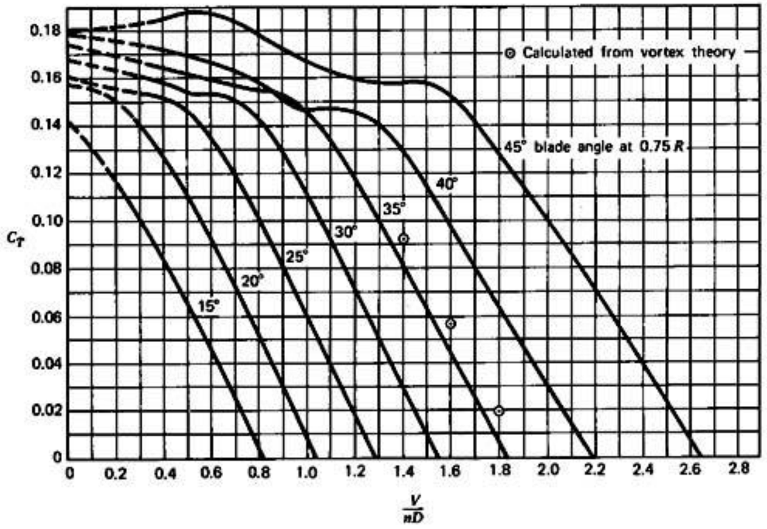
More accurate Model

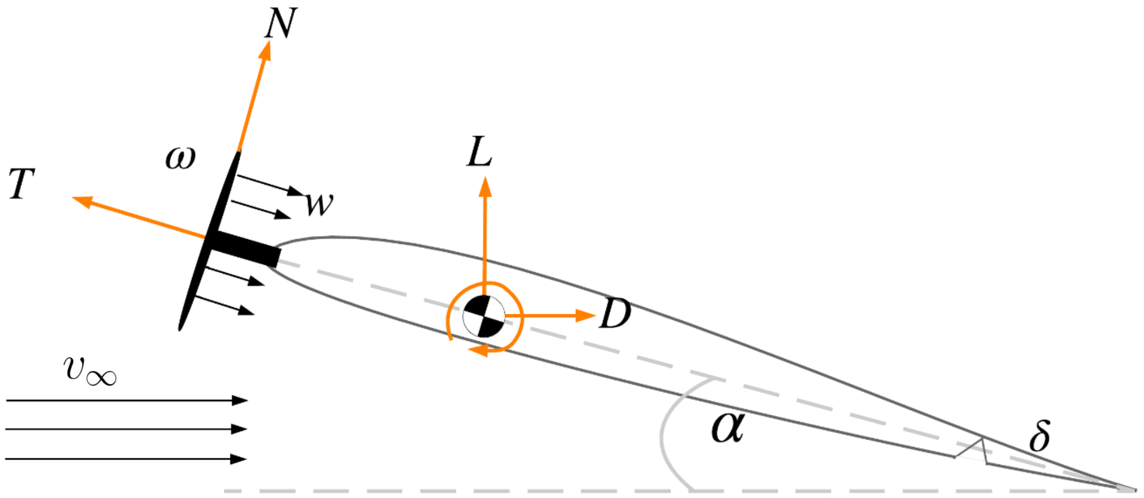
$$J = \frac{v_{\infty,N}}{\omega D}$$

$$c_T = f_1(J)$$

$$T = c_T \omega^2$$

$$N = c_2 \sqrt{T} \sin(\alpha) |\boldsymbol{v}_\infty|$$



