ETH zürich

Robot Dynamics

Fixed-wing UAVs: Case Study

Autonomy for Solar-powered UAVs Beyond the Horizon

151-0851-00L

Marco Hutter, Roland Siegwart, **Thomas Stastny**

Solar-powered Unmanned Aerial Vehicles (UAVs)

Remote sensing

Dealing with wind

Exploring the post-stall regime

Optimization-based guidance

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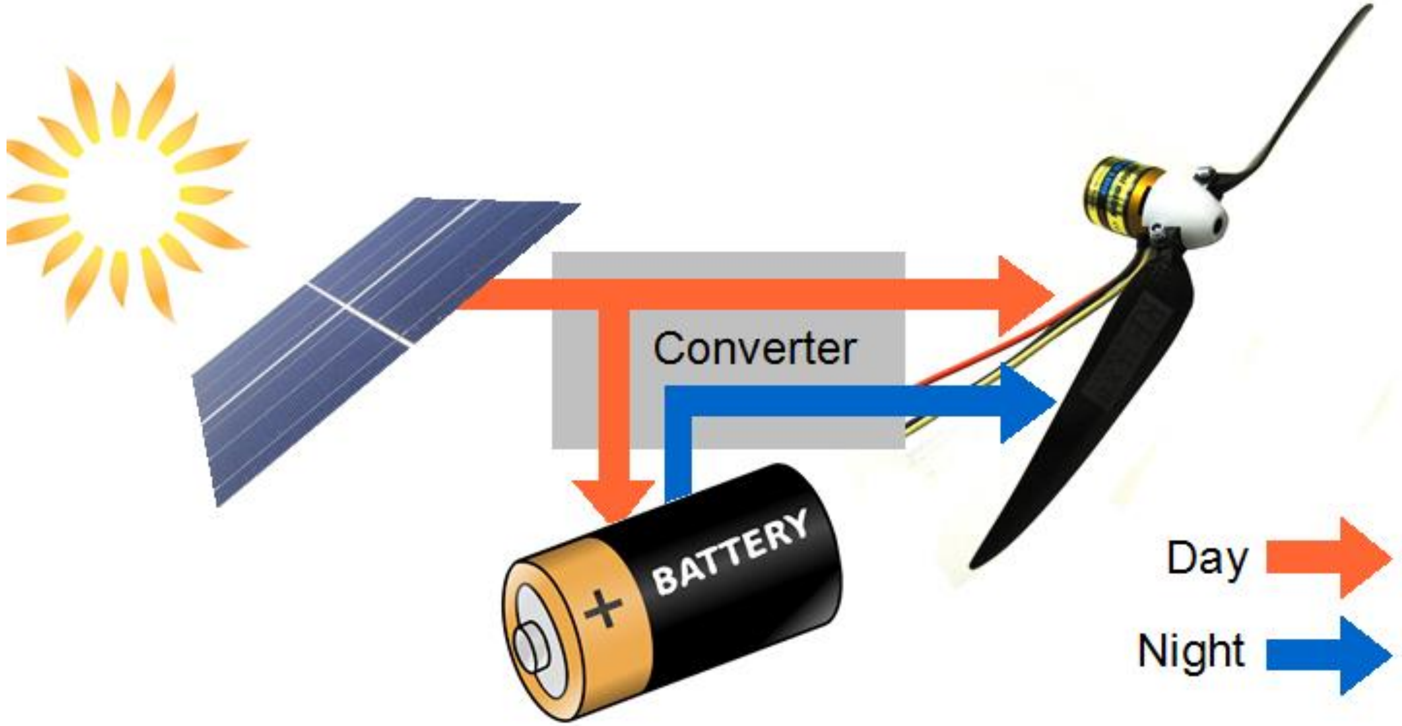
Working Principle of Solar-Electric Airplanes



Solar aircraft design

High-Altitude Long-Endurance (HALE) - Industry

- Solar cell efficiency
- Battery capacity
- Light weight airframe
- Efficient avionics/propulsion

Low-Altitude Long-Endurance (LALE) – ASL Research

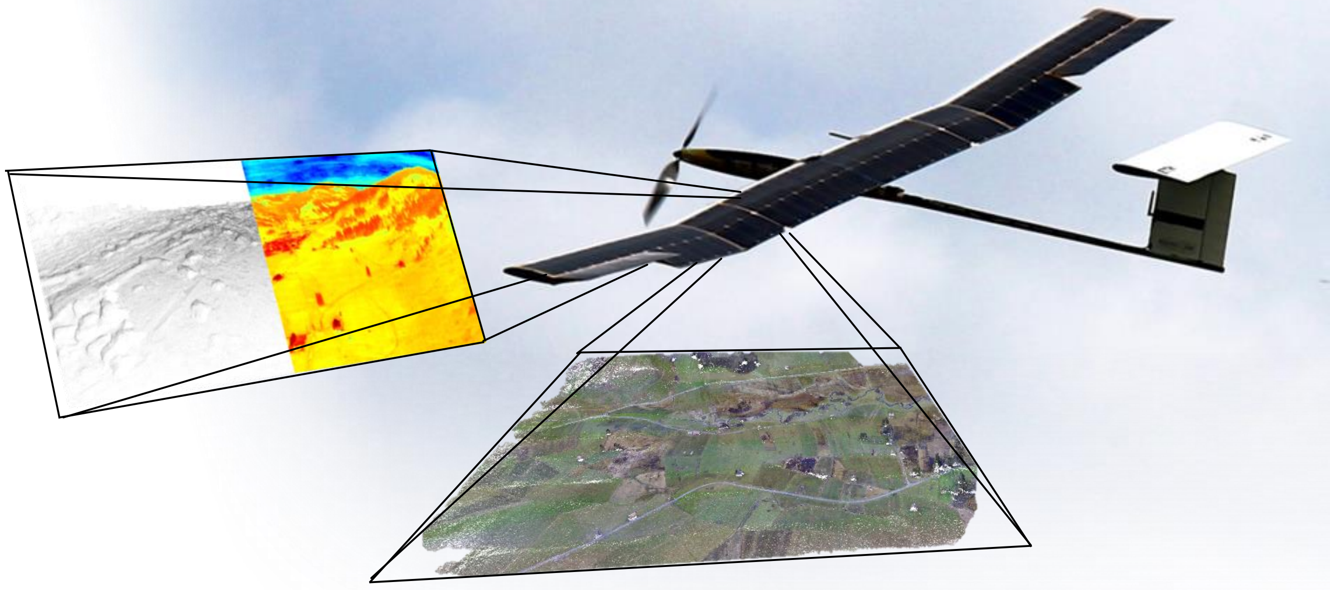
SkySailor (2005-2008)

SenseSoar (2008-2017)

AtlantikSolar (2012-2017)

SenseSoar2 (2017-present)

AtlantikSolar

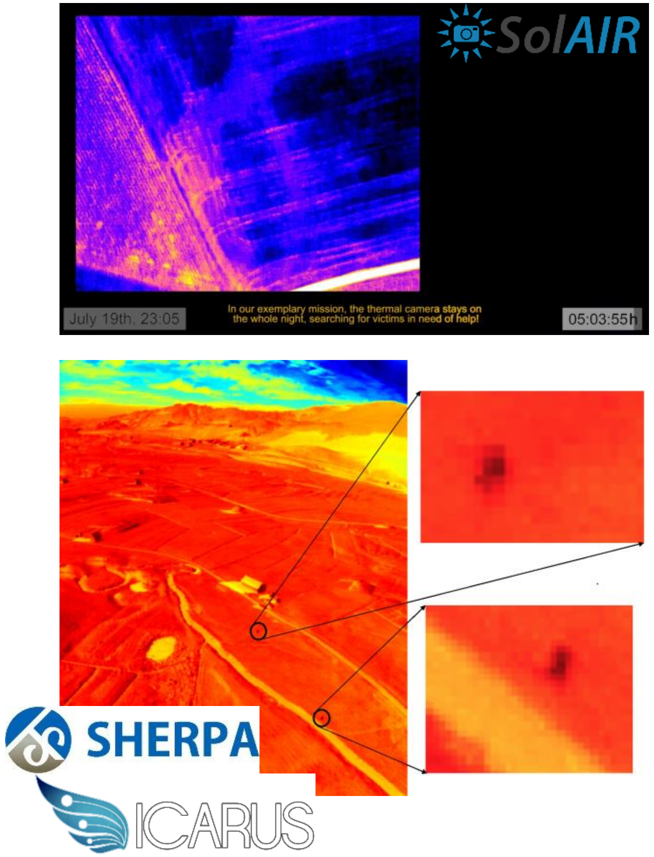


- Hand-launchable and rapidly deployable
- Fully automatic, minimal supervisory requirements
- Versatile sensor payload

AtlantikSolar UAV	
Wingspan	5.65 m
Mass	6.9 kg
Nominal cruise speed	10 m/s
Minimum endurance[a]	13 hrs
Record endurance	**81.5 hrs**
Maximum endurance	???
Max. solar power	280 W
Power consumption	40 W

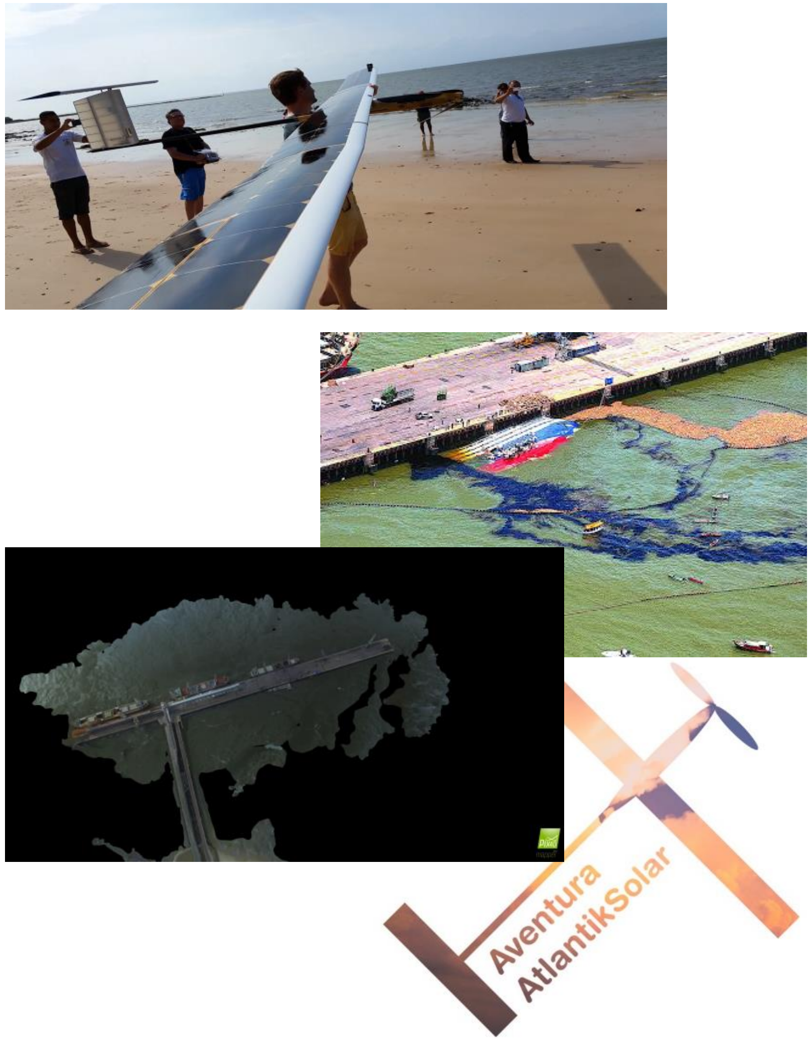
a – full battery with no solar charging

Search & Rescue

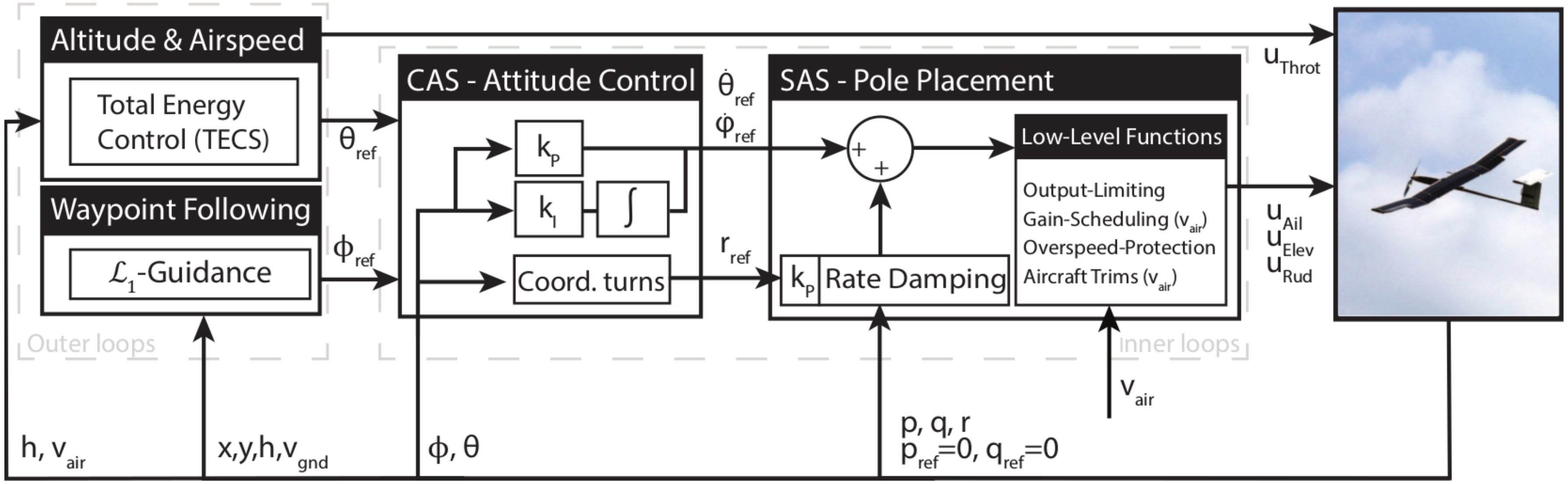


Precision Farming

Disaster Management



Standard control of solar-powered UAS



- More details on launch/landing logic in:

Oettershagen et. al. "Robotic Technologies for Solar-powered UAVs: Fully-autonomous Updraft-aware Aerial Sensing for Multi-day Search-and-rescue Missions". Journal of Field Robotics. 2018.

Solar-powered Unmanned Aerial Vehicles (UAVs)

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>Challenges over the horizon

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Optimization-based guidance

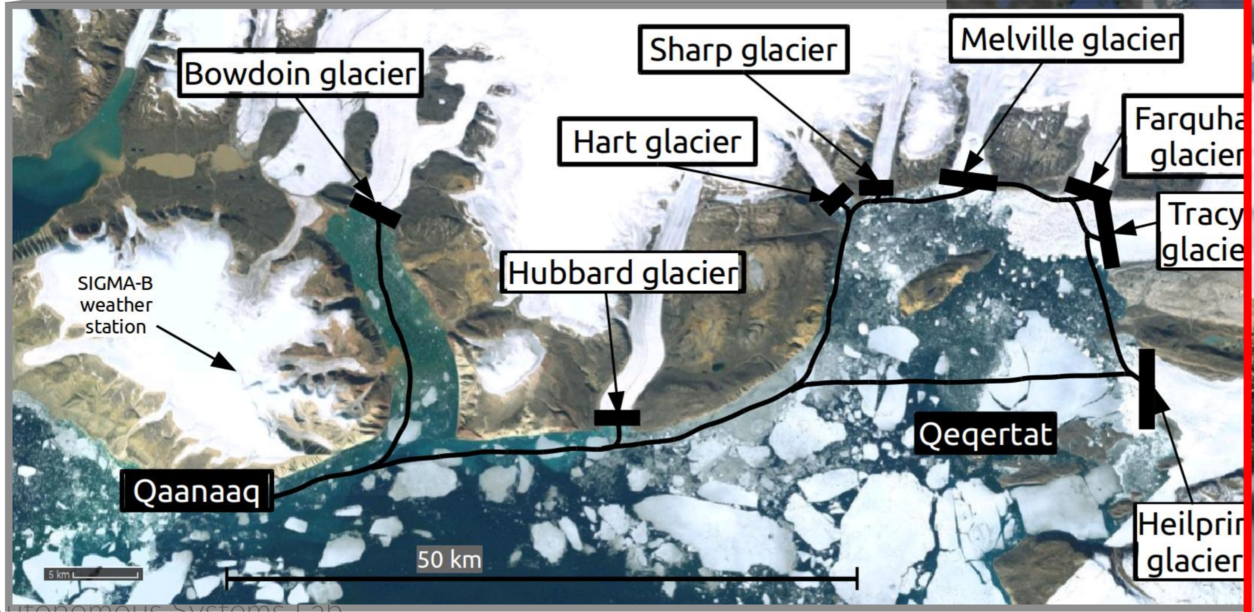
Monitoring glaciers with solar-UAVs

- **Sun2ice** summer 2017 field campaign
- sun2ice.ethz.ch

Collaboration with:
Laboratory of Hydraulics, Hydrology, and Glaciology

The destination

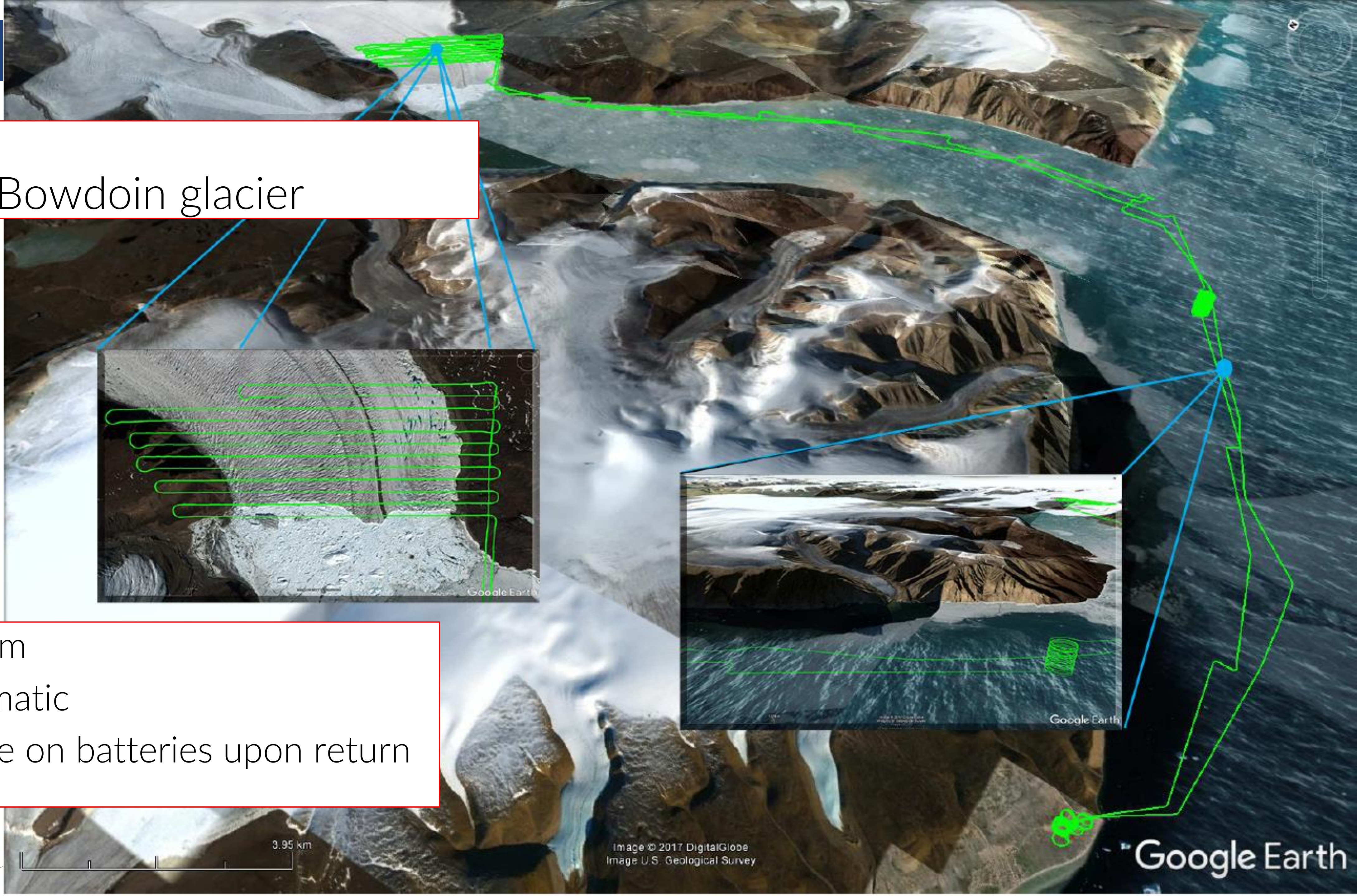
- **Qaanaaq, Greenland** (77˚N)
- 600 inhabitants **+ 1e7 dogs**
- Surrounded by tens of calving glaciers



ARCTIC Solar

ArcticSolar | Sensor suite

Mission to Bowdoin glacier



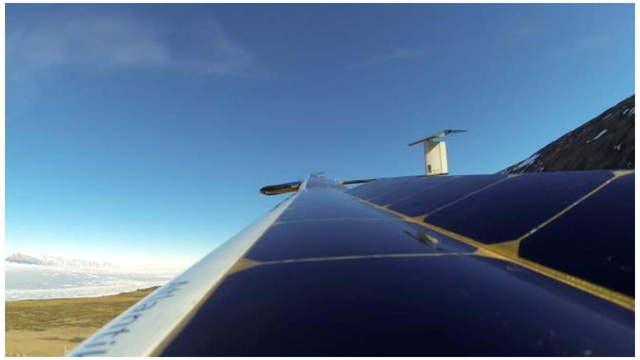
- 5hrs, 230km
- Fully automatic
- 97% charge on batteries upon return

Mission to Bowdoin Glacier
Goal: Map the calving front!

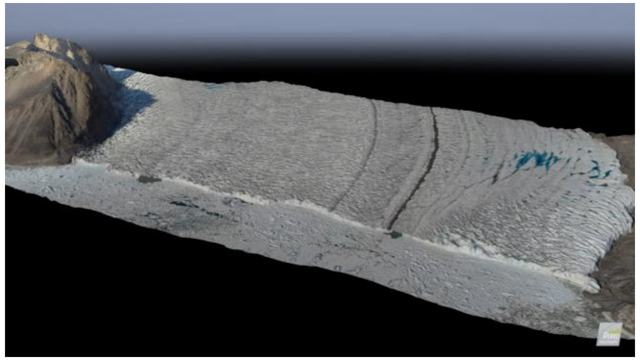
Hand-launch

En route

Landing (w/ foam goalie*)



3D reconstruction



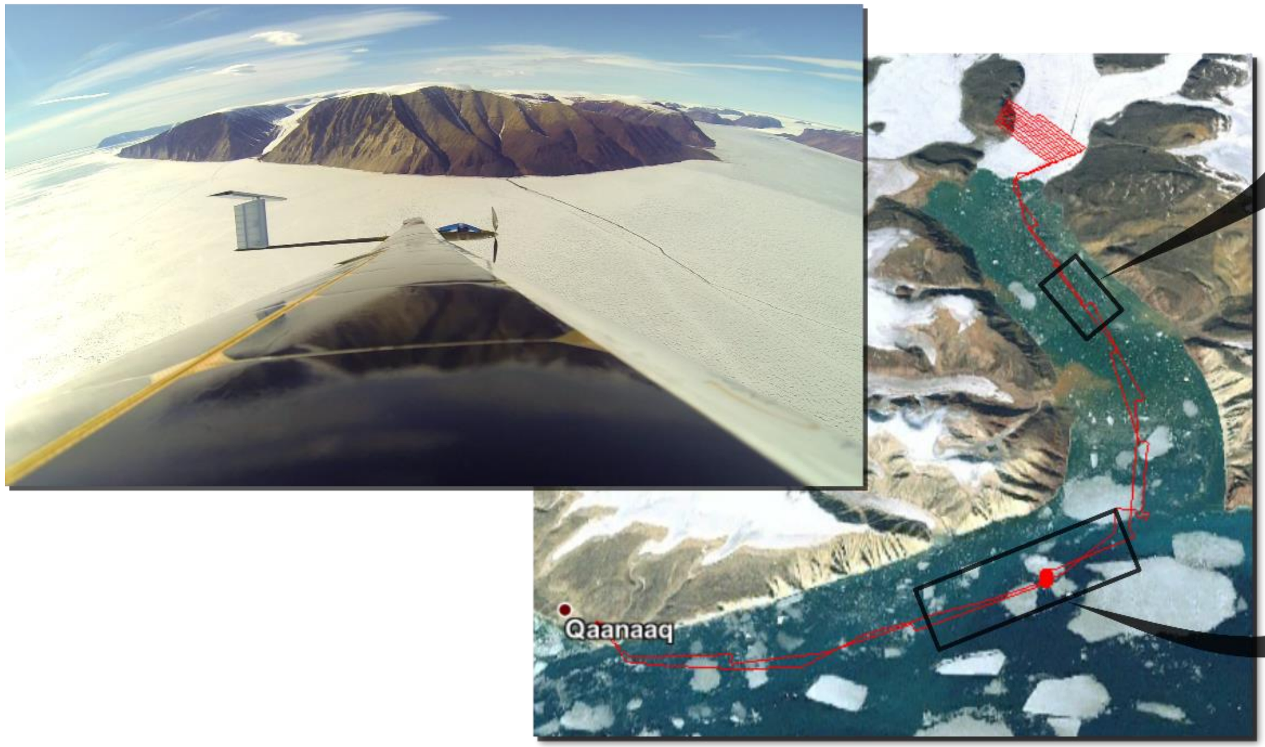
Wind…

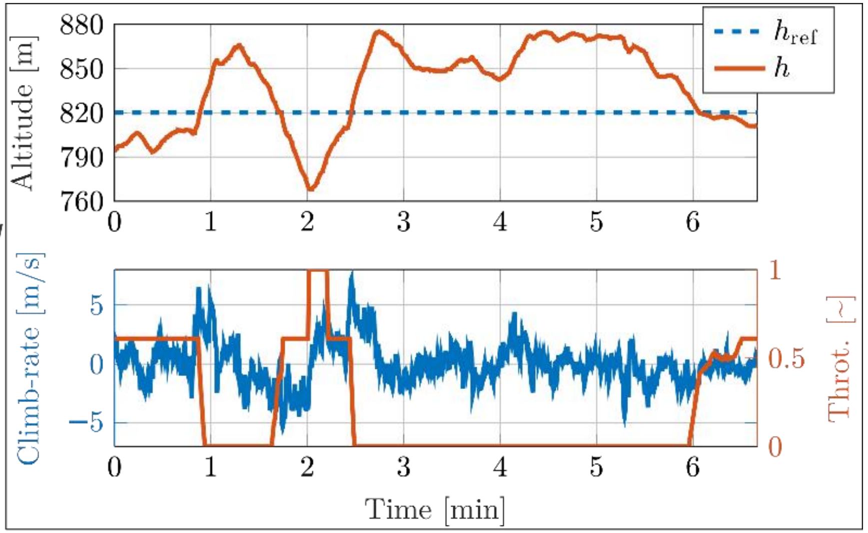
Valley winds / mountain waves

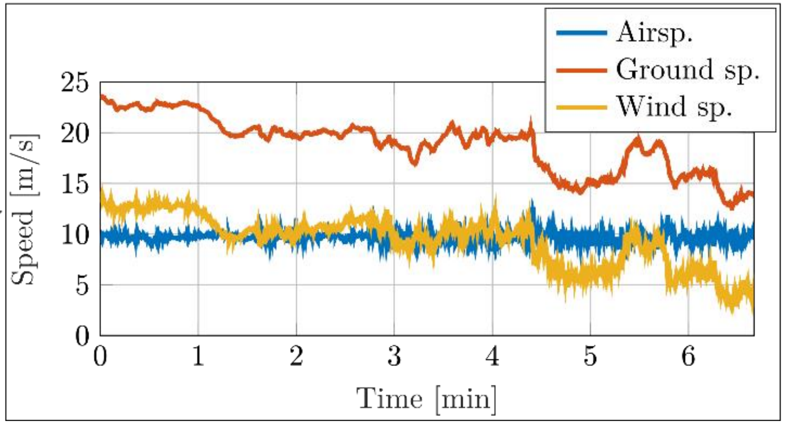
Rotor induced downdraft / turbulence

Valley winds
thermally induced
Cliff & slope winds
forced by mesoscale flow
High altitude mountain waves
forced by mesoscale flow
Domain of interest
Flight path

Unfavorable fjords







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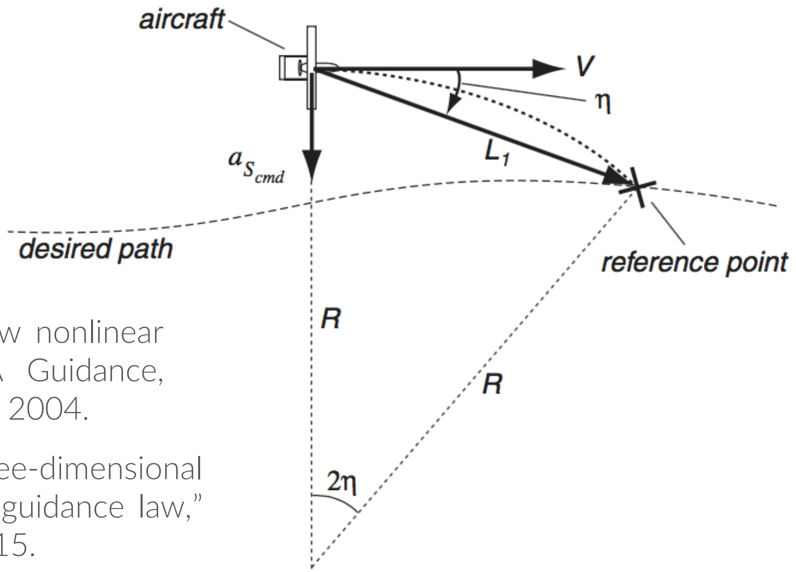
What happens when we **can't** fight the flow?

Line-of-sight Approach (state-of-the-art)

- Simple analytic implementation
- Suited for **unicyclic-like** vehicles
- UAV **community standard** - on open-source platforms such as *Pixhawk Autopilot*.

- 3D extension based on differential geometry – tracks any curvature.



P. Sanghyuk, D. John, and H. Jonathan, "A new nonlinear guidance logic for trajectory tracking," AIAA Guidance, Navigation, and Control Conference and Exhibit, 2004.

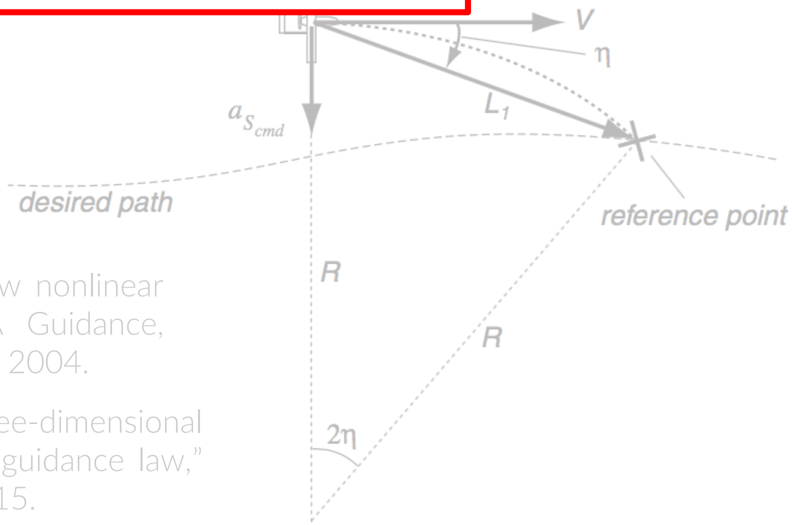
C. Namhoon, K. Youdan, and P. Sanghyuk, "Three-dimensional nonlinear differential geometric path-following guidance law," Journal of Guidance, Control, and Dynamics, 2015.

Line-of-sight Approach (state-of-the-art)

- Simple analytic implementation
- Suited for **unicyclic-like** v
- UAV **community standar** *k Autopilot*.

These laws break down in wind speed approaching or exceeding the nominal airspeed!

  - 3D extensio
    geometry – tracks any curvature.



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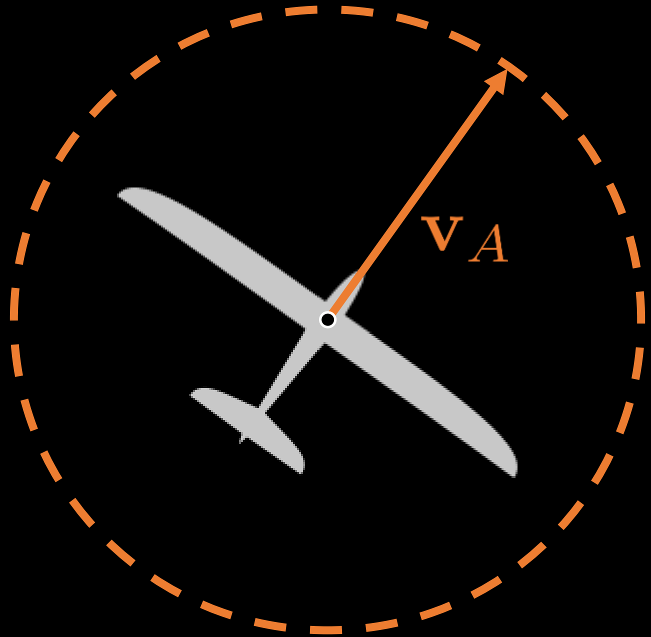
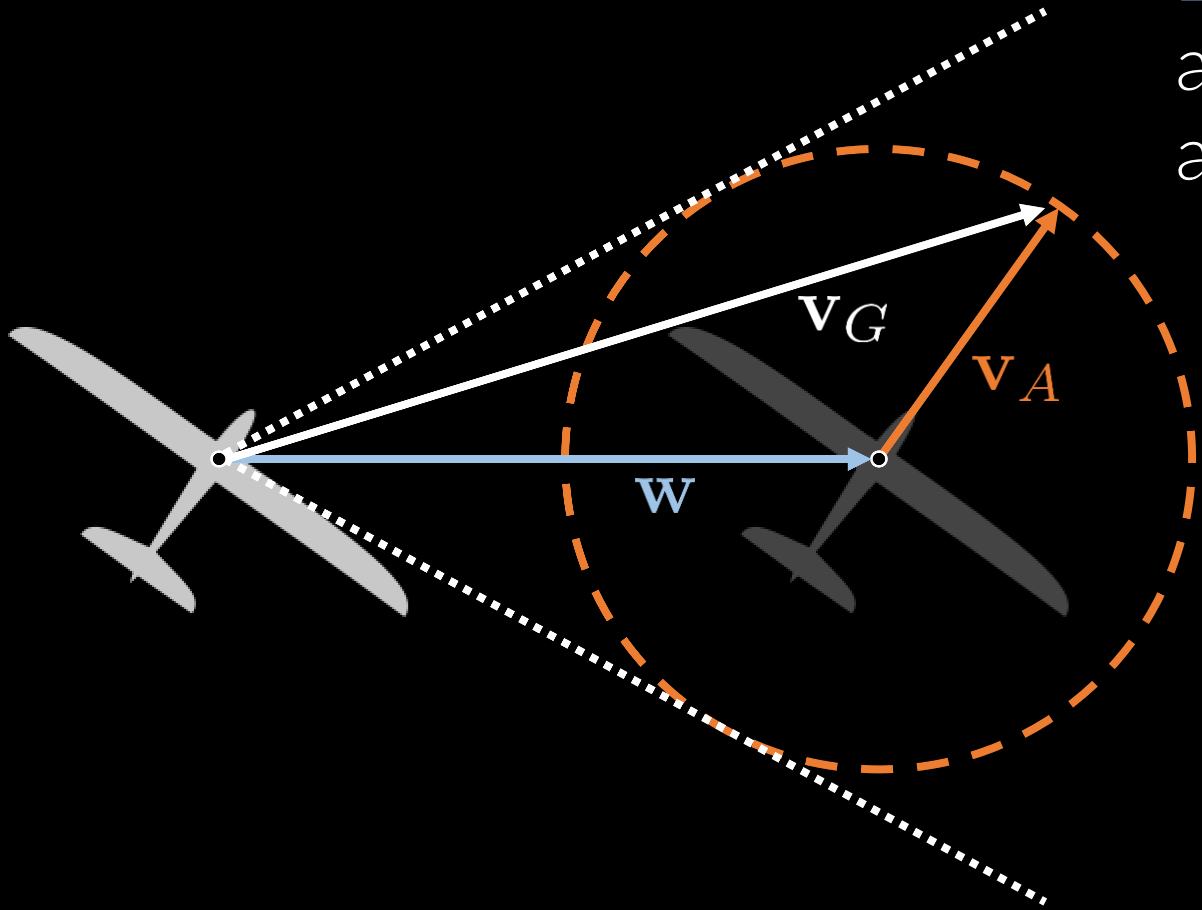
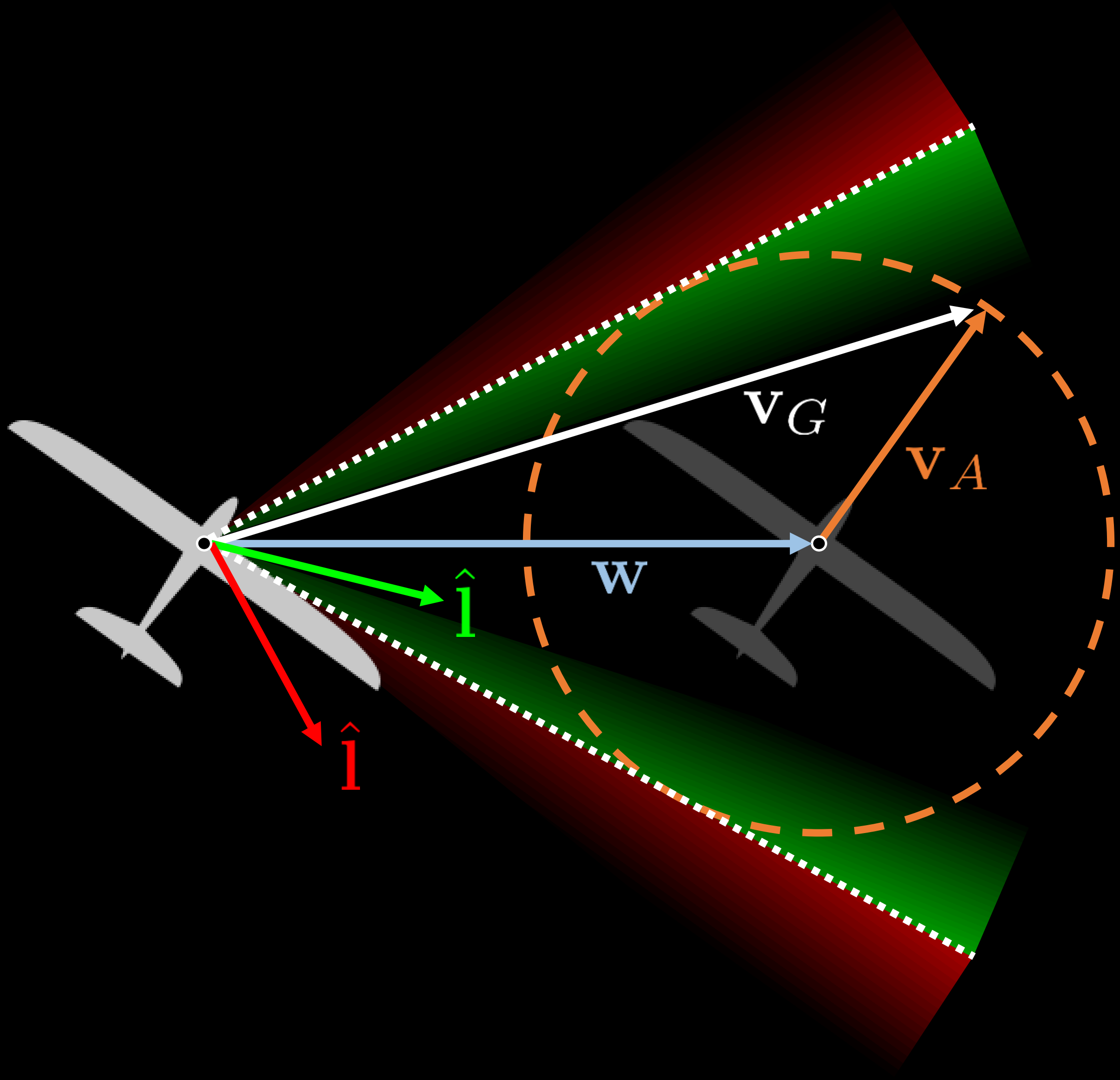
Consider a UAV flying with a given **airspeed**





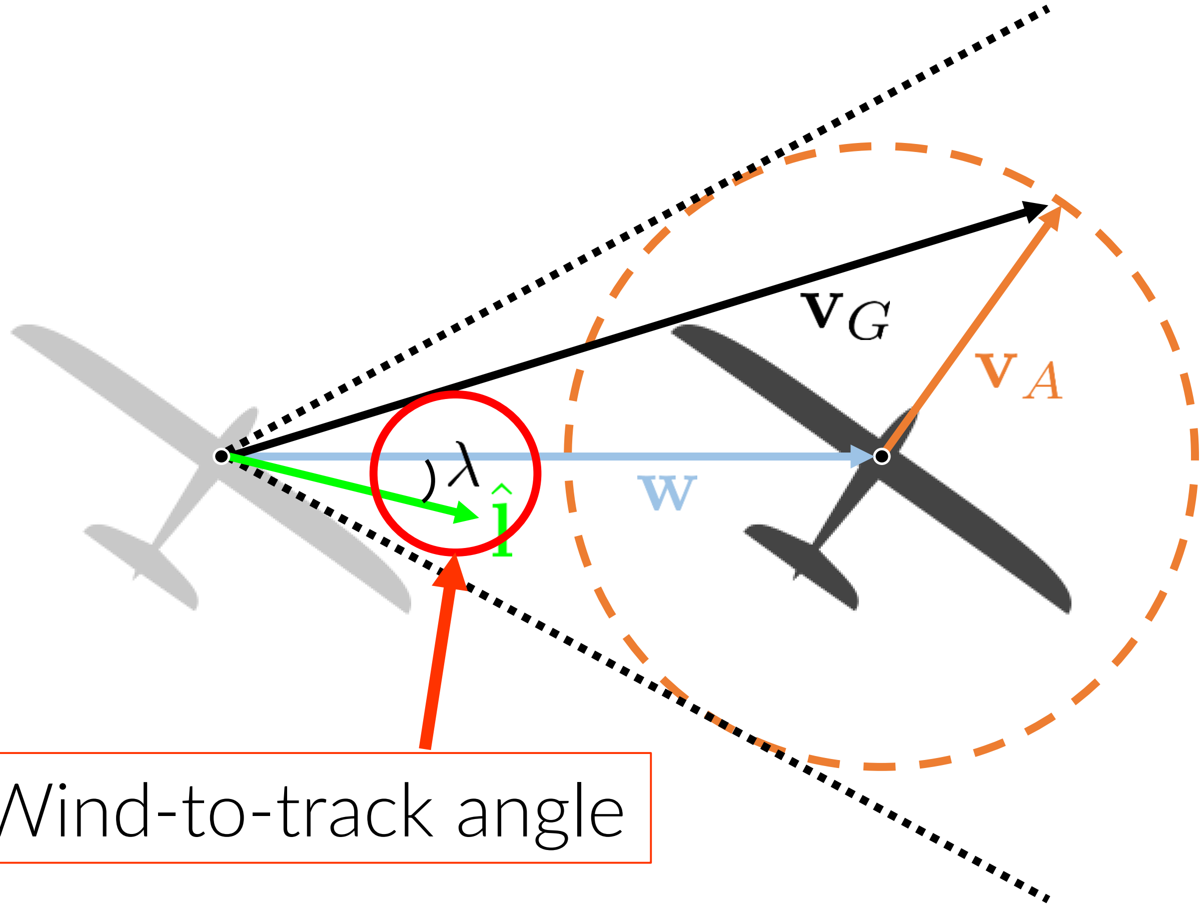
Excess wind (i.e. wind speed > airspeed) creates a "cone" of achievable **ground velocities**



Bearing vectors commanded within the cone are **feasible**

And those commanded outside the cone, **infeasible**

Some notation…



Wind ratio: $\beta = w/v_A$

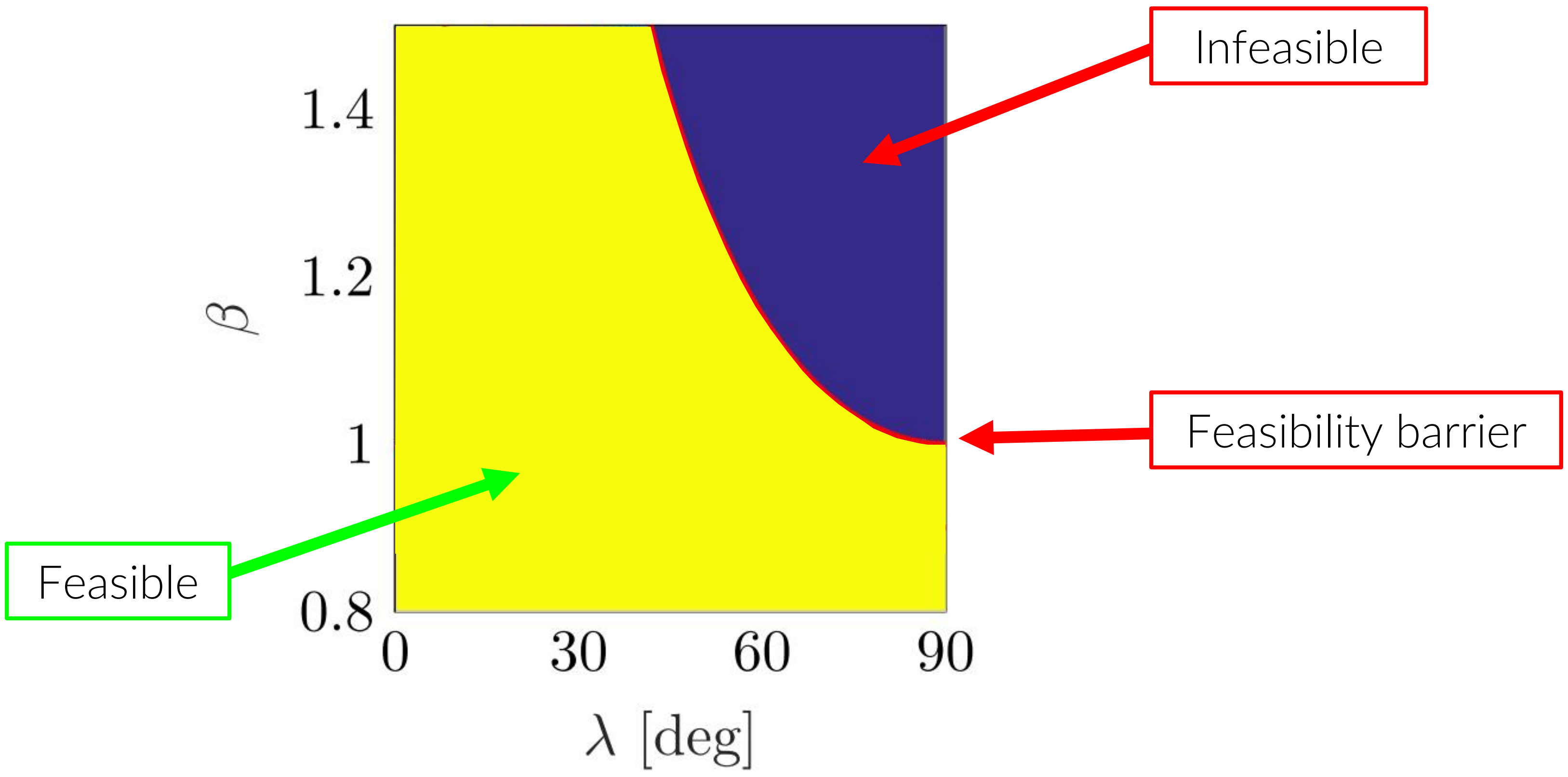
Wind-to-track angle

How* feasible is our bearing?

Furieri et. al. "Gone with the wind: Nonlinear guidance for small fixed-wing aircraft in arbitrarily strong windfields". American Control Conference (ACC), 2017.

- Binary definition:

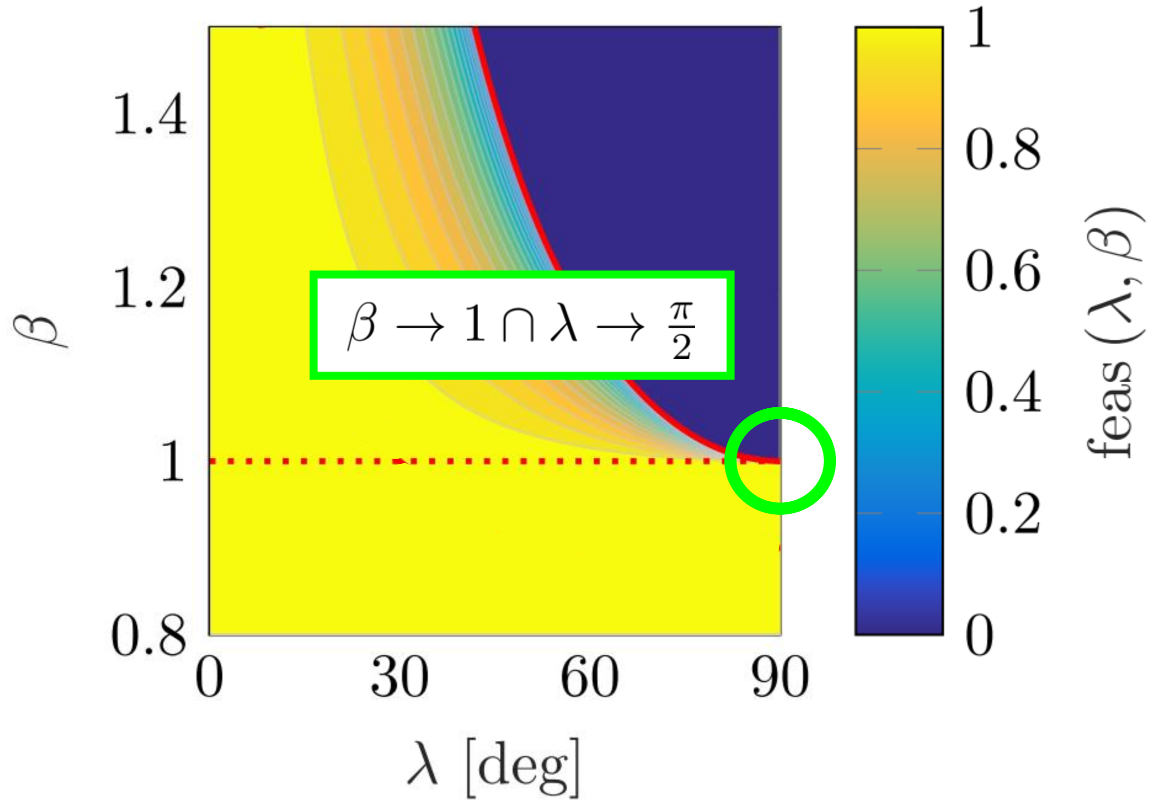
$$\begin{array}{ll} \beta \sin|\lambda| \geq 1 \cup \left(|\lambda| \geq \frac{\pi}{2} \cap \beta > 1\right) & \text{(infeasible)} \\ \text{else} & \text{(feasible)} \end{array}$$



How* feasible is our bearing?

Furieri et. al. "Gone with the wind: Nonlinear guidance for small fixed-wing aircraft in arbitrarily strong windfields". American Control Conference (ACC), 2017.

- Continuous definition[1]: $$\text{feas}(\lambda, \beta) = \frac{\sqrt{1-(\beta \sin \bar{\lambda})^2}}{\cos \bar{\lambda}}$$

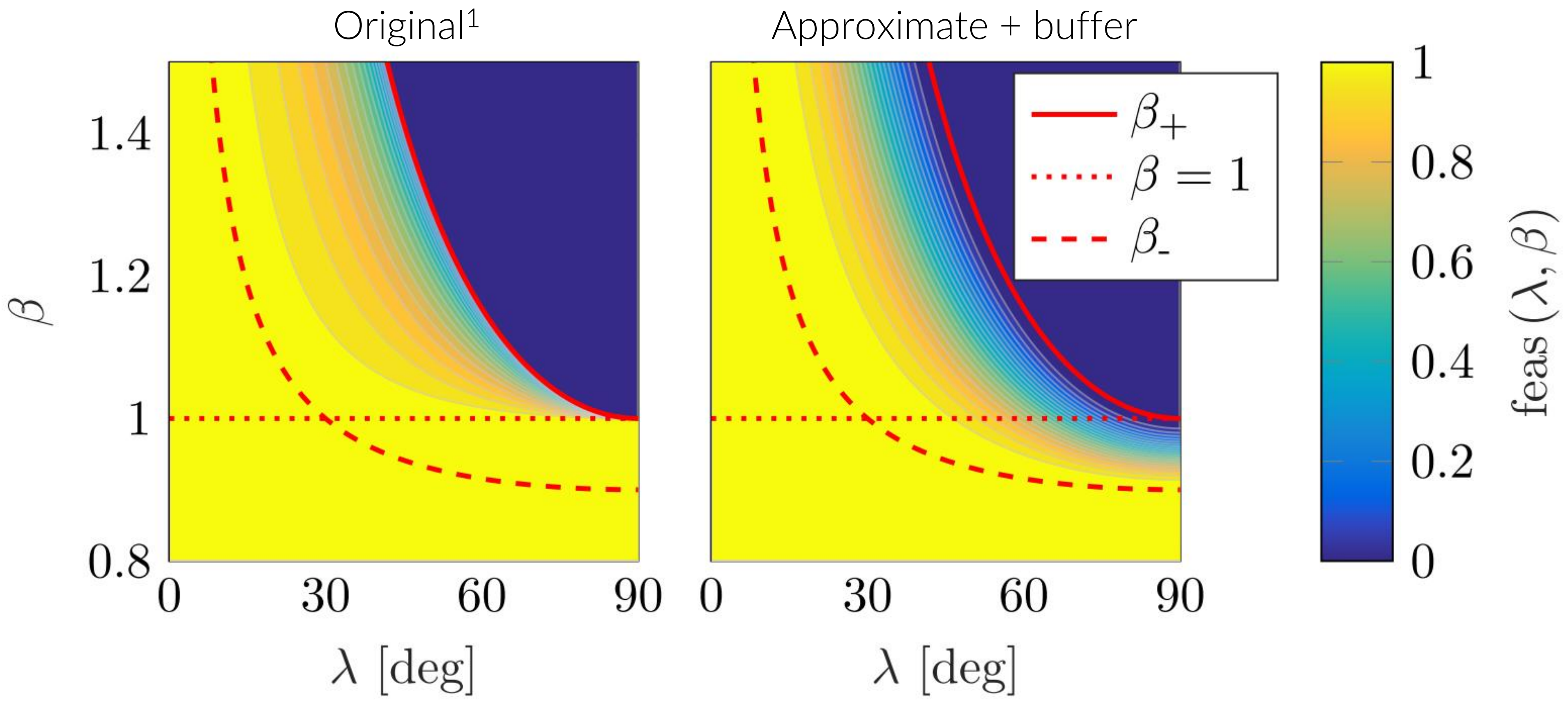


How* feasible is our bearing?

Stastny et. al. "On Flying Backwards: Preventing Run-away of Small, Low-speed Fixed-wing UAVs in Strong Winds". International Conference on Intelligent Robots and Systems (IROS), 2019.

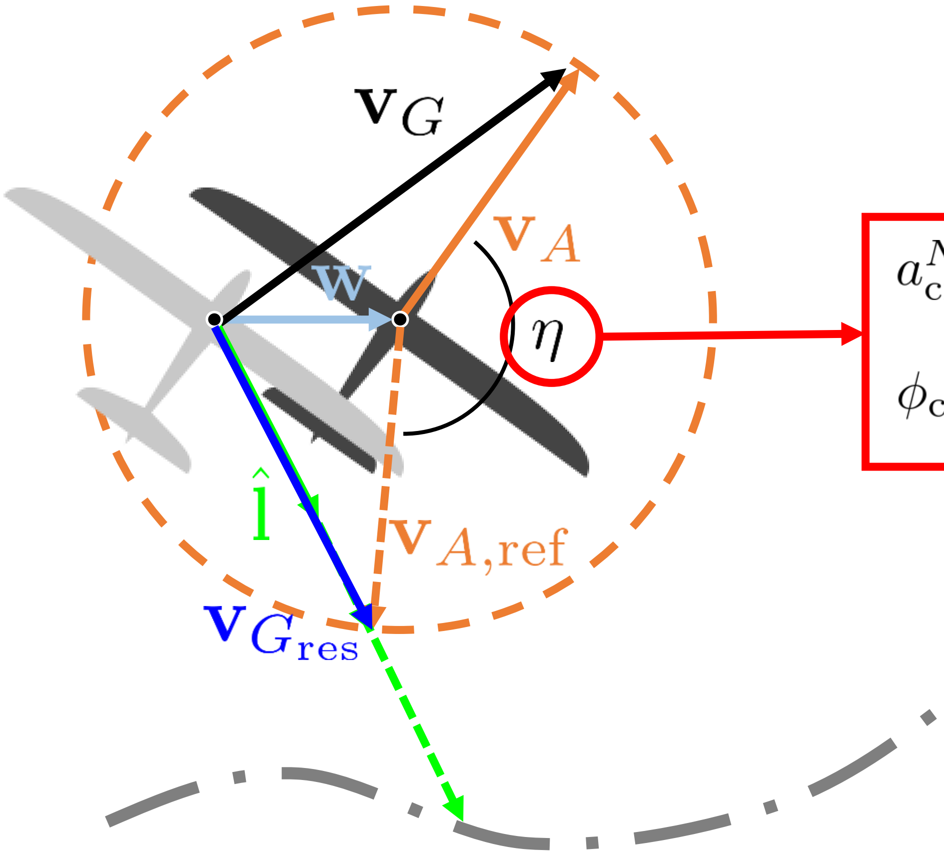
- Practical definition:

$$\text{feas}\left(\lambda, \beta\right) = \begin{cases} 0 & \beta > \beta_+ \\ \cos^2\left(\frac{\pi}{2}\,\text{sat}\left(\frac{\beta-\beta_-}{\beta_+-\beta_-}, 0, 1\right)\right) & \beta > \beta_- \\ 1 & \text{else} \end{cases}$$



Directional guidance (feasible case)

Stastny et. al. "On Flying Backwards: Preventing Run-away of Small, Low-speed Fixed-wing UAVs in Strong Winds". International Conference on Intelligent Robots and Systems (IROS), 2019.



$$a^N_{\mathrm{cmd}} = f(\eta)$$

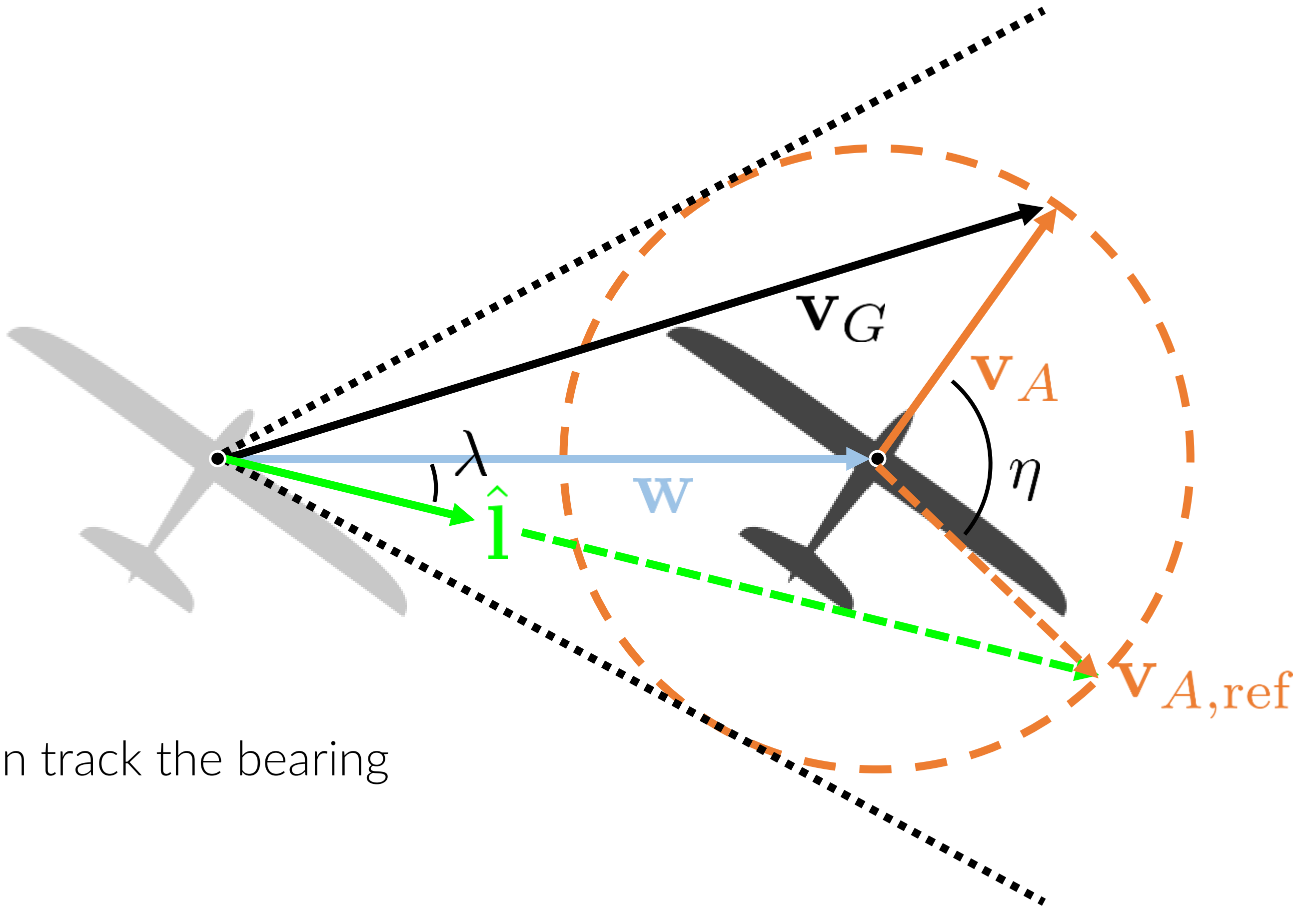
$$\phi_{\mathrm{cmd}} = \tan^{-1}\left(\frac{a^N_{\mathrm{cmd}}}{g}\right)$$

Directional guidance ("partially" feasible case)

Stastny et. al. "On Flying Backwards: Preventing Run-away of Small, Low-speed Fixed-wing UAVs in Strong Winds". International Conference on Intelligent Robots and Systems (IROS), 2019.

$$\beta > 1$$

$$\beta \sin|\lambda| < 1$$



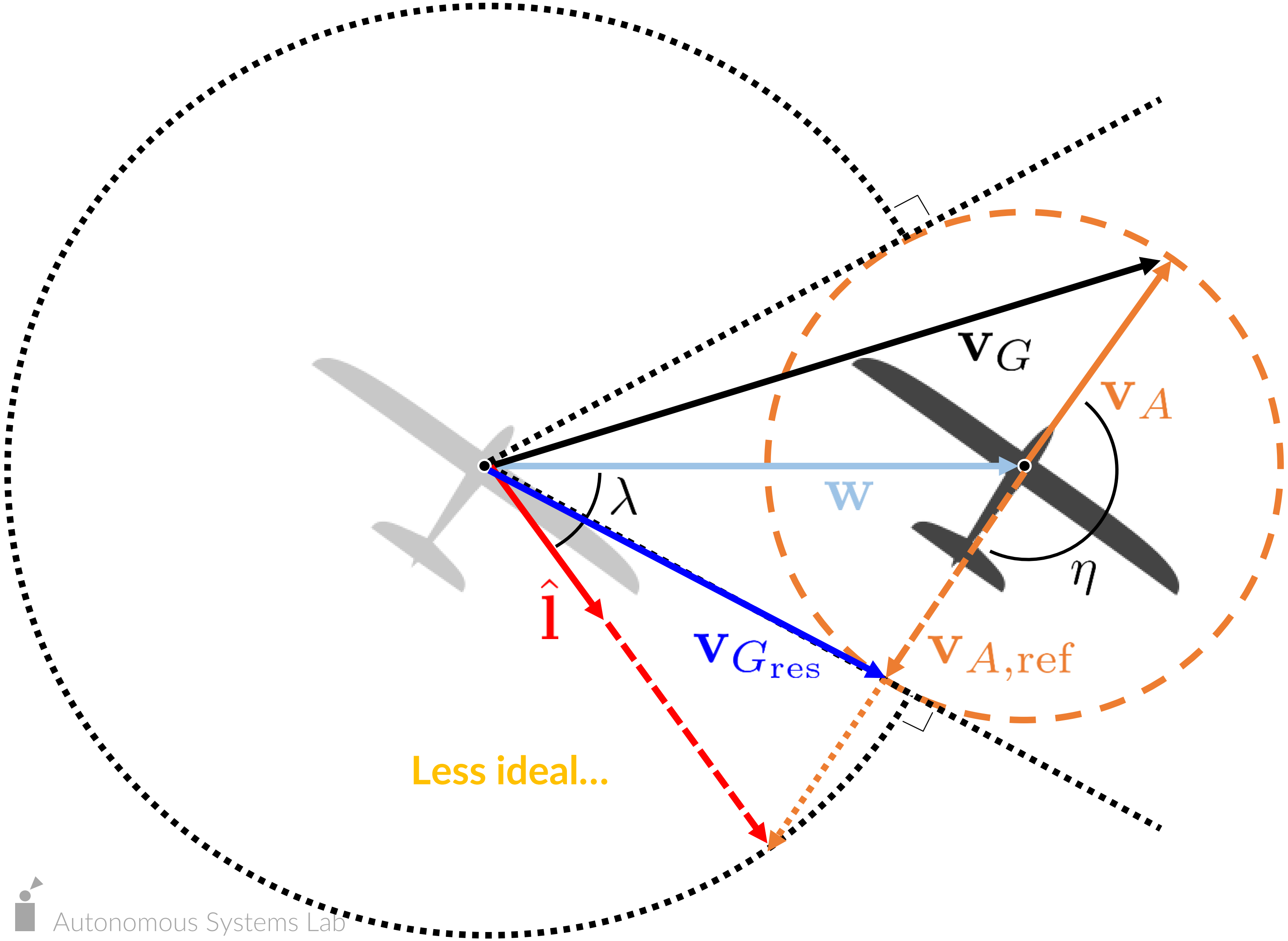
"**Ideal case**": we can track the bearing

Directional guidance (infeasible case)

Stastny et. al. "On Flying Backwards: Preventing Run-away of Small, Low-speed Fixed-wing UAVs in Strong Winds". International Conference on Intelligent Robots and Systems (IROS), 2019.

$$\beta > 1$$

$$\beta \sin|\lambda| \geq 1$$



Directional guidance (infeasible case)

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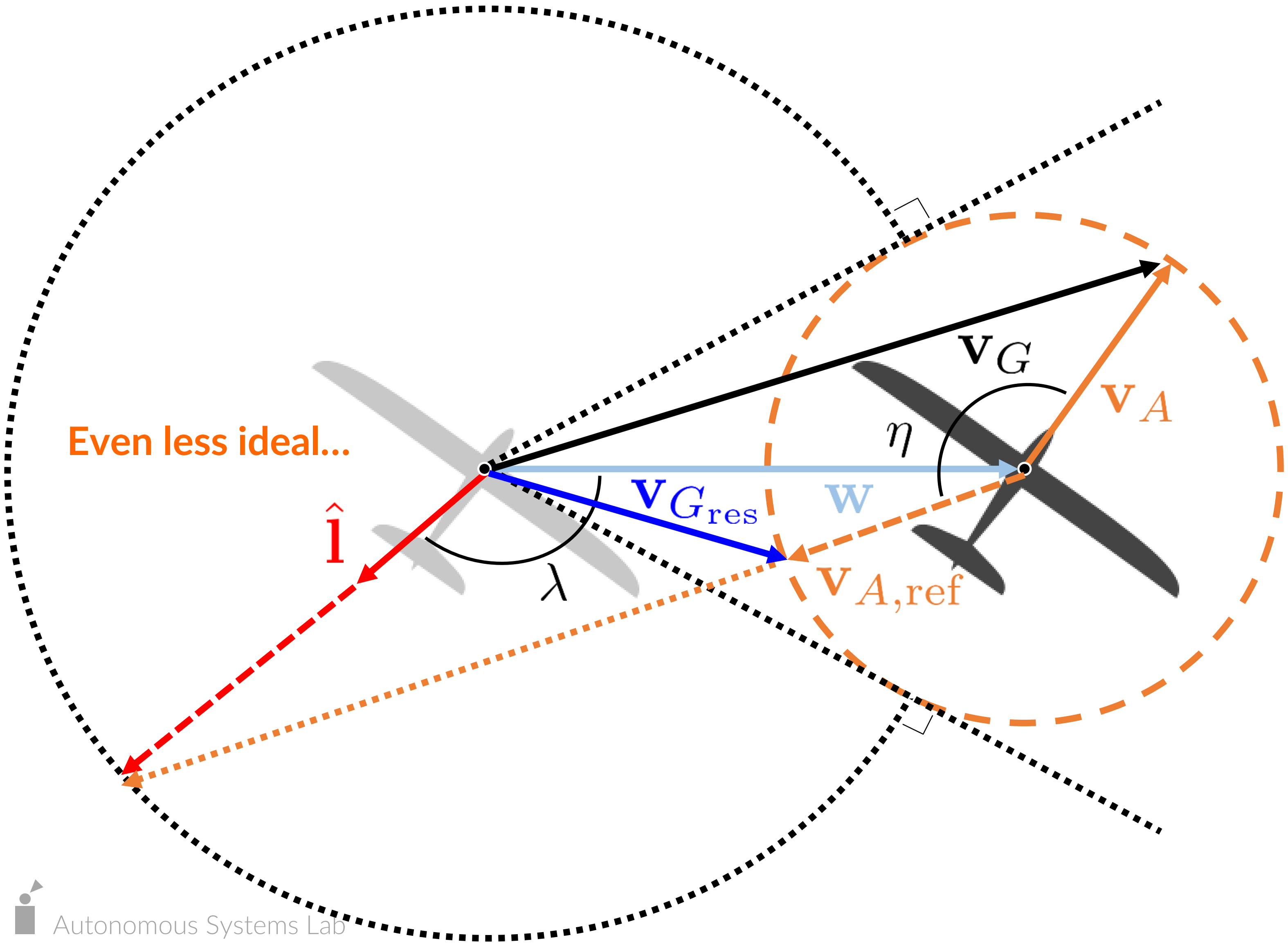
$$\beta > 1$$