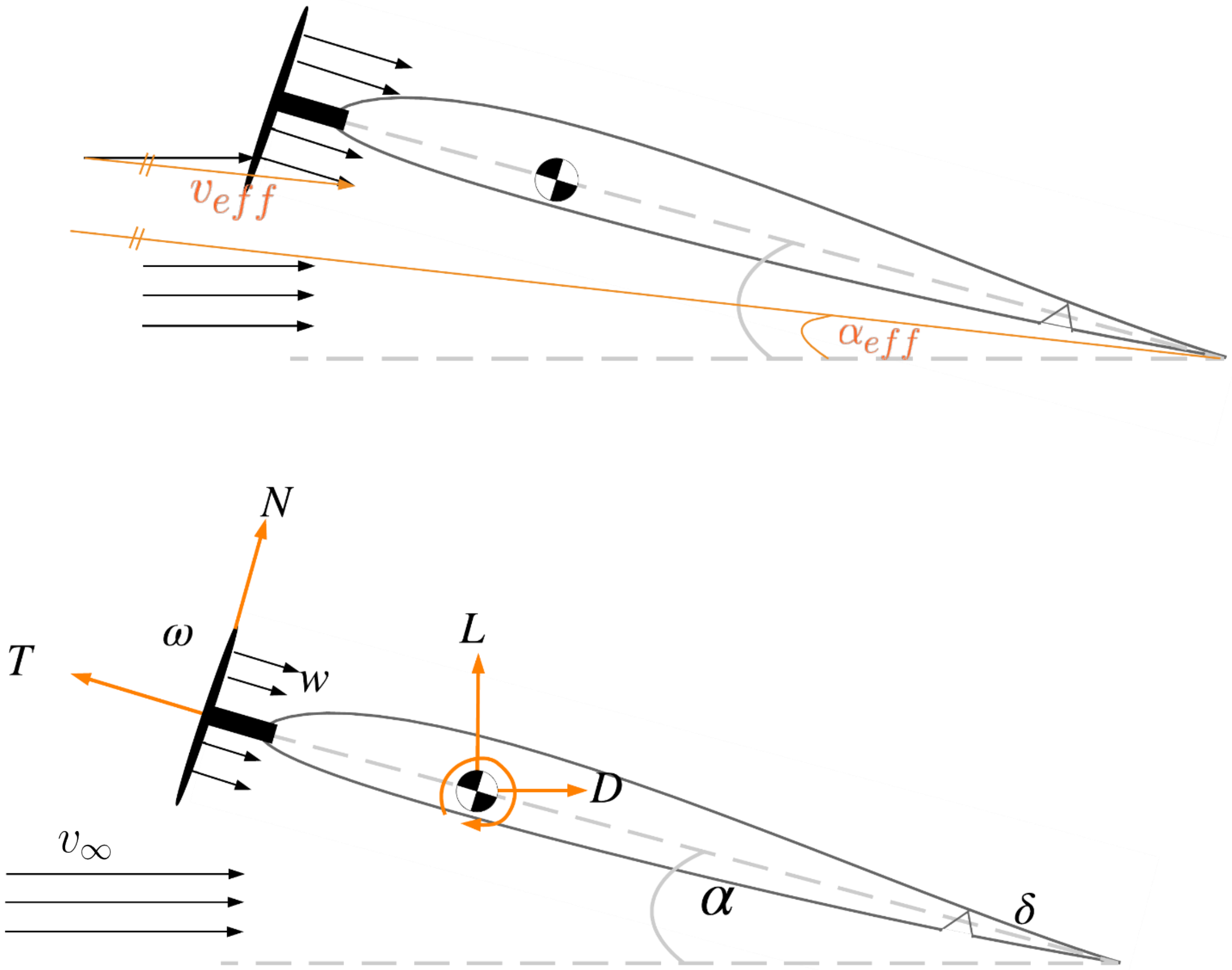


More accurate Model

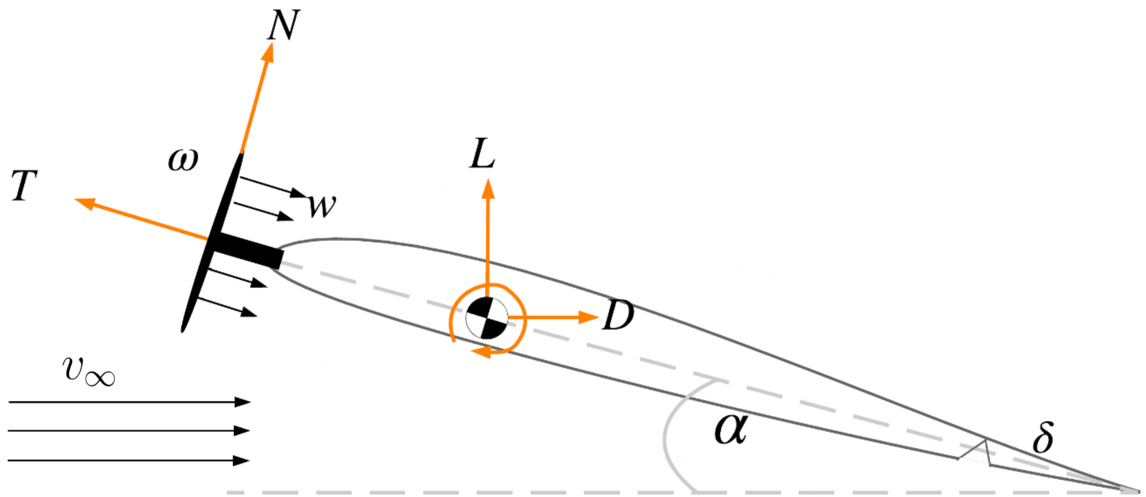
$$w = \frac{1}{2}\left(-v_{\infty,N} + \sqrt{v_{\infty,N}^2 + \left(\frac{2T}{\rho A}\right)}\right)$$