$$\beta \sin|\lambda| \geq 1$$



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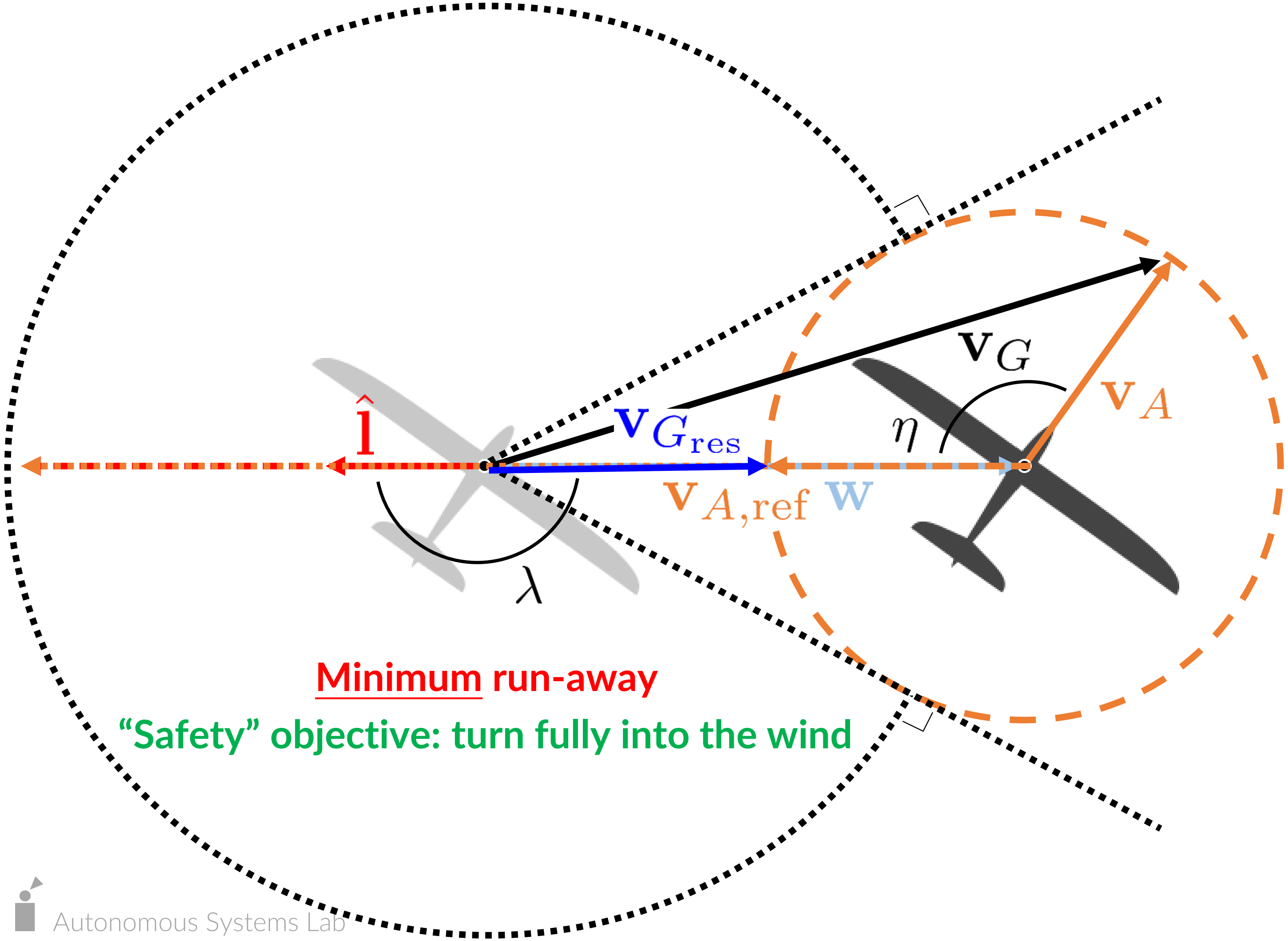
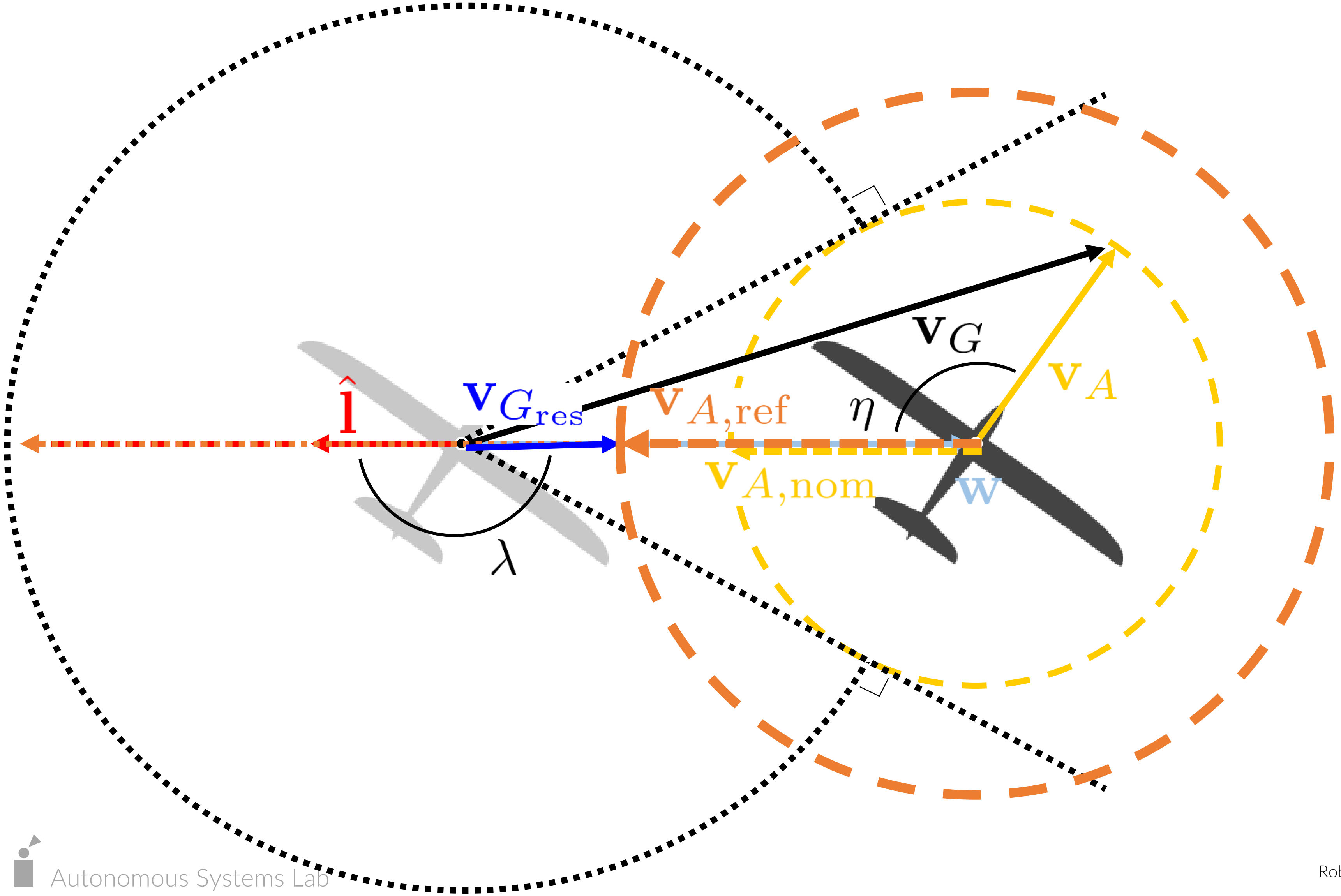


Minimum run-away

"Safety" objective: turn fully into the wind

Airspeed reference compensation

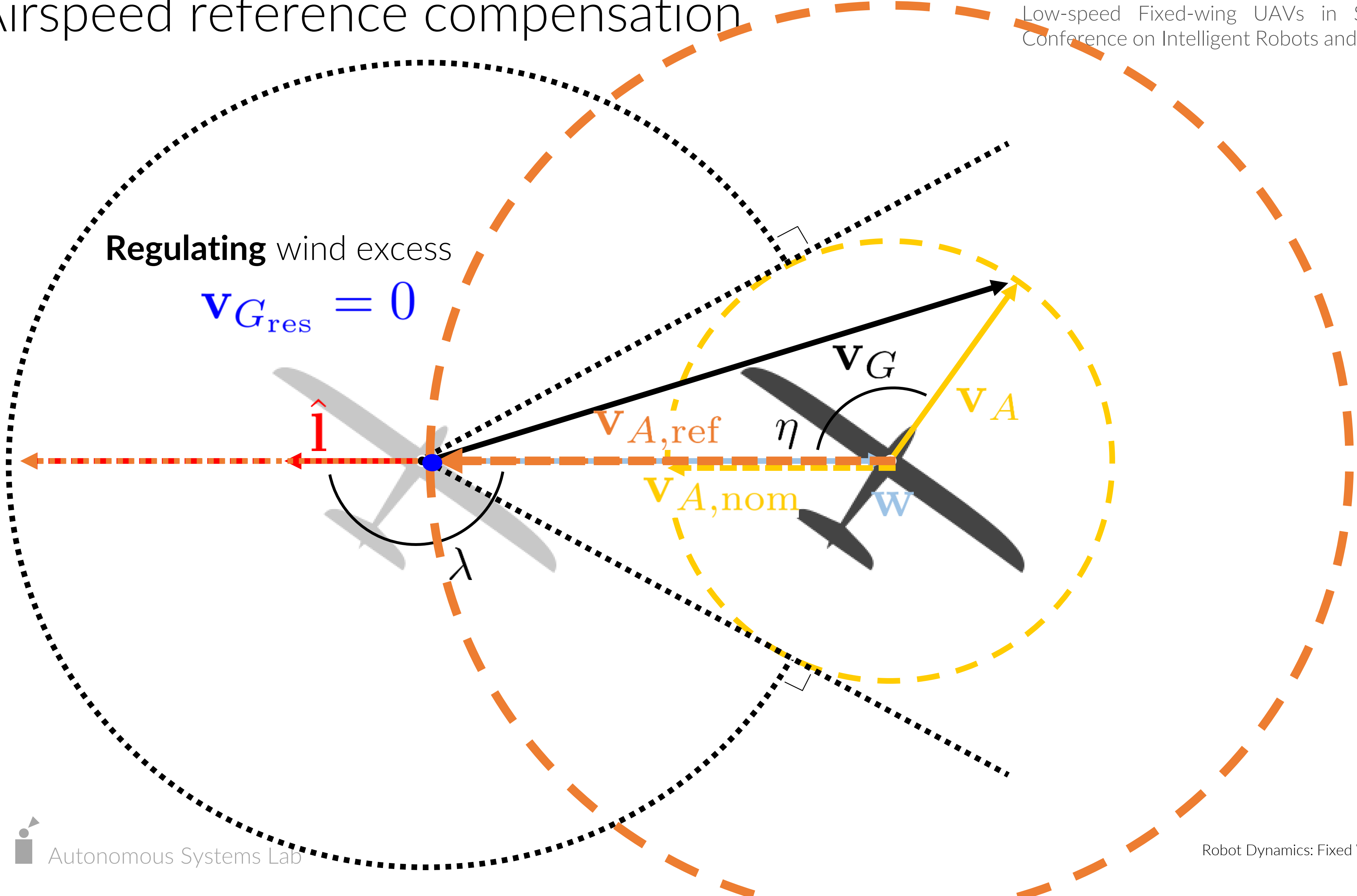
Stastny et. al. "On Flying Backwards: Preventing Run-away of Small, Low-speed Fixed-wing UAVs in Strong Winds". International Conference on Intelligent Robots and Systems (IROS), 2019.



We can also increase the airspeed reference **if** power is available.

Airspeed reference compensation

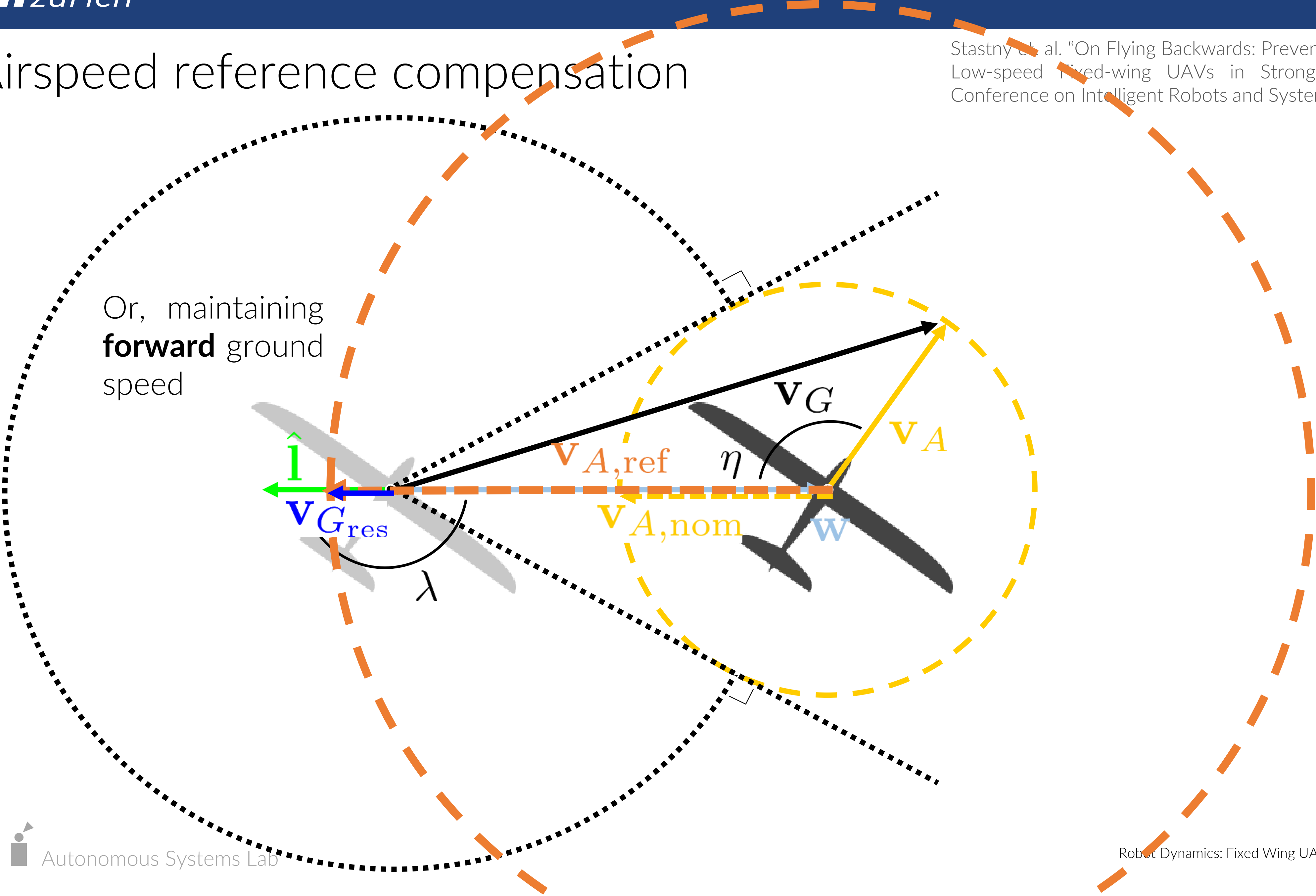
Stastny et. al. "On Flying Backwards: Preventing Run-away of Small, Low-speed Fixed-wing UAVs in Strong Winds". International Conference on Intelligent Robots and Systems (IROS), 2019.



Airspeed reference compensation

Stastny et al. "On Flying Backwards: Preventing Run-away of Small, Low-speed Fixed-wing UAVs in Strong Winds". International Conference on Intelligent Robots and Systems (IROS), 2019.

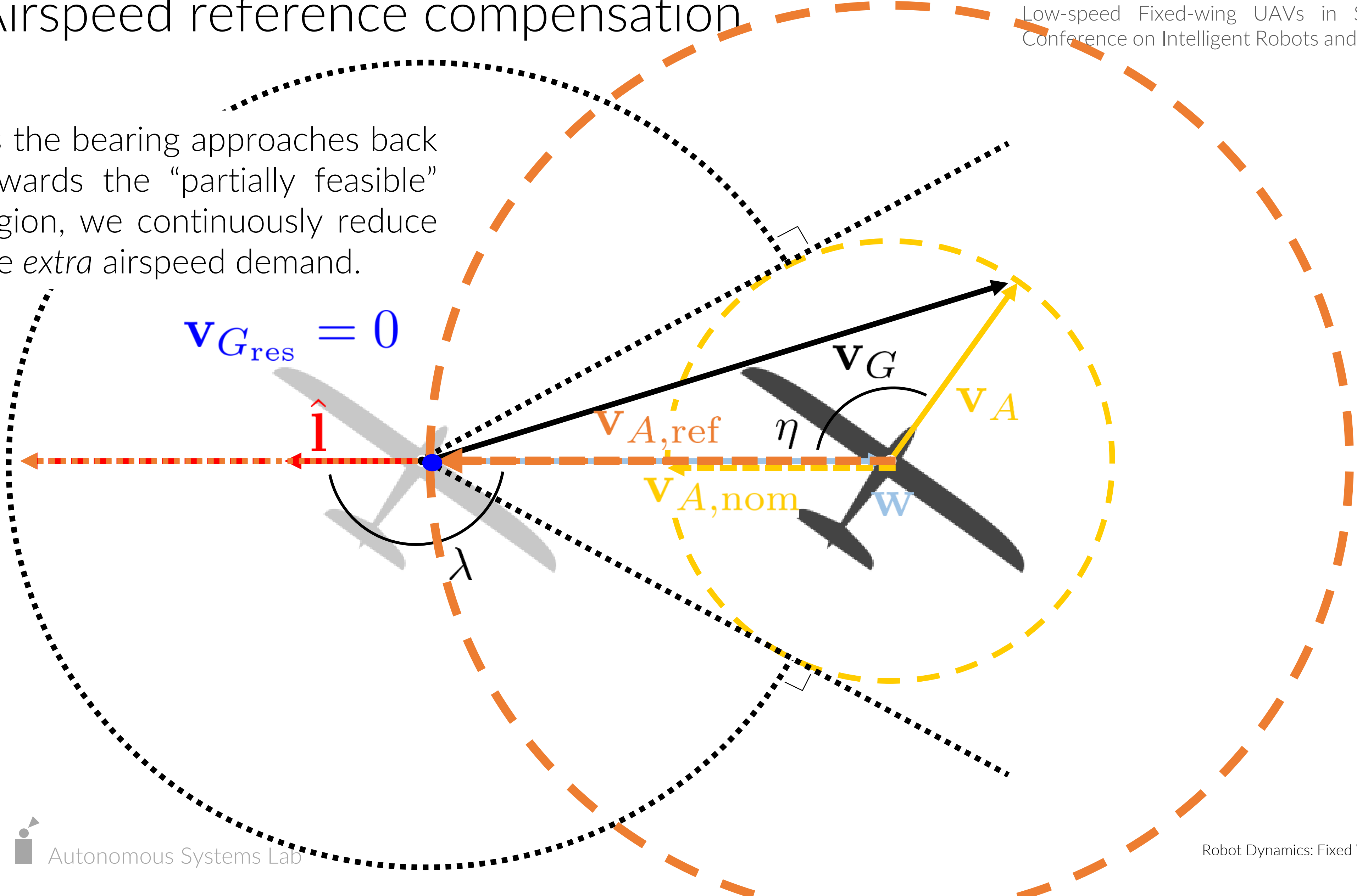
Or, maintaining **forward** ground speed



Airspeed reference compensation

Stastny et. al. "On Flying Backwards: Preventing Run-away of Small, Low-speed Fixed-wing UAVs in Strong Winds". International Conference on Intelligent Robots and Systems (IROS), 2019.

As the bearing approaches back towards the "partially feasible" region, we continuously reduce the *extra* airspeed demand.



Airspeed reference compensation

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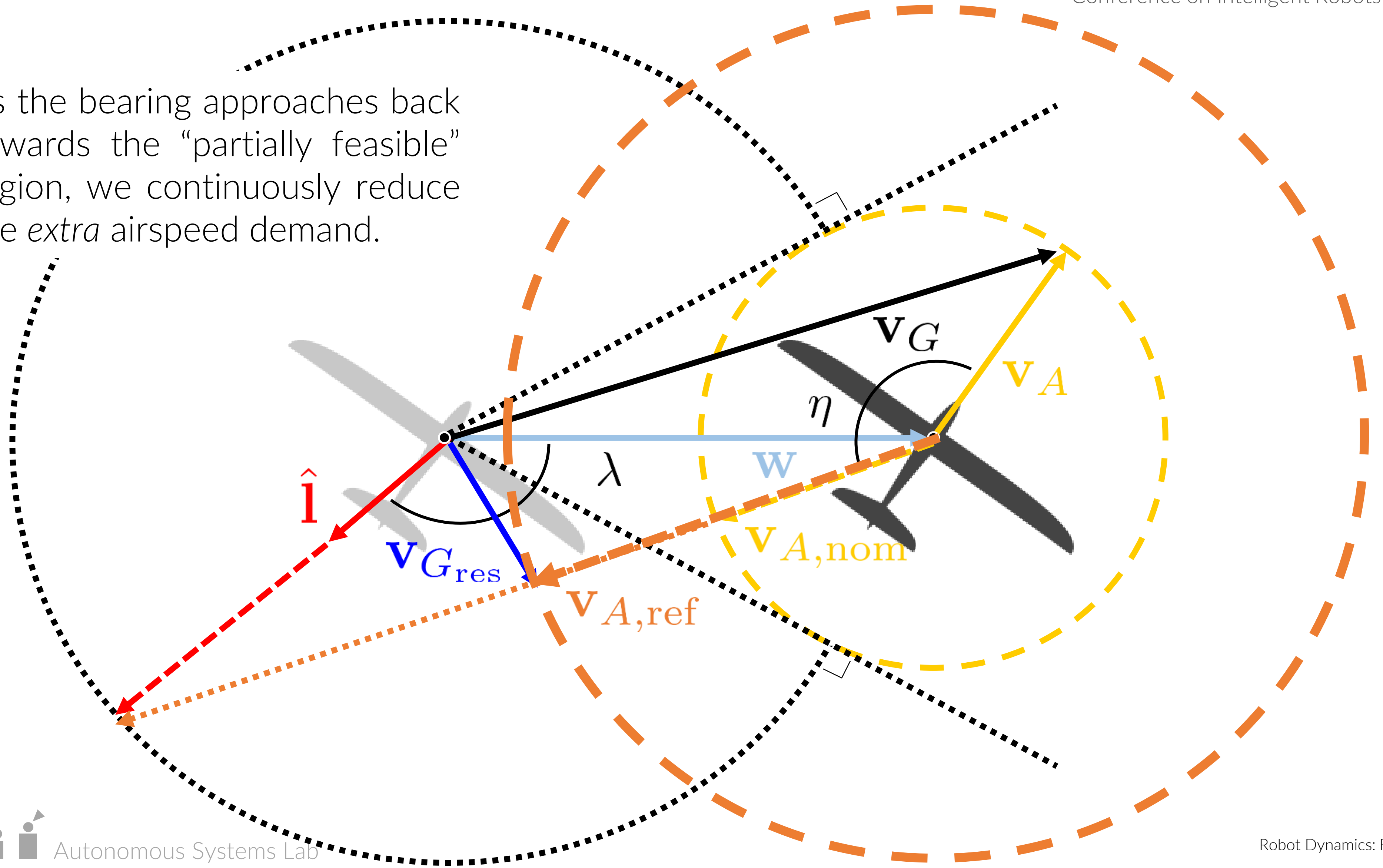

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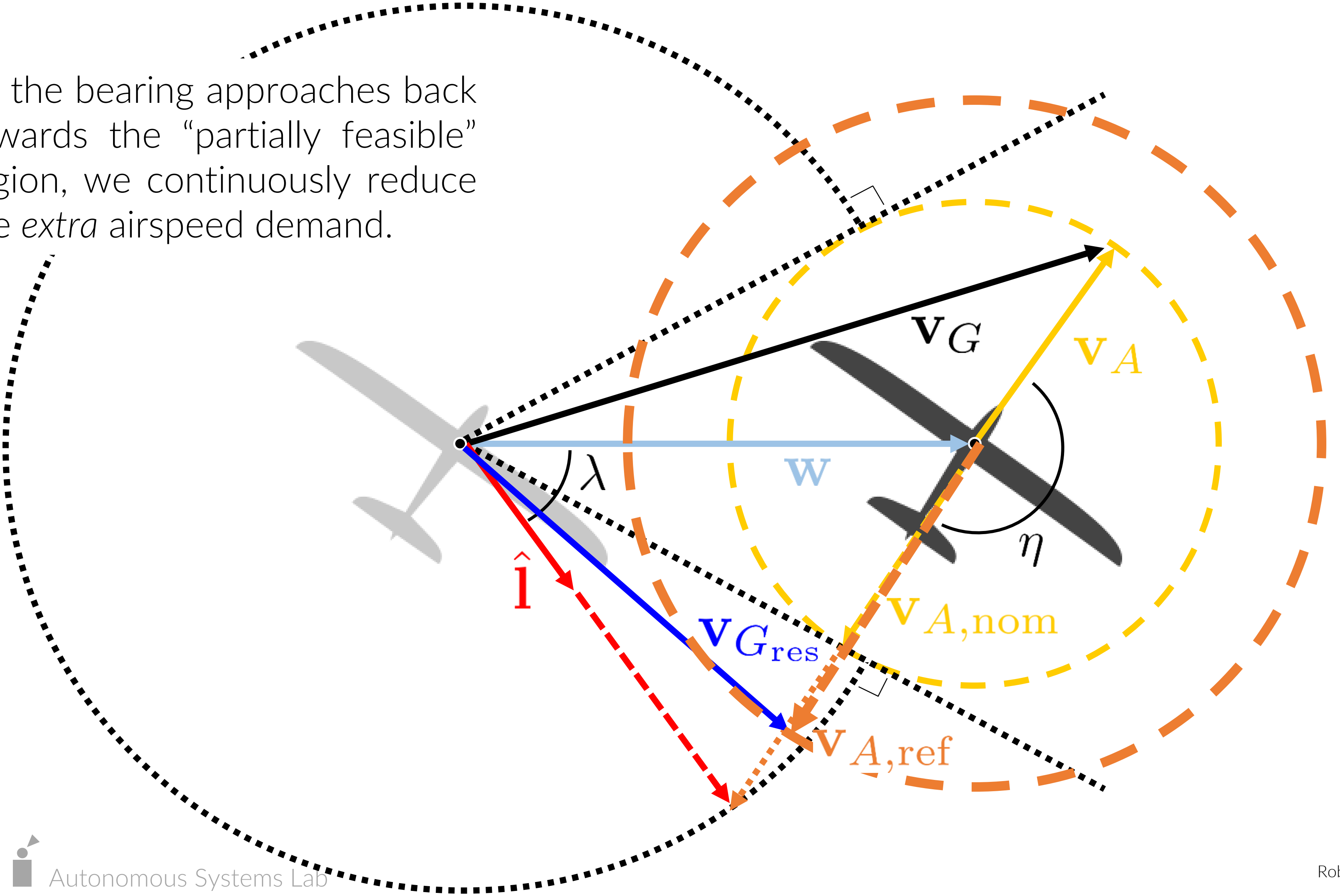

Airspeed reference compensation

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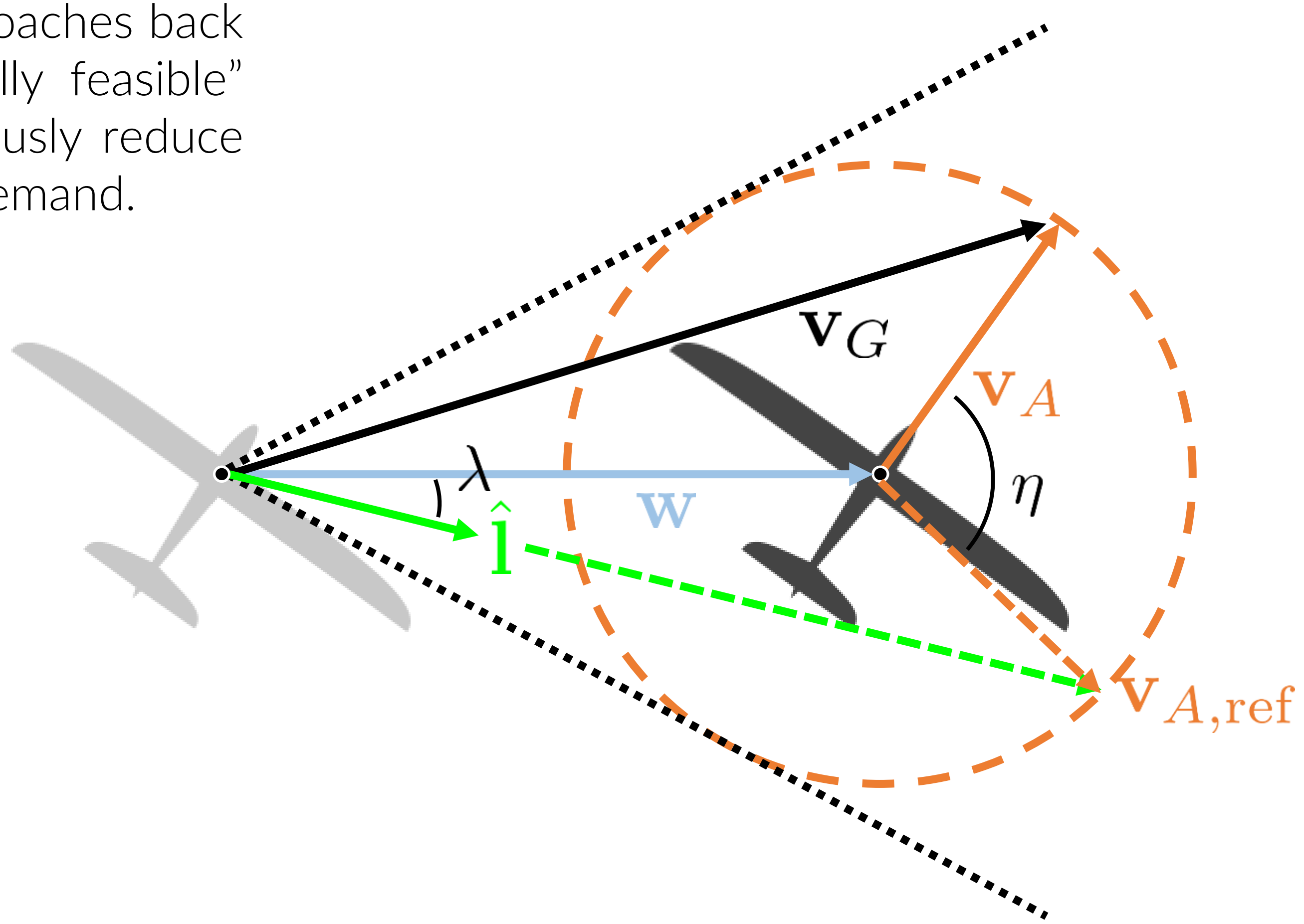

Now, back to the nominal reference.

FLIGHT EXPERIMENT: **TRACK KEEPING**

AIRSPEED REF. COMPENSATION: **ENABLED**

Wind Speed = 9.70 (10.0) m/s

Nom. Airspeed = 8.8 m/s

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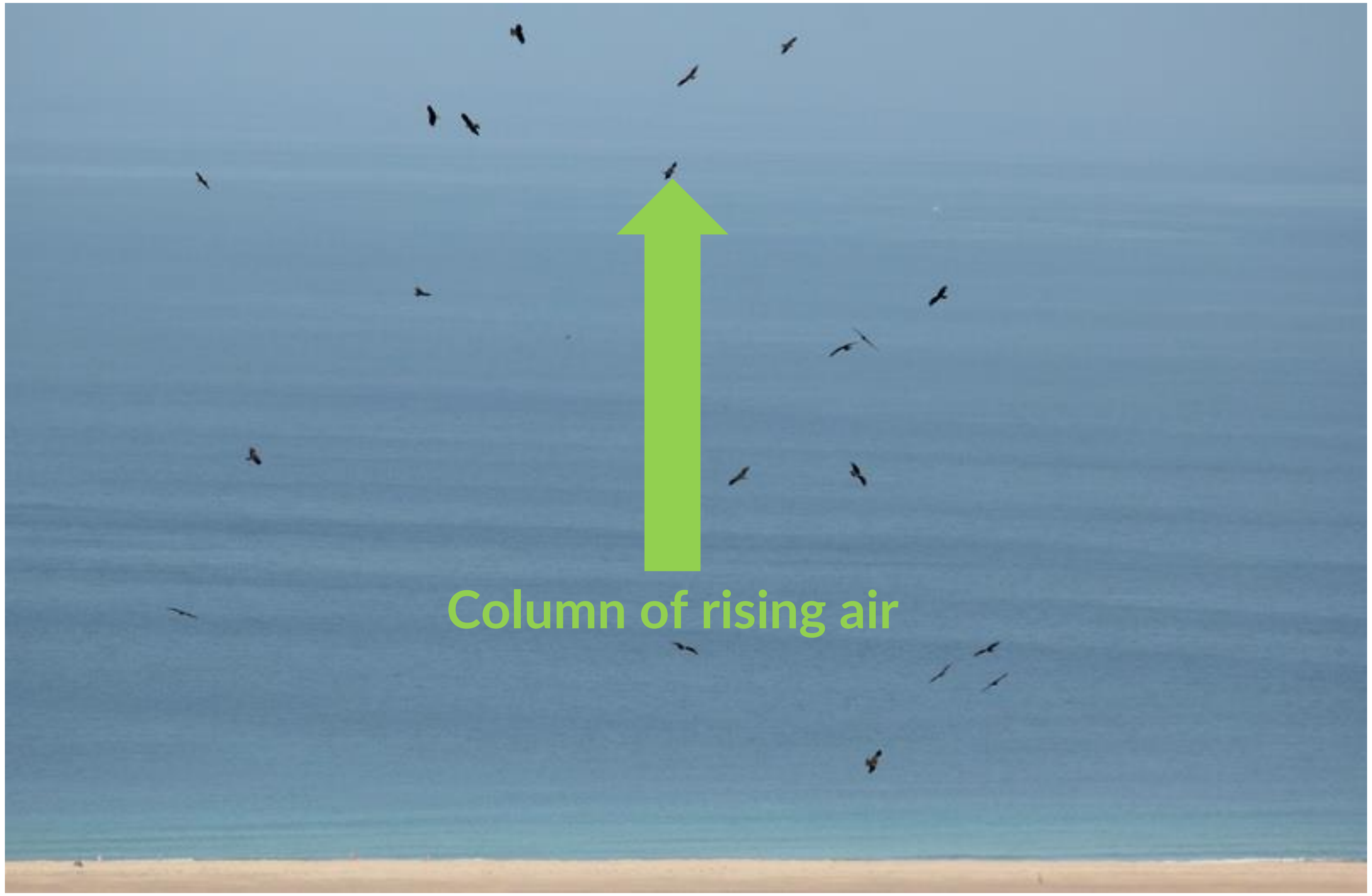
Optimization-based guidance

Wind exploitation:
Autonomous thermal updraft tracking



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Wind exploitation:
Autonomous Thermal Updraft Tracking

Attempt tracking of
- a single thermal updraft represented as
- a Gaussian updraft speed distribution
- with an Extended Kalman Filter (EKF)

Use simple 4-state EKF:

State

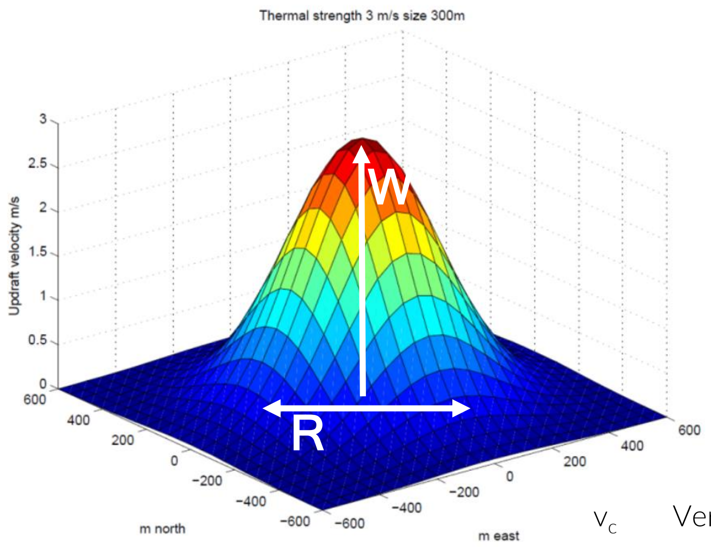
$$X = \begin{bmatrix} W \\ R \\ x \\ y \end{bmatrix} = \begin{bmatrix} Max.updraft\ strength \\ Radius \\ Distance\ north\ of\ A/C \\ Distance\ east\ of\ A/C \end{bmatrix}$$

System model

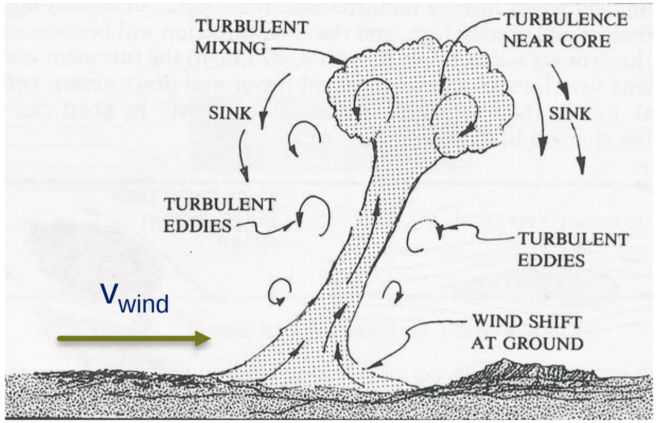
$$X_{k+1} = f(X_k) = X_k + \begin{bmatrix} 0 \\ 0 \\ -v_{wind,north} \cdot \Delta h / v_c \\ -v_{wind,east} \cdot \Delta h / v_c \end{bmatrix}$$

Measurement

$$z_1 = w(W,R,x,y) = W \cdot e^{-\frac{x^2+y^2}{R^2}}$$



v_c Vertical speed of thermal bubble [m/s]
h Altitude [m]



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Wind exploitation:
Autonomous Thermal Updraft Tracking

Goal: Map (1) location and (2) orientation in thermal to an expected roll angle tracking error while in attitude stabilized mode.

$$\boxed{z_2} = \frac{c \cdot r \cdot W}{R^2} \cdot e^{-\frac{r^2}{R^2}} \cdot \boxed{\sin\zeta \cdot \cos\phi}$$

Roll Moment Error

Updraft gradient at current position

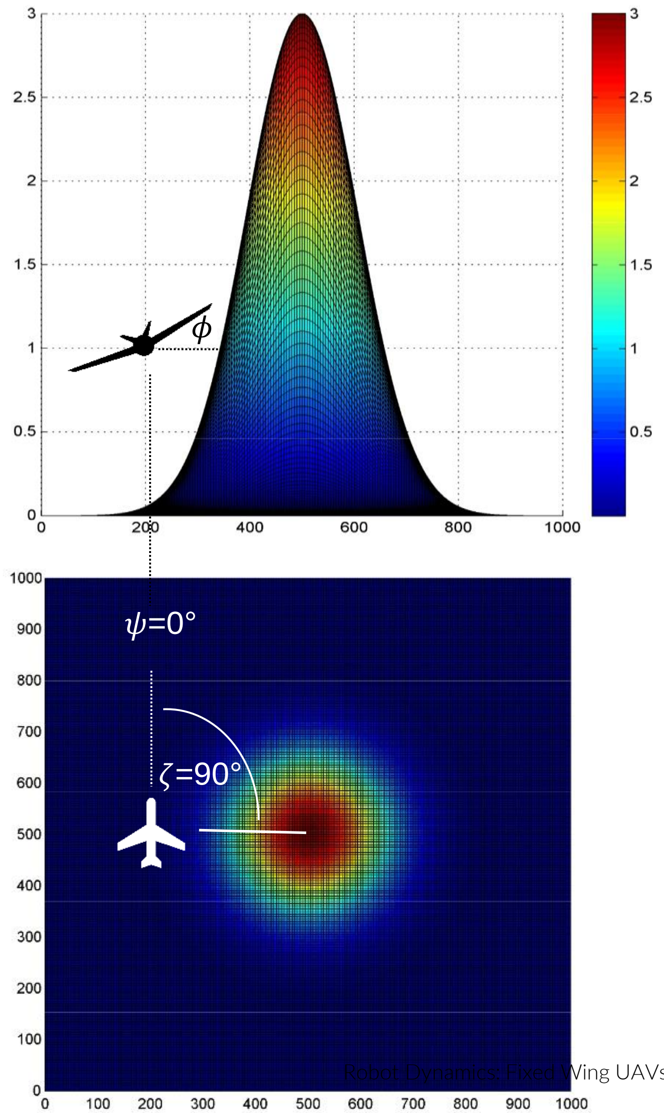
(Lateral) orientation of A/C w.r.t thermal core

ϕ = Roll angle. ψ = Yaw Angle. ζ = Direction of. thermal center

$$r = \sqrt{x^2 + y^2} \qquad sin\zeta = \frac{\cos\psi \cdot y - \sin\psi \cdot x}{r}$$

Further possible filtering approaches:

- Unscented Kalman Filter (UKF)
- Particle Filter (PF)



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Wind exploitation:
Autonomous Thermal Updraft Tracking

Step #3:
Autonomous tracking of thermal updrafts

Procedure:
After a calm morning, the aircraft is allowed to autonomously detect and track columns of rising air (thermal updrafts). The technique can help to further improve the aircraft power consumption and flight times.

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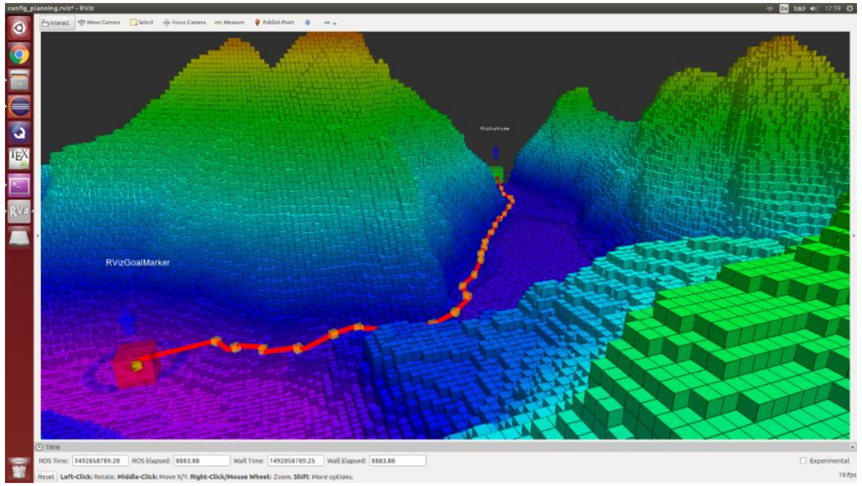
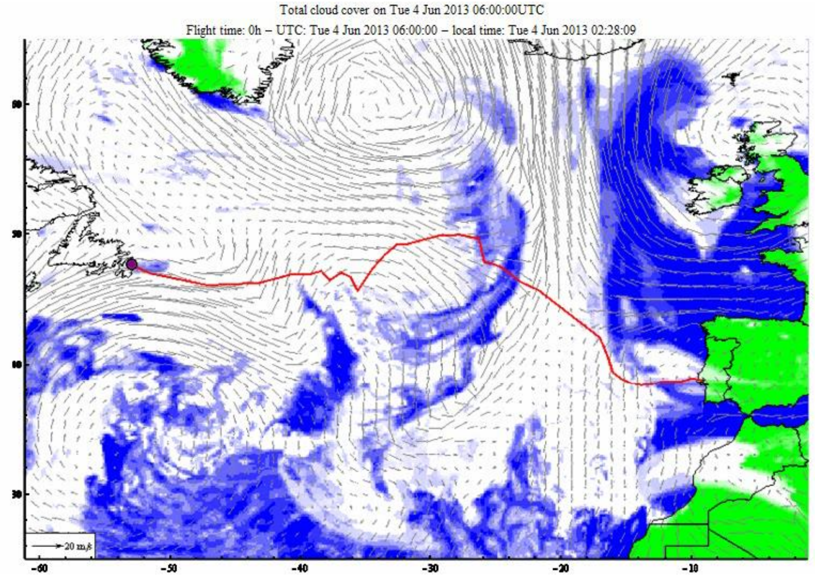
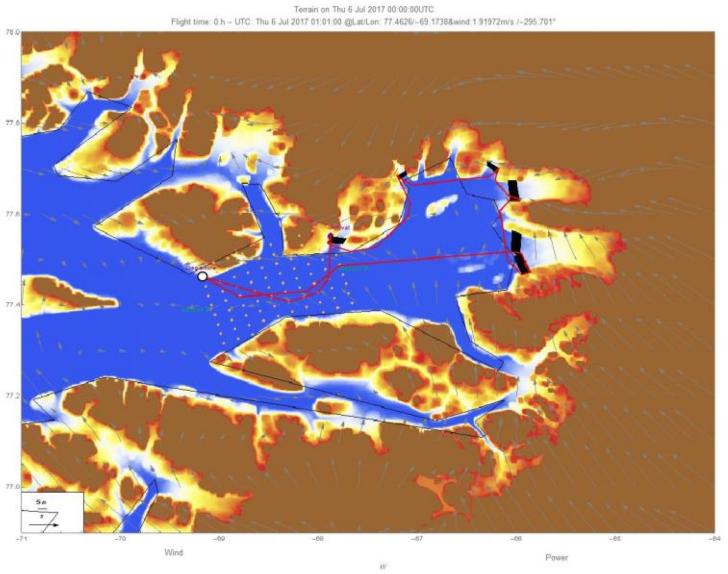
Problems for planning/guidance

- Wind fields *heavily* influence **efficiency** and **safety** in planning/guidance
- A 3D **spatial** *and* **temporal** multi-objective problem





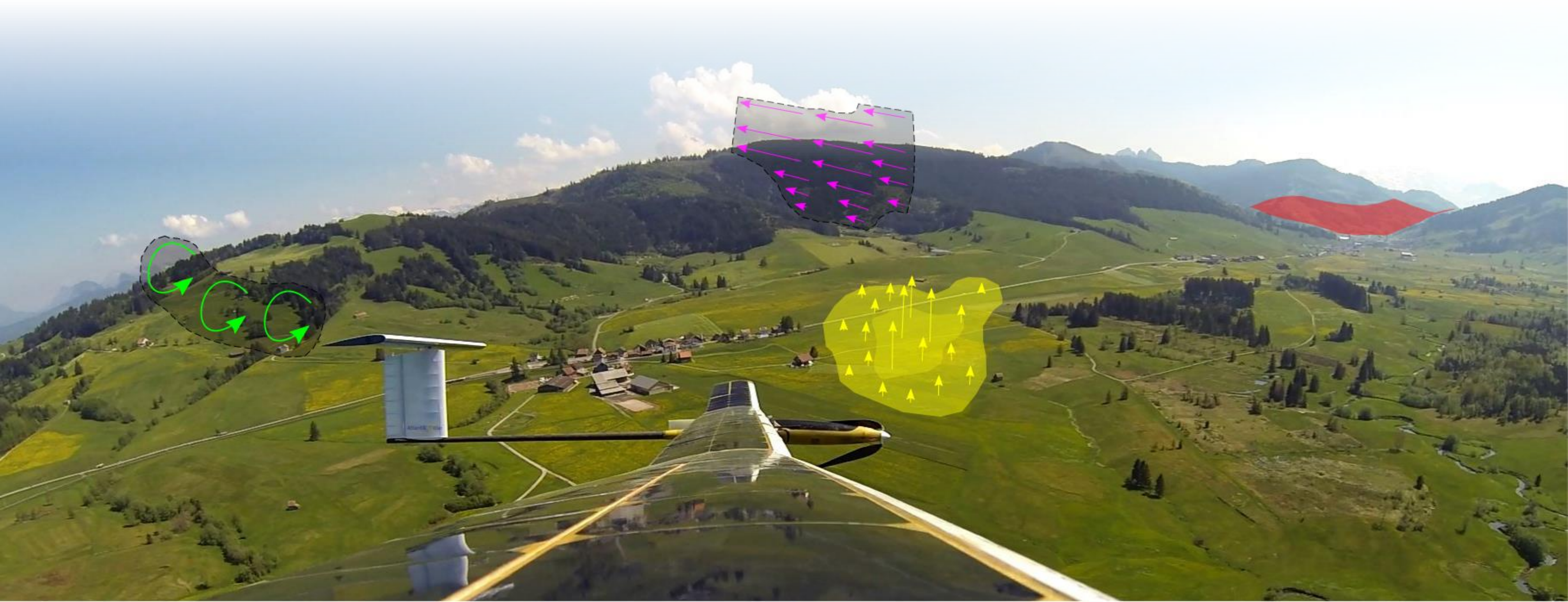
Wirth et. al. "Meteorological path planning using dynamic programming for a solar-powered UAV". IEEE Aerospace Conference. 2015.



Oettershagen et. al. "Meteorology-Aware Multi-Goal Path Planning for Large-Scale Inspection Missions with Long-Endurance Solar-Powered Aircraft". Journal of Aerospace Information Systems (JAIS), 2018.

- Methods **exist**, but need **high resolution** characterization of the environment

Can we forecast these effects?



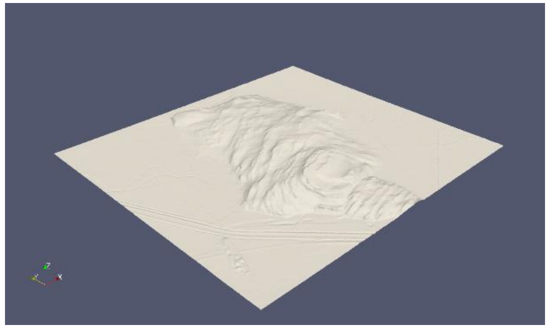
Achermann et. al. "Learning to Predict the Wind for Safe Aerial Vehicle Planning". International Conference on Robotics and Automation (ICRA). 2019.

Predicting the weather

ASL / Intel Collaboration

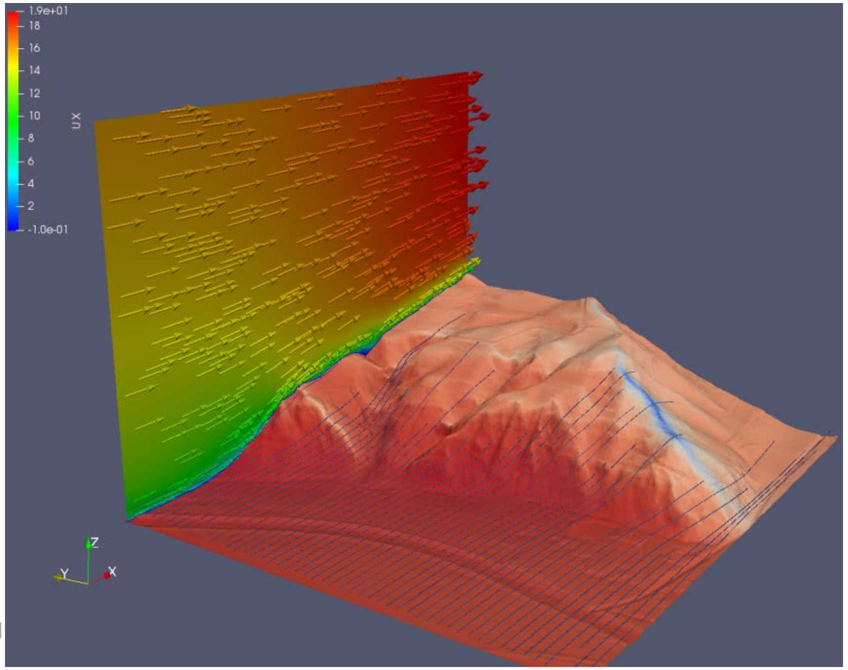
geodata4edu.ch

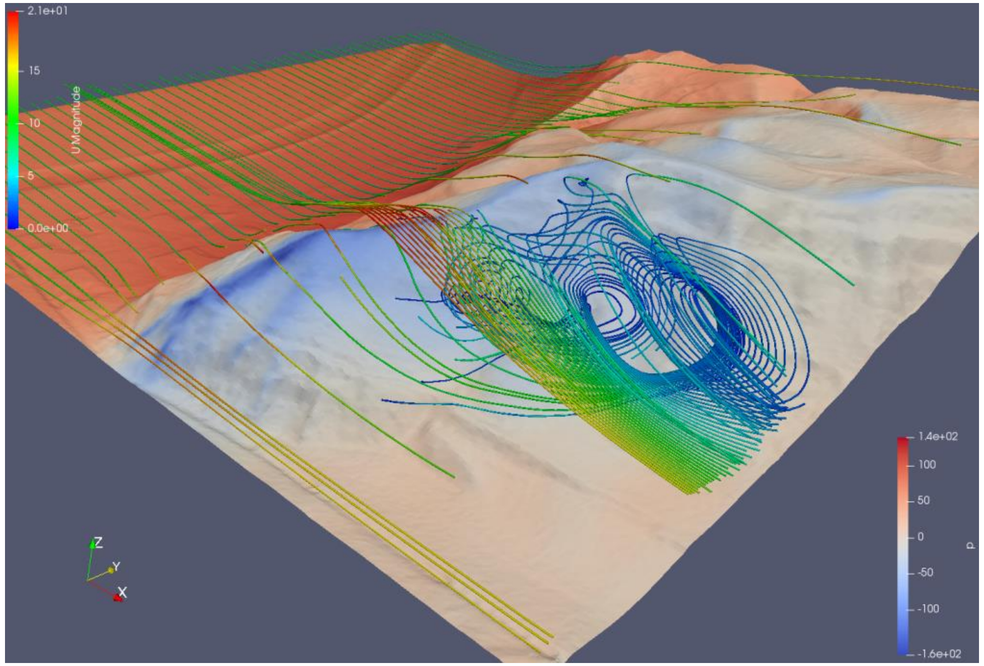
GEOTIFF -> STL



OpenFOAM
The OpenFOAM Foundation

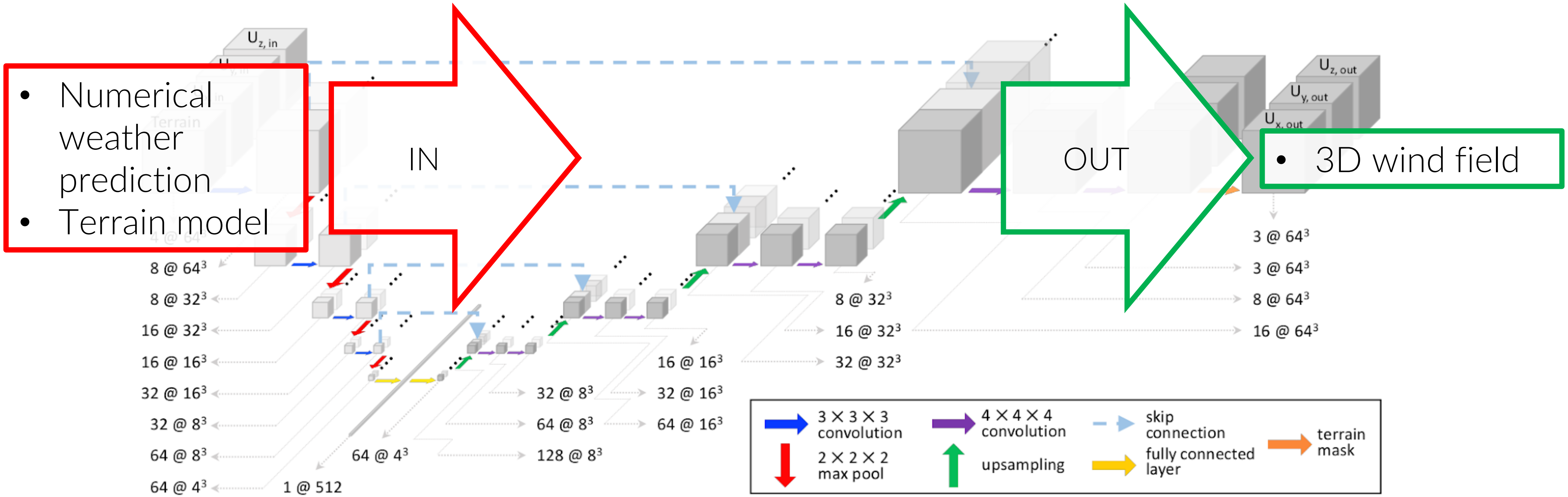
- Generate mesh (snappyHexMesh)
- Solve CFD (multiple input seeds)
- Resample onto regular grid





Achermann et. al. "Learning to Predict the Wind for Safe Aerial Vehicle Planning". International Conference on Robotics and Automation (ICRA). 2019.

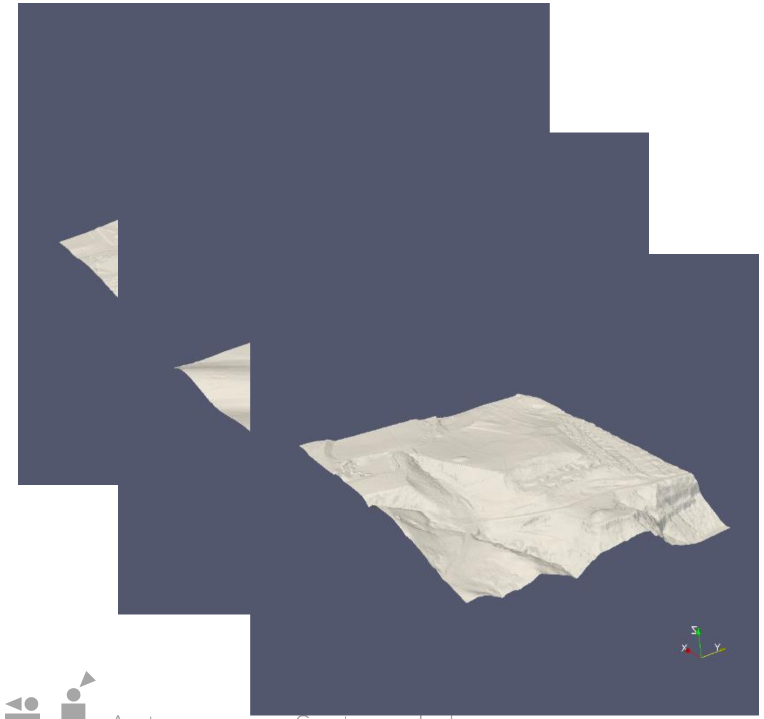
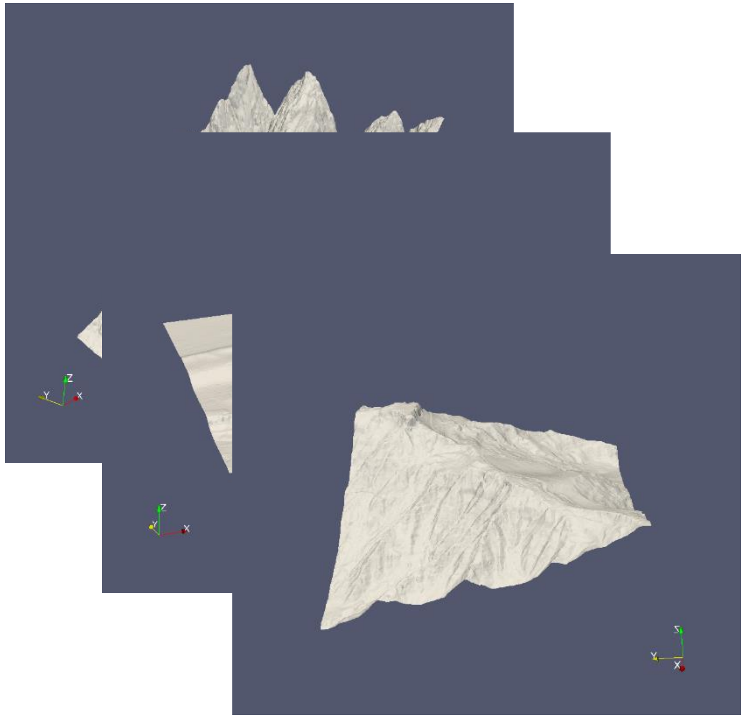
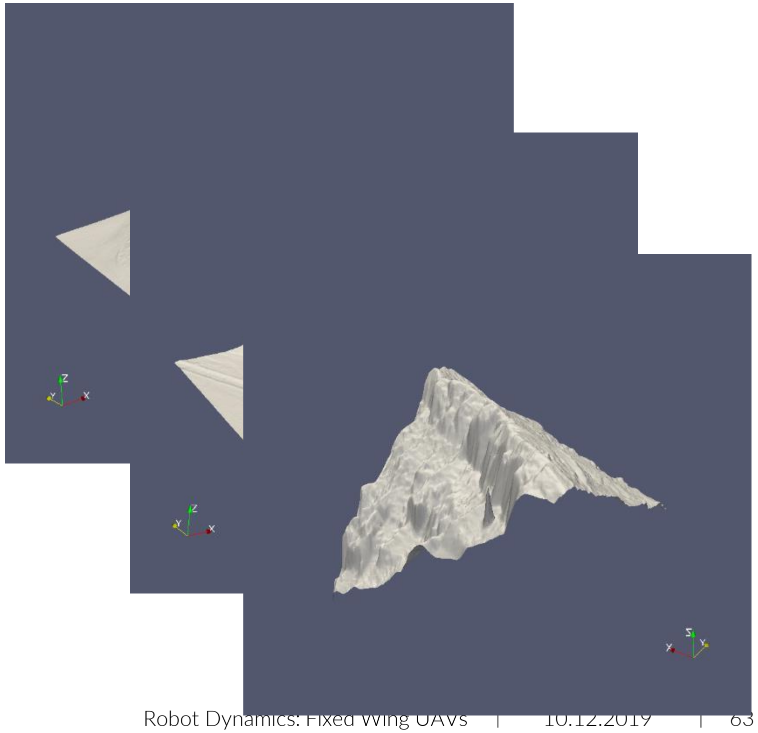
3D prediction – convolutional neural network



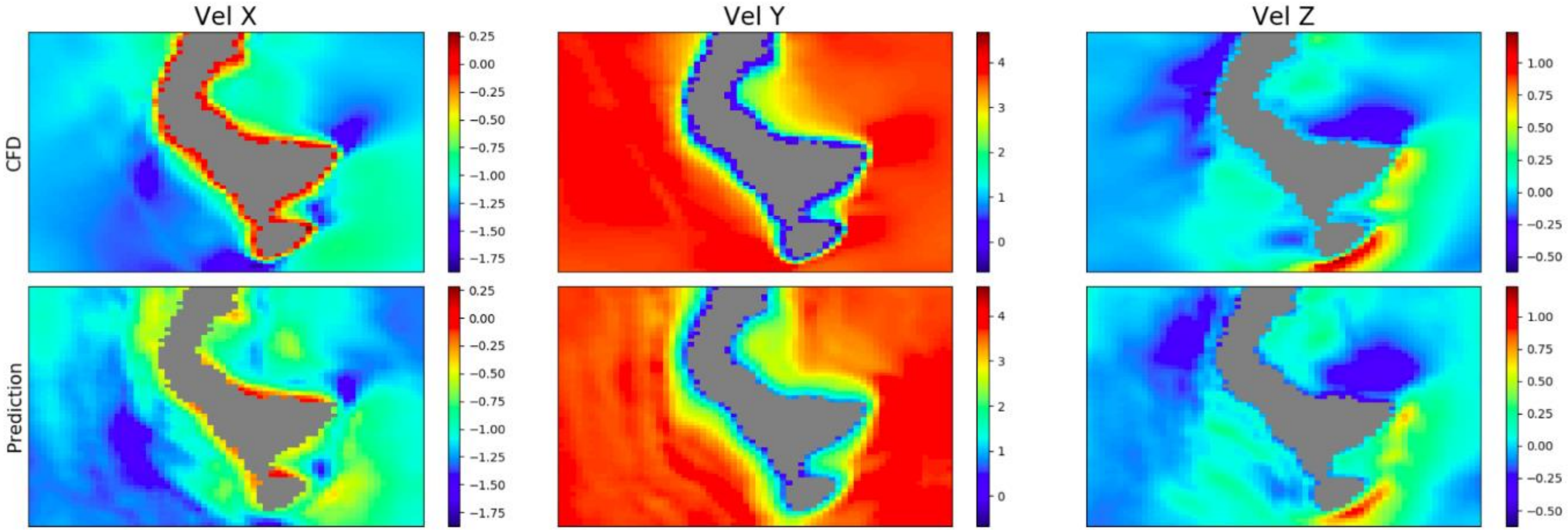
Achermann et. al. “Learning to Predict the Wind for Safe Aerial Vehicle Planning”. International Conference on Robotics and Automation (ICRA). 2019.

Training

- 3318 CFD solutions from 370 Swiss terrain samples with 15 different wind speeds each
- ~20,000 processor hours

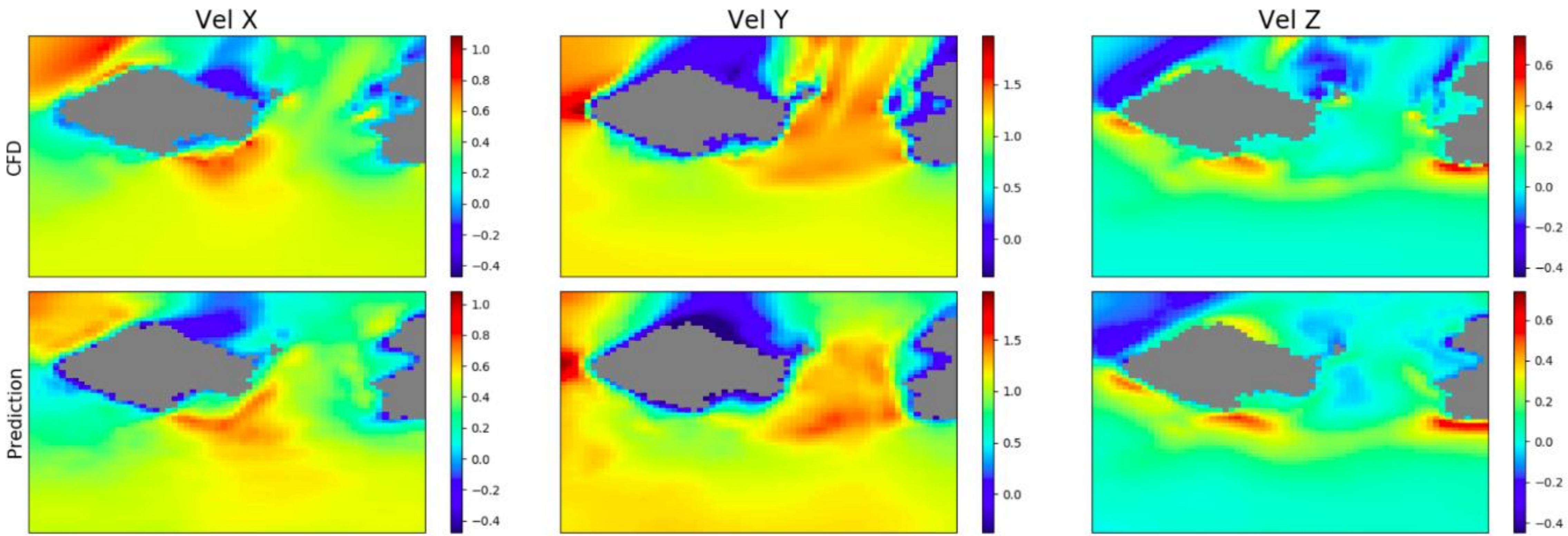




Prediction performance



Complex terrain – horizontal slice

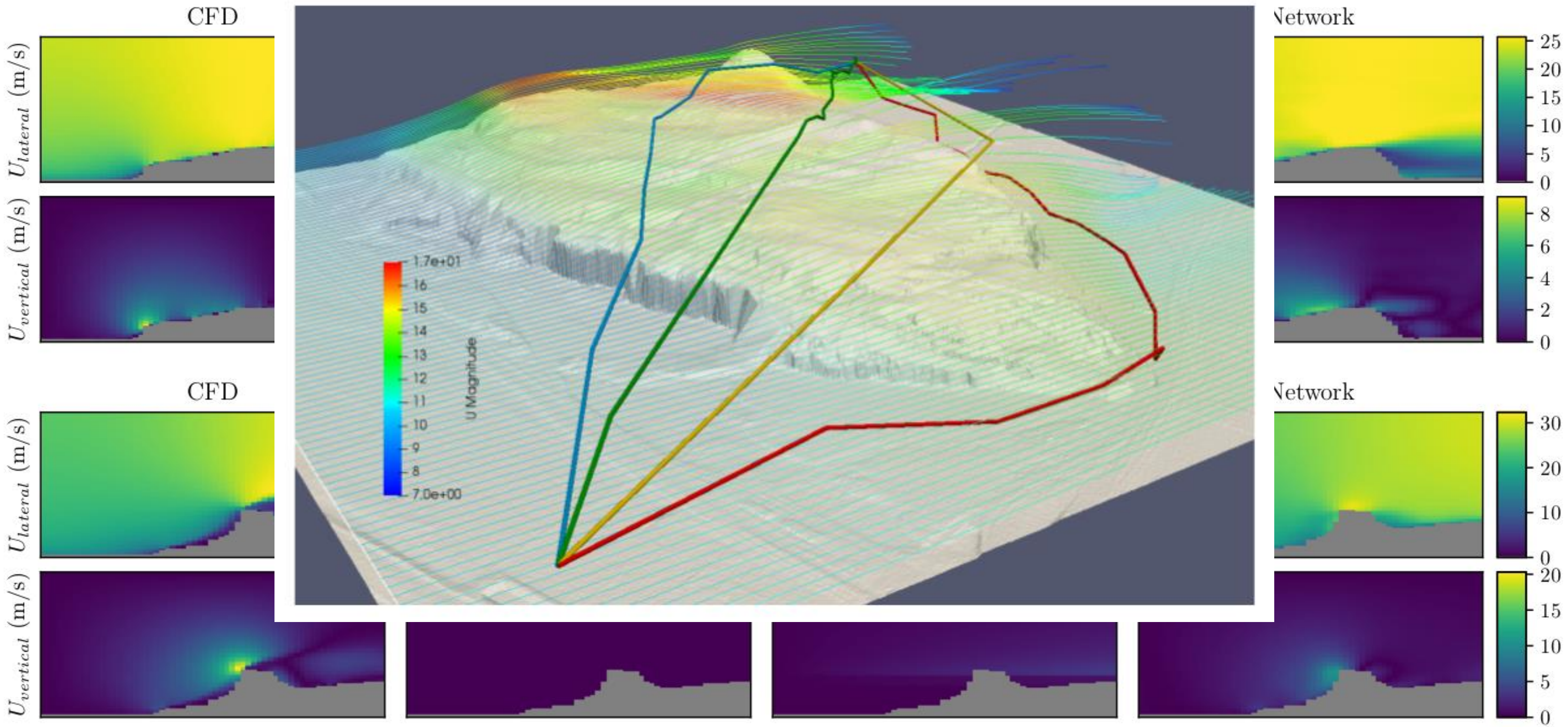
Prediction performance



Complex terrain – horizontal slice

Achermann et. al. “Learning to Predict the Wind for Safe Aerial Vehicle Planning”. International Conference on Robotics and Automation (ICRA). 2019.

Prediction performance



Solar-powered Unmanned Aerial Vehicles (UAVs)

Remote sensing

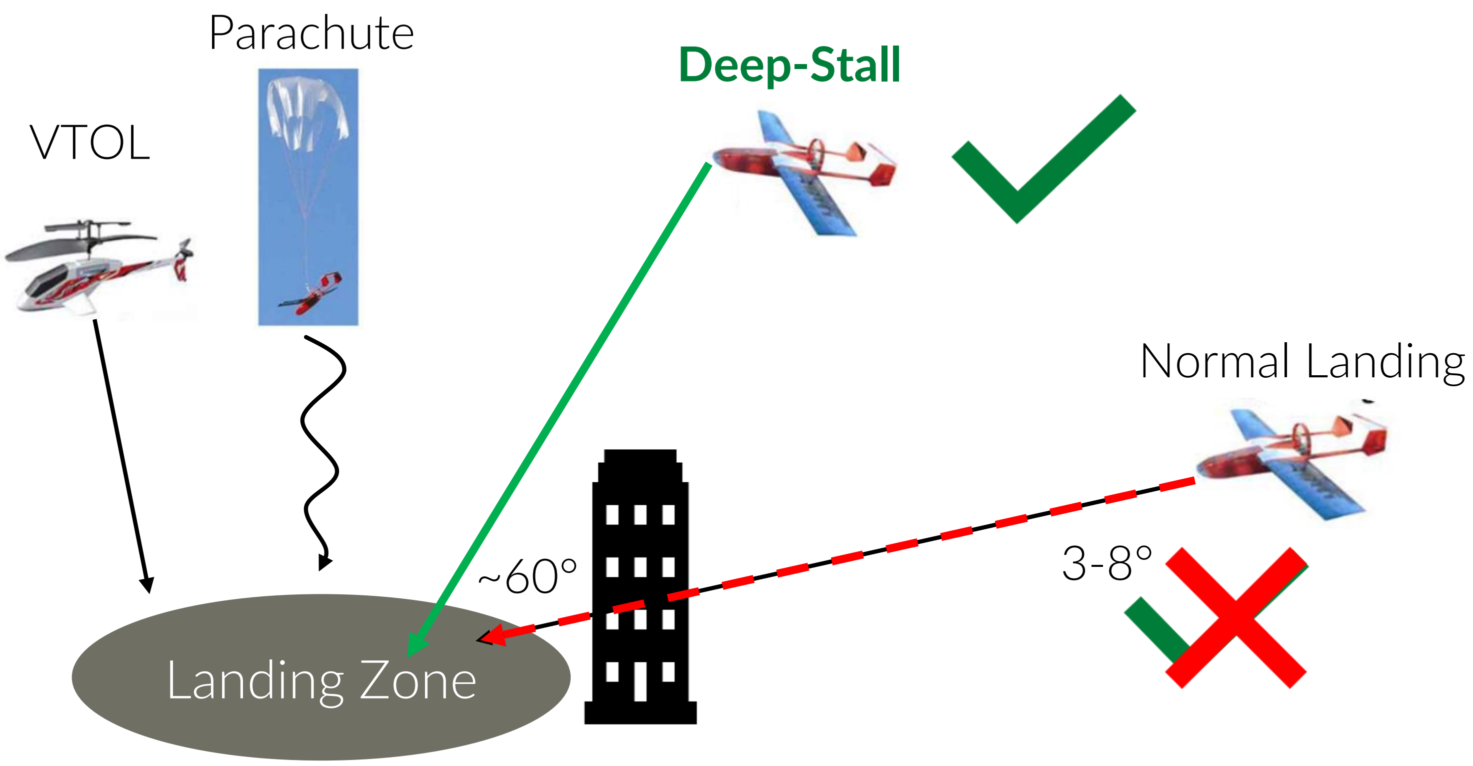
Dealing with wind

Exploring the post-stall regime

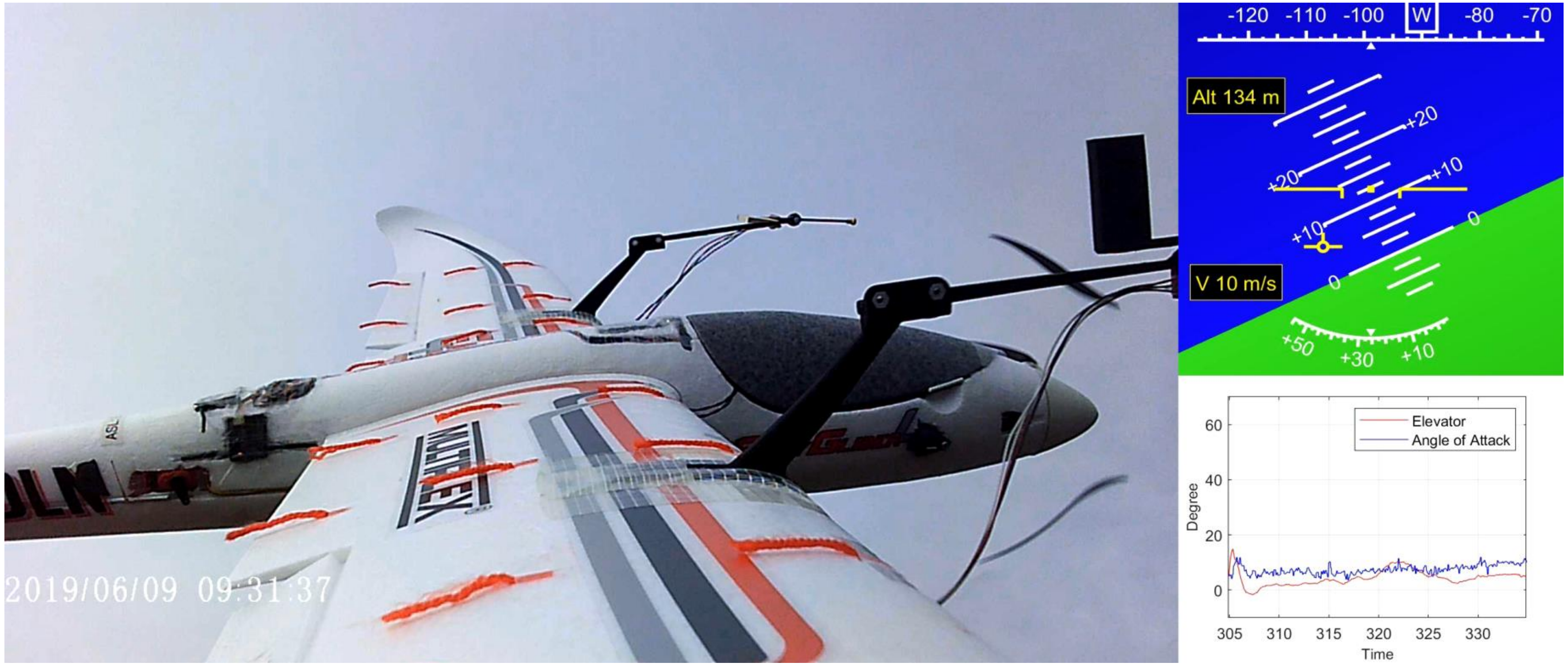
> Deep stall landing

Optimization-based guidance

Deep stall landing



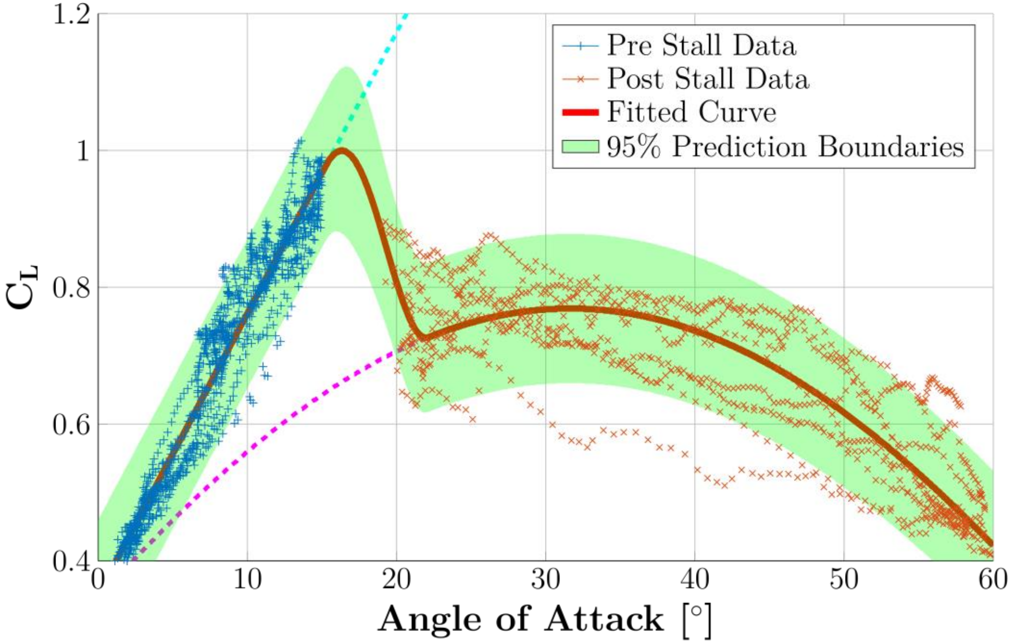
In flight

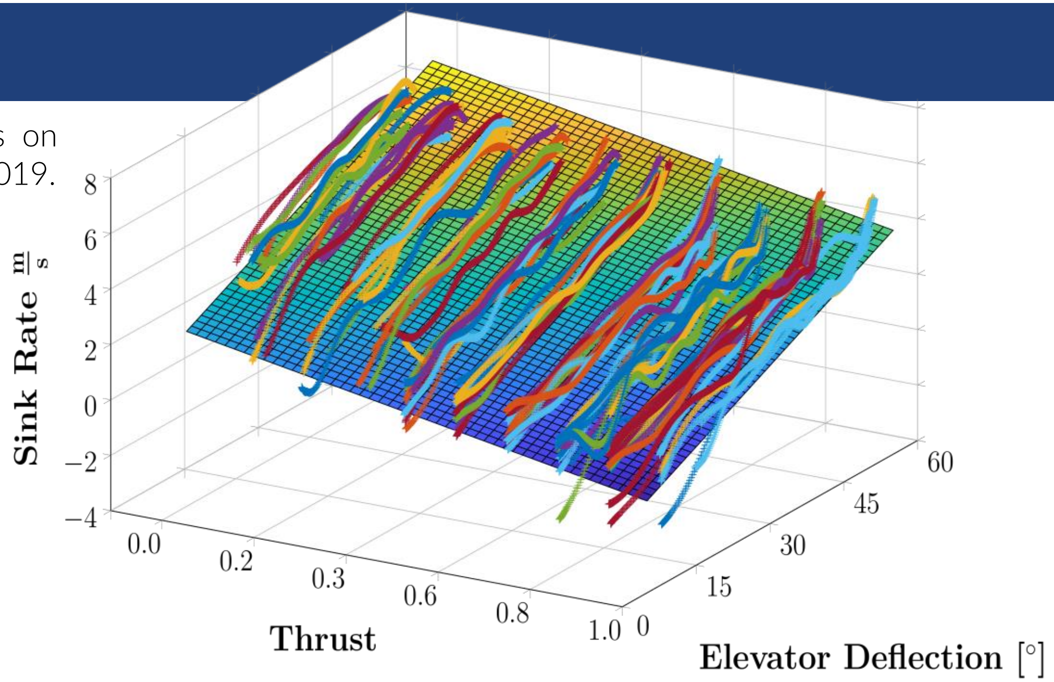


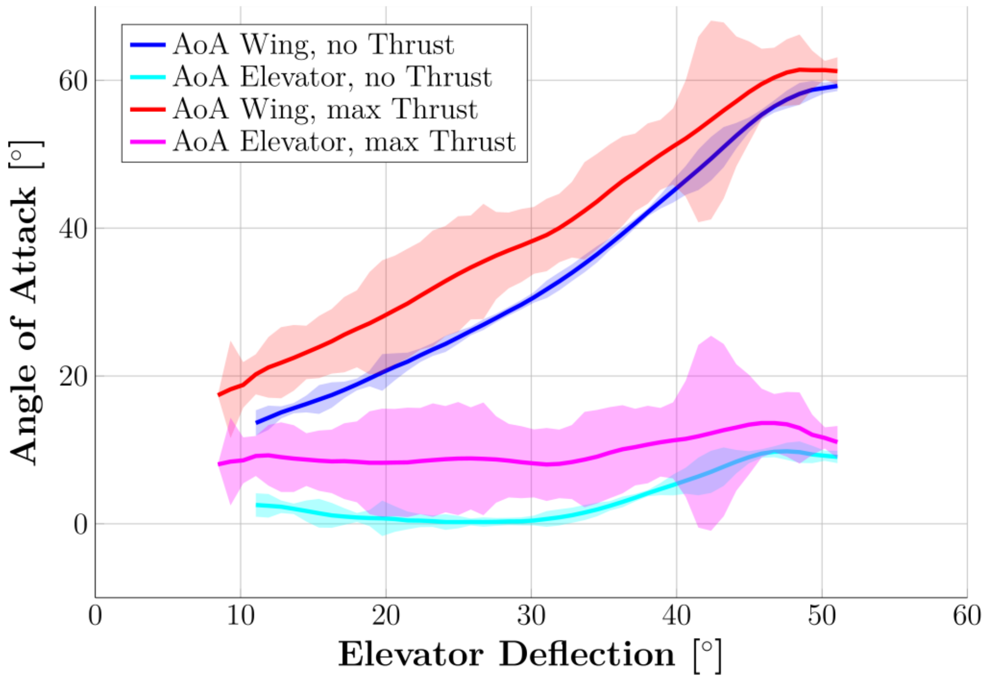
2019/06/09 09:31:37
-120 -110 -100 W -80 -70
Alt 134 m
V 10 m/s
+20
+10
0
+50 +30 +10
Elevator
Angle of Attack
Degree
60
40
20
0
305 310 315 320 325 330
Time

G. Heinrich. "Optimizing Deep-stall Landing Maneuvers on Small Fixed-wing UAVs". Semester Project, ETH Zurich, 2019.

Data analysis







- Sink rate to thrust/elevator can be approximated by a plane
- Steeper AoA can be achieved @ higher thrust settings, **BUT** at cost of larger variances

Solar-powered Unmanned Aerial Vehicles (UAVs)

Remote sensing

Dealing with wind

Exploring the post-stall regime

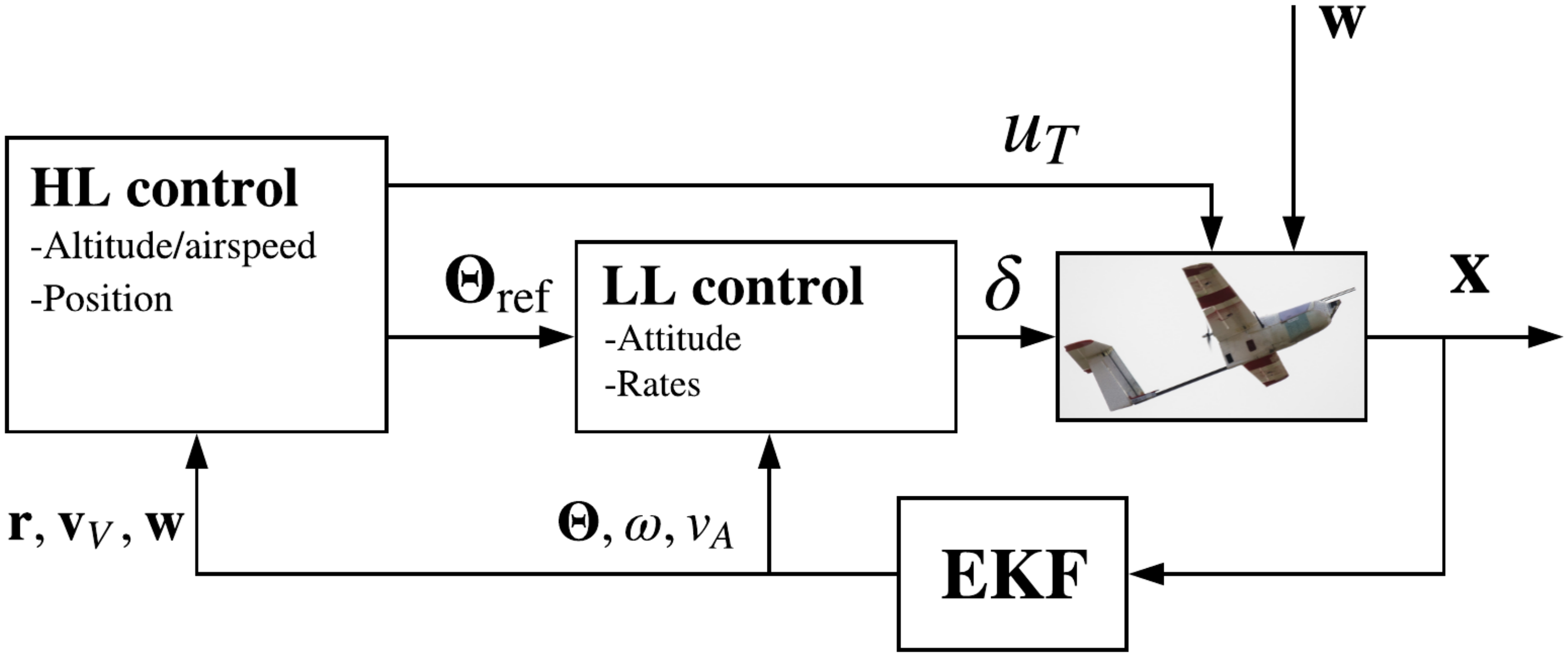
Optimization-based guidance

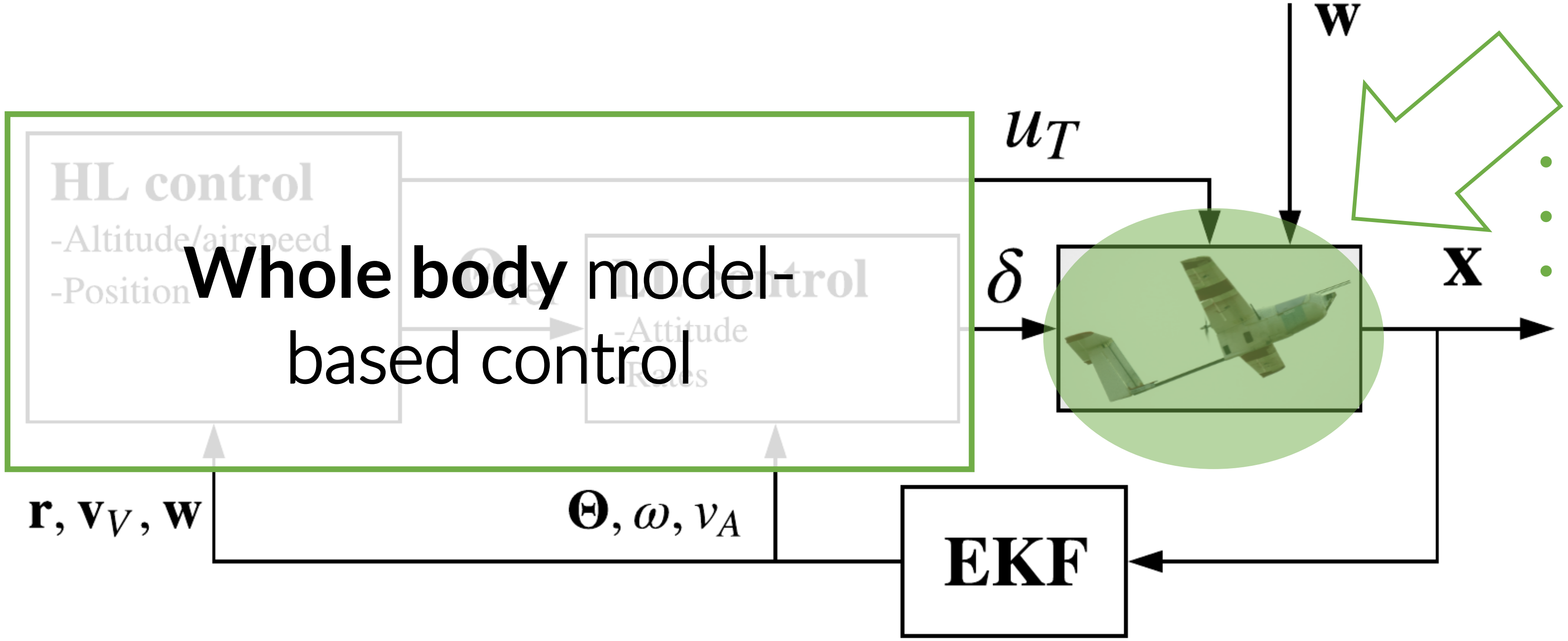
> Control-augmented modeling for control

Planning pangs

- RRT / trajectory optimization?
  - Computationally expensive for real-time fixed-wing computing budget
  - Relies on adequate tracking of lower-level loops
- Need a **real-time** solution with sufficient foresight considering fixed-wing dynamics

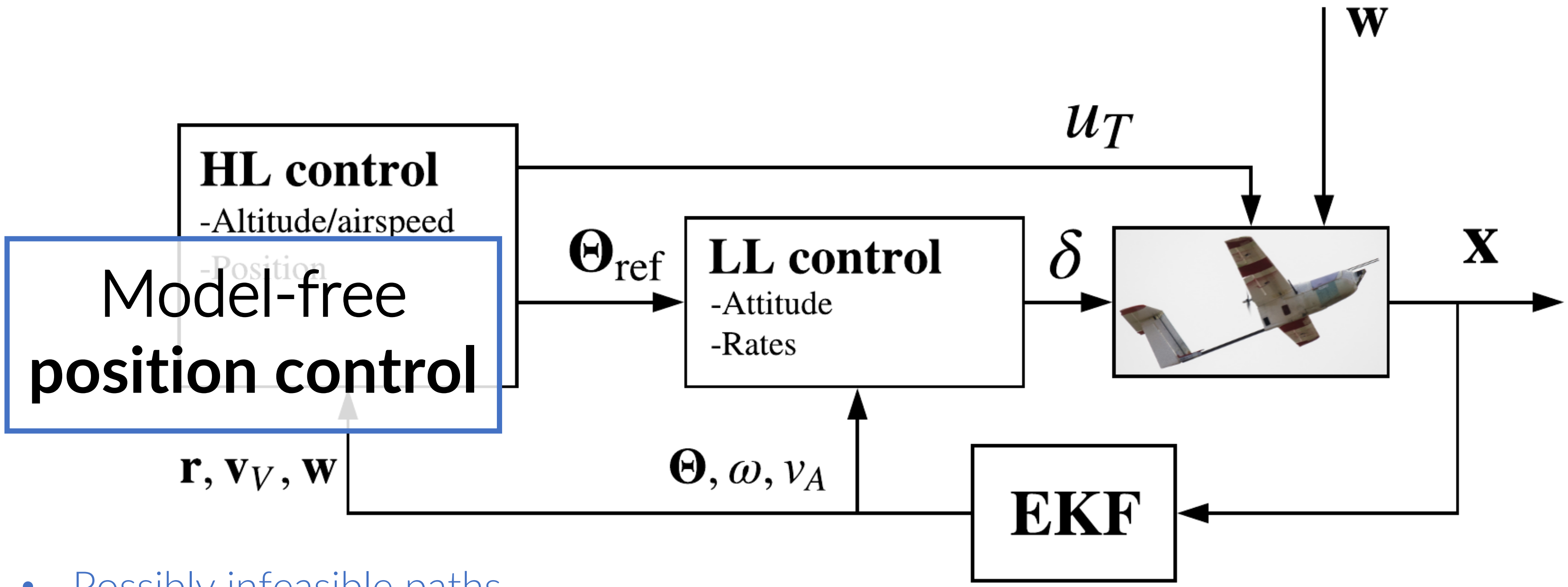
- Formulate NMPC as a long-horizion "**local-planner**"


HL control
-Altitude/airspeed
-Position
$\mathbf{\Theta}_{\mathrm{ref}}$
LL control
-Attitude
-Rates
δ
u_T
$\mathbf{w}$
$\mathbf{x}$
EKF
$\mathbf{r}, \mathbf{v}_V, \mathbf{w}$
$\mathbf{\Theta}, \omega, v_A$

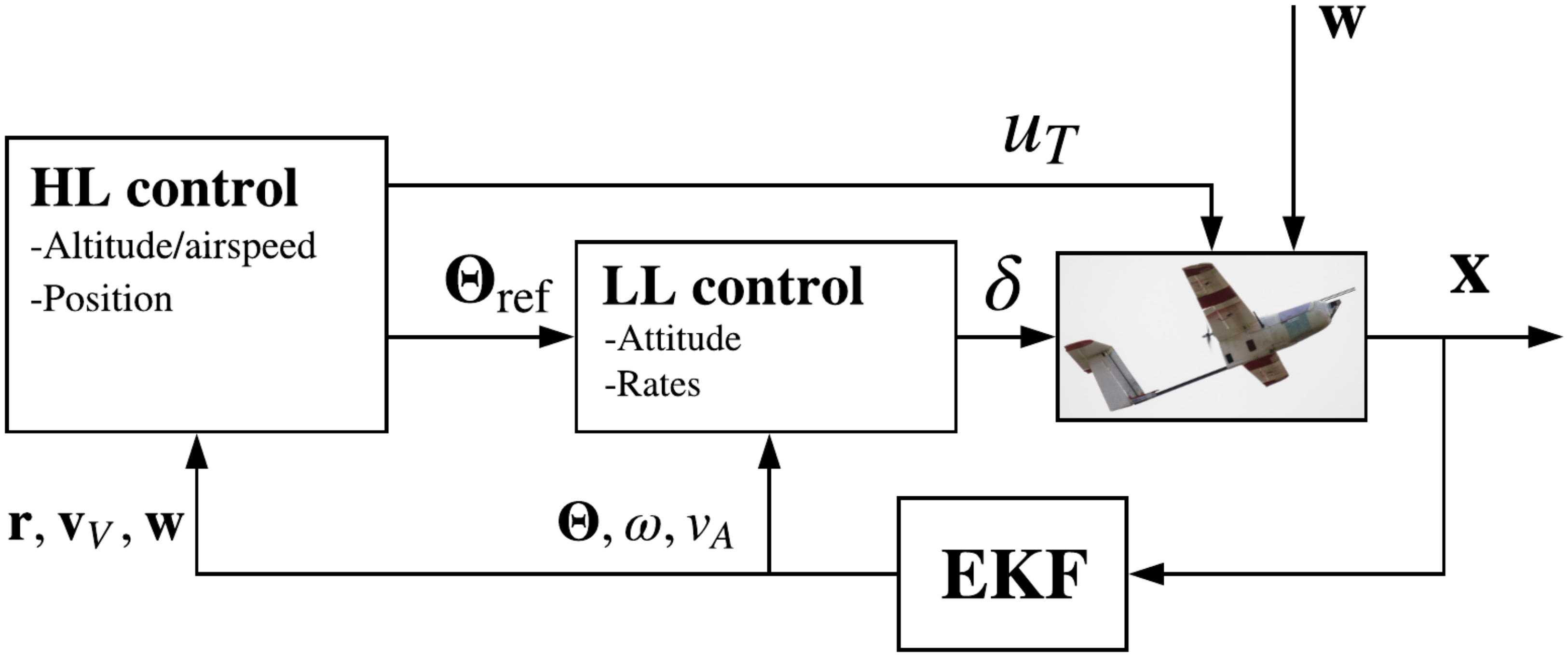


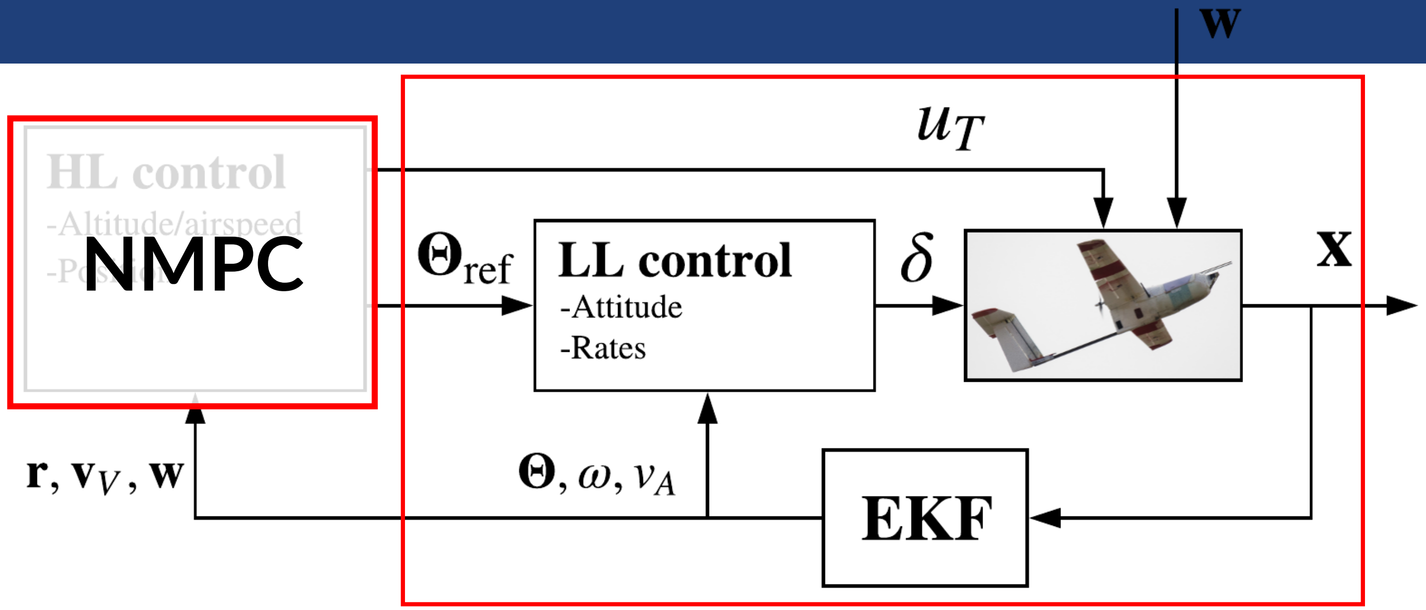
Whole body model-based control

- Low-level aerodynamics
- Short horizons
- CPU expensive!

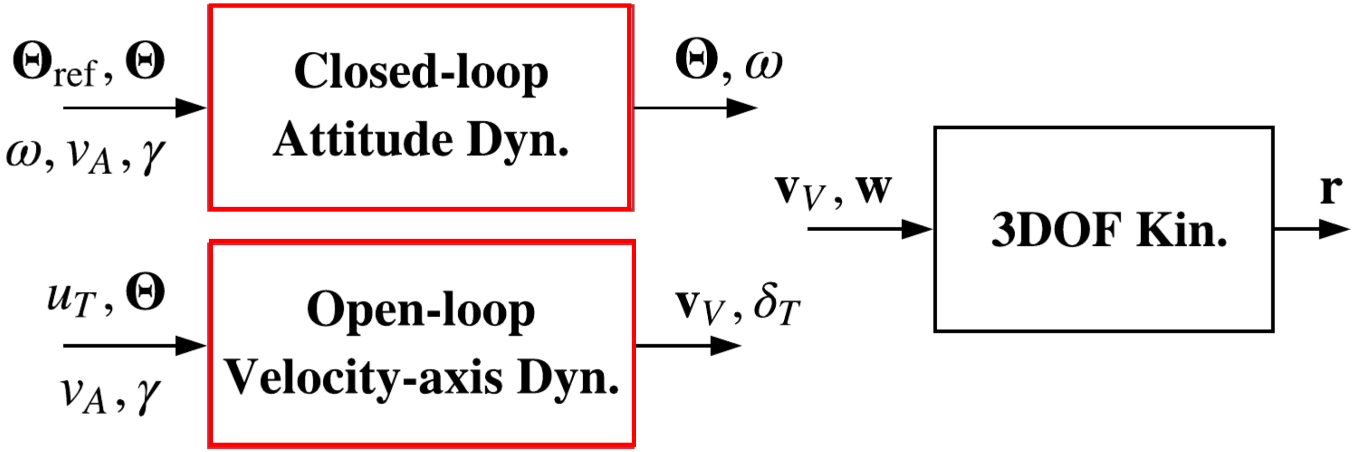


- Possibly infeasible paths
- Autopilot architecture mismatch


HL control
-Altitude/airspeed
-Position
Θ_{ref}
LL control
-Attitude
-Rates
u_T
$\mathbf{w}$
δ
$\mathbf{x}$
$\mathbf{r}, \mathbf{v}_V, \mathbf{w}$
Θ, ω, v_A
EKF



Control-augmented modeling



Stastny et. al. "Nonlinear Model Predictive Guidance for Small Fixed-wing UAVs Using Identified Control-augmented Dynamics". International Conference on Unmanned Aerial Systems (ICUAS). 2018.

Closed-loop attitude dynamics

- The low-level autopilot response to **pitch** and **roll** commands
- Dynamics:

$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{pmatrix} = \begin{pmatrix} p \\ q\cos\phi - r\sin\phi \\ l_p p + l_r r + l_{e_\phi}\left(\phi_{\text{ref}} - \phi\right) \\ {v_A}^2\left(m_0 + m_\alpha \alpha + m_q q + m_{e_\theta}\left(\theta_{\text{ref}} - \theta\right)\right) \\ n_r r + n_\phi \phi + n_{\phi_{\text{ref}}} \phi_{\text{ref}} \end{pmatrix}$$

Nonlinearities

- Parameters to identify:

$$\boldsymbol{\varphi}_{\text{CL}} = \left[l_p, l_r, l_{e_\phi}, m_0, m_\alpha, m_q, m_{e_\theta}, n_r, n_\phi, n_{\phi_{\text{ref}}}\right]^T$$

Stastny et. al. "Nonlinear Model Predictive Guidance for Small Fixed-wing UAVs Using Identified Control-augmented Dynamics". International Conference on Unmanned Aerial Systems (ICUAS). 2018.

Open-loop velocity-axis dynamics

- The **non-stabilized** open-loop response to **throttle** and *quasi-steady* **aerodynamic/thrusting forces**
  - 3DoF dynamics:

$$\begin{pmatrix} \dot{v}_A \\ \dot{\gamma} \\ \dot{\xi} \\ \dot{\delta}_T \end{pmatrix} = \begin{pmatrix} \frac{1}{m}\left(T\cos\alpha - D\right) - g\sin\gamma \\ \frac{1}{m v_A}\left[\left(T\sin\alpha + L\right)\cos\phi - mg\cos\gamma\right] \\ \frac{\sin\phi}{m v_A\cos\gamma}\left(T\sin\alpha + L\right) \\ \left(u_T - \delta_T\right)/\tau_T \end{pmatrix}$$

$$T = \left(c_{T_1}\delta_T + c_{T_2}{\delta_T}^2 + c_{T_3}{\delta_T}^3\right)/v_{\infty_{\mathrm{prop}}}$$
$$D = \bar{q}S\left(c_{D_0} + c_{D_\alpha}\alpha + c_{D_{\alpha^2}}\alpha^2\right)$$
$$L = \bar{q}S\left(c_{L_0} + c_{L_\alpha}\alpha + c_{L_{\alpha^2}}\alpha^2\right)$$

  - Assumptions:

$$\alpha \approx \theta - \gamma \qquad \beta \approx 0 \rightarrow \xi \approx \psi \qquad v_{\infty_{prop}} \approx v_A \cos\alpha$$

  - Parameters to identify:

$$\varphi_{\mathrm{OL}} = \left[c_{T_1}, c_{T_2}, c_{T_3}, \tau_T, c_{D_0}, c_{D_\alpha}, c_{D_{\alpha^2}}, c_{L_0}, c_{L_\alpha}, c_{L_{\alpha^2}}\right]^T$$

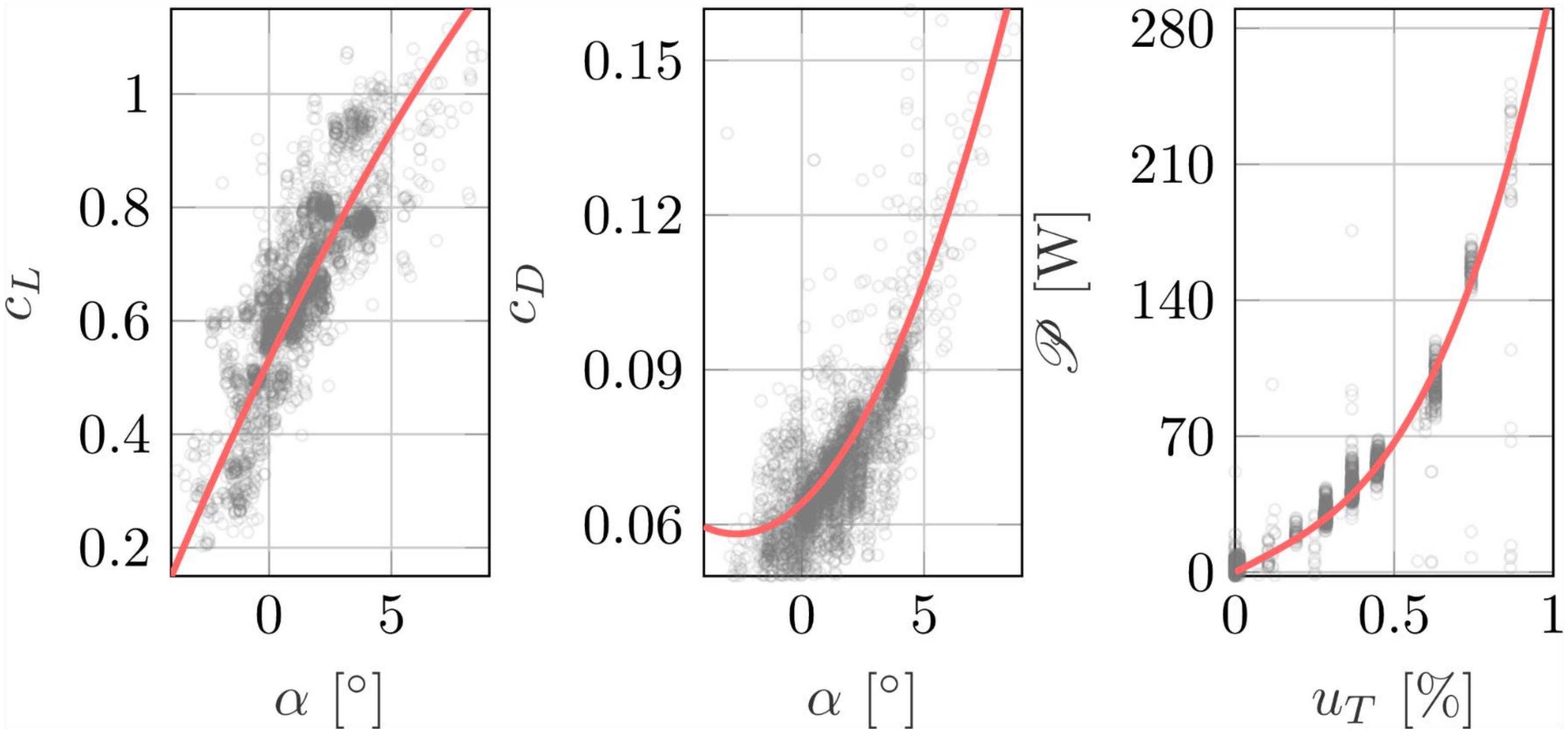
Kinematics

Stastny et. al. "Nonlinear Model Predictive Guidance for Small Fixed-wing UAVs Using Identified Control-augmented Dynamics". International Conference on Unmanned Aerial Systems (ICUAS). 2018.

- **Parameterless** 3DoF kinematics in **wind**

$$\begin{pmatrix} \dot{n} \\ \dot{e} \\ \dot{d} \end{pmatrix} = \begin{pmatrix} v_A \cos\gamma \cos\xi + w_n \\ v_A \cos\gamma \sin\xi + w_e \\ -v_A \sin\gamma + w_d \end{pmatrix}$$

System Identification | static aero / thrusting coefficients

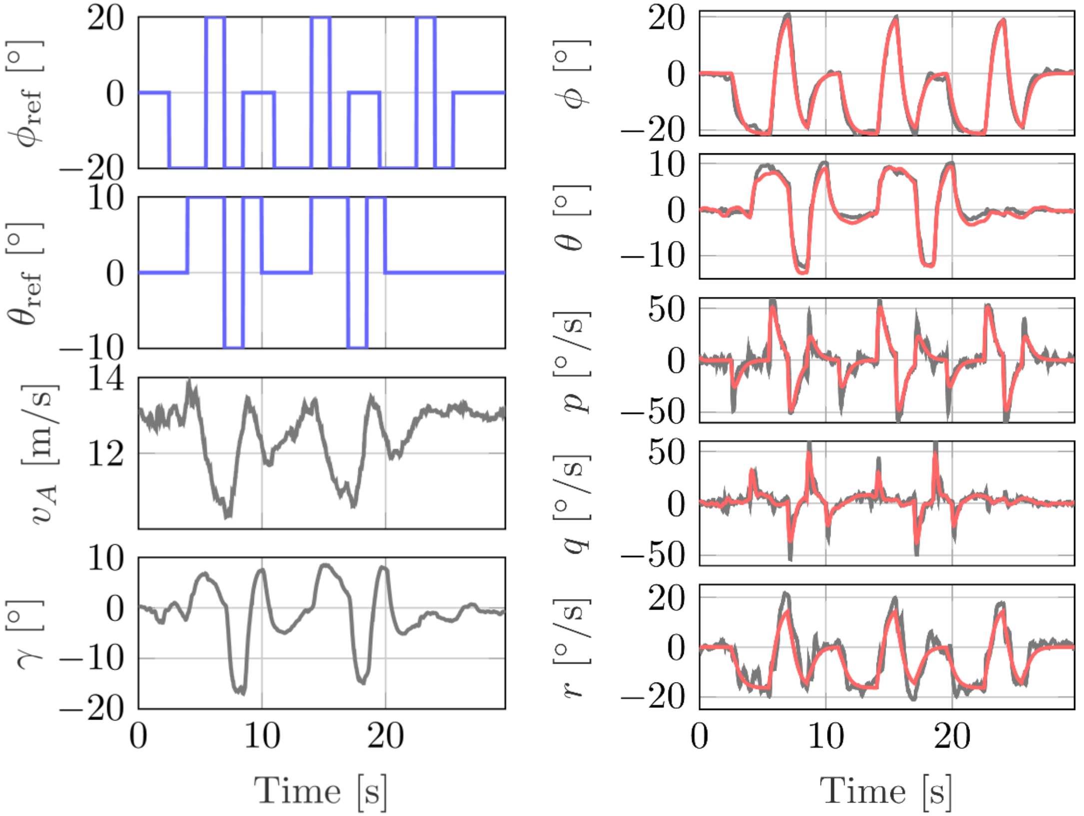


Stastny et. al. "Nonlinear Model Predictive Guidance for Small Fixed-wing UAVs Using Identified Control-augmented Dynamics". International Conference on Unmanned Aerial Systems (ICUAS). 2018.

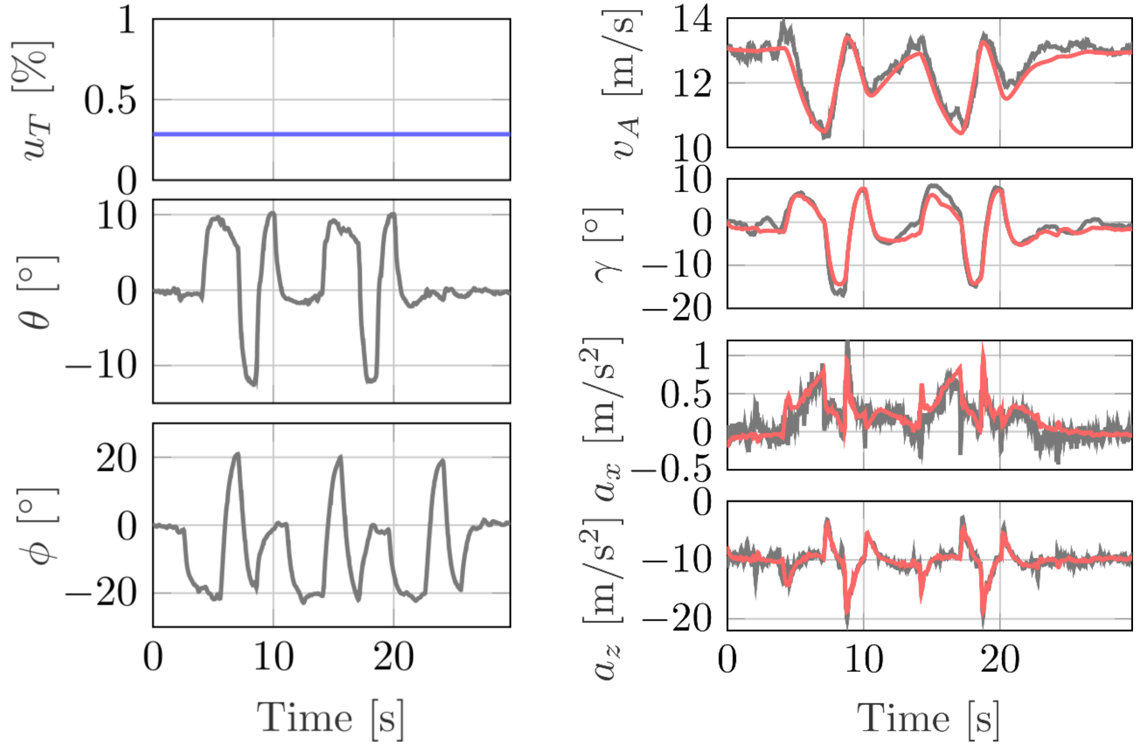
Model validation | coupled maneuver

Flight data
Control input
Model output

Closed-loop dynamics



Open-loop dynamics



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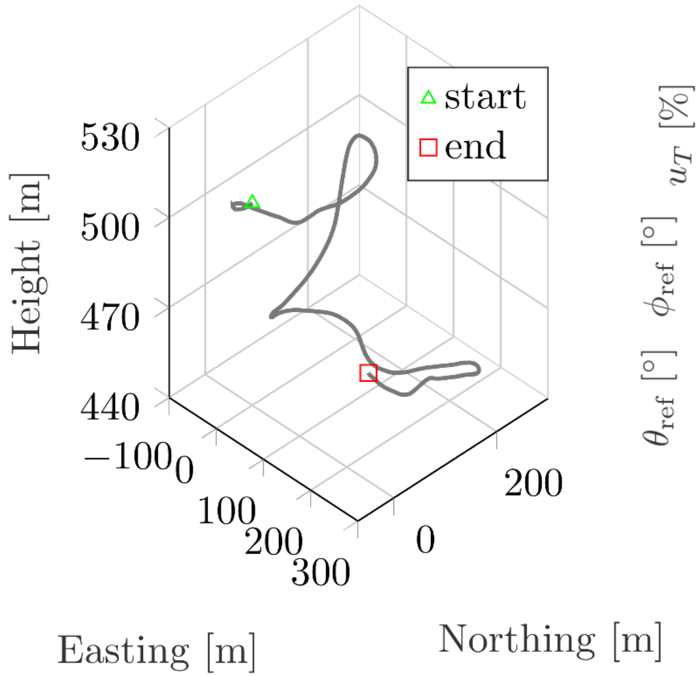
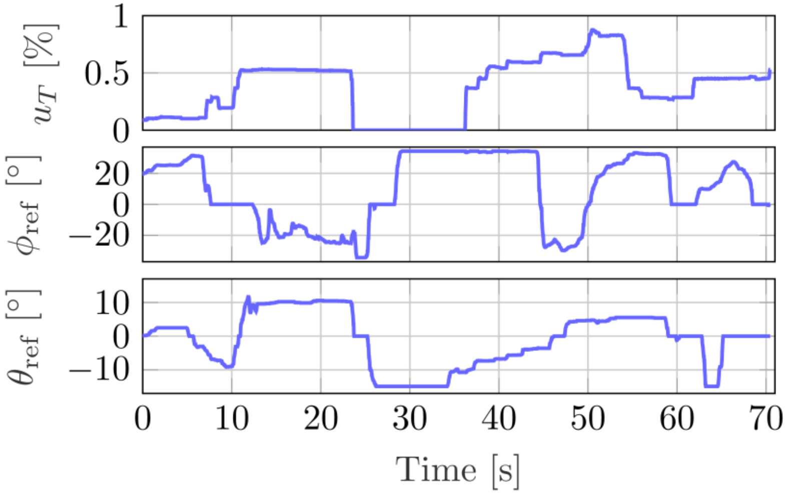