$$\boldsymbol{v_{eff}} = \boldsymbol{v_\infty} - k_w w \boldsymbol{n_{prop}}$$

$$\alpha_{eff} = \arctan 2(v_{eff_z}, v_{eff_x})$$



More accurate Model

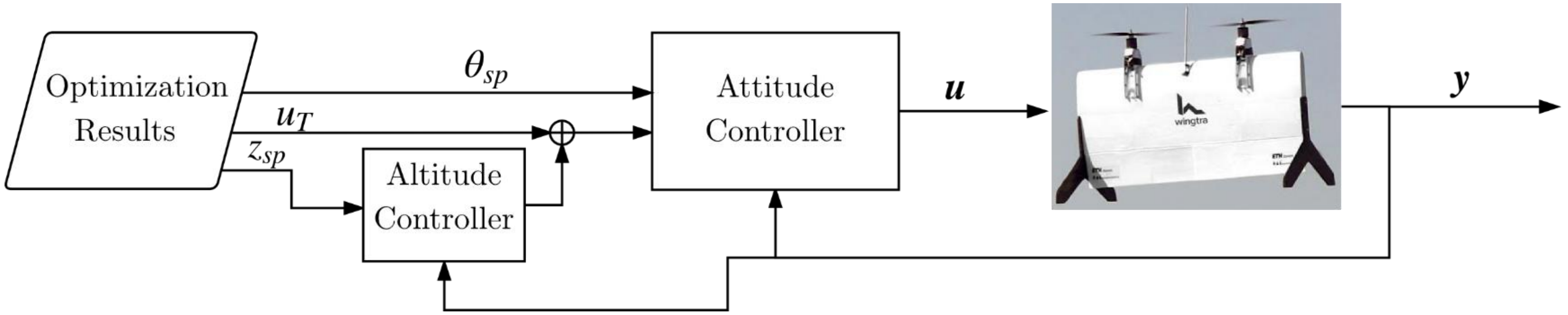


$$D = c_d |\boldsymbol{v_{eff}}|^2 + c_1 |\boldsymbol{v_\infty}|^2 c_{d,2}$$

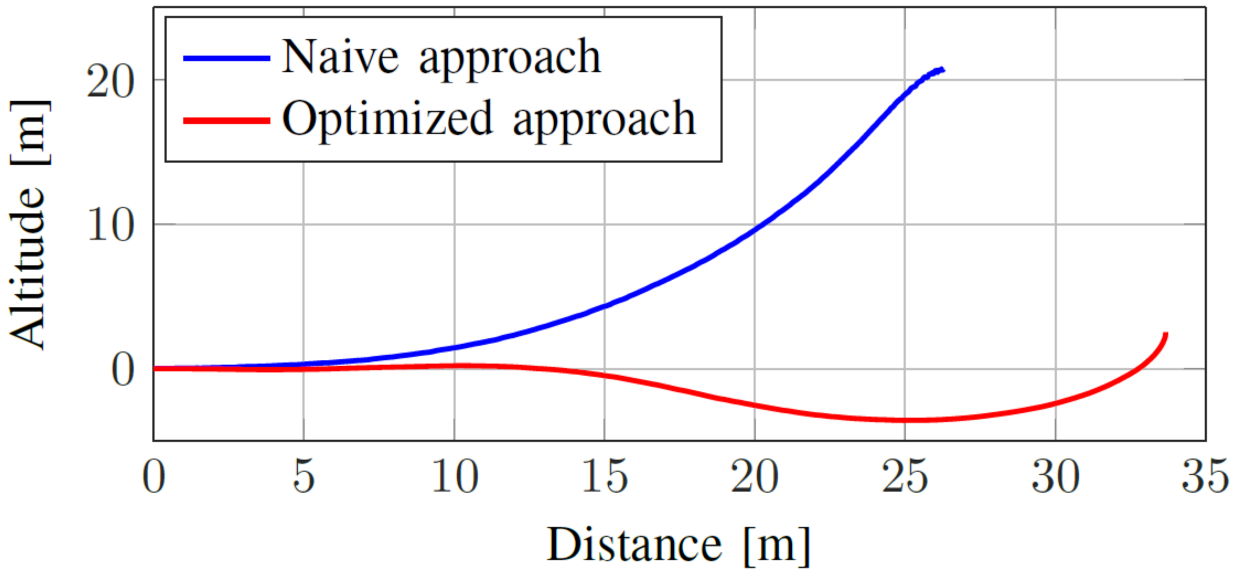
$$L = |\boldsymbol{v_{eff}}|^2 \left(c_{l,c} + c_{l,f}\delta\right) + c_1 |\boldsymbol{v_\infty}|^2 \left(c_{l,c2} + c_{l,f2}\delta\right)$$

$$M = |\boldsymbol{v_{eff}}|^2 \left(c_{m,c} + c_{m,f}\delta\right) + c_1 |\boldsymbol{v_\infty}|^2 \left(c_{m,c2} + c_{m,f2}\delta\right)$$

Control Structure of the Transition



Transition - Results



All Hardware Iterations

Questions?

www.wingtra.com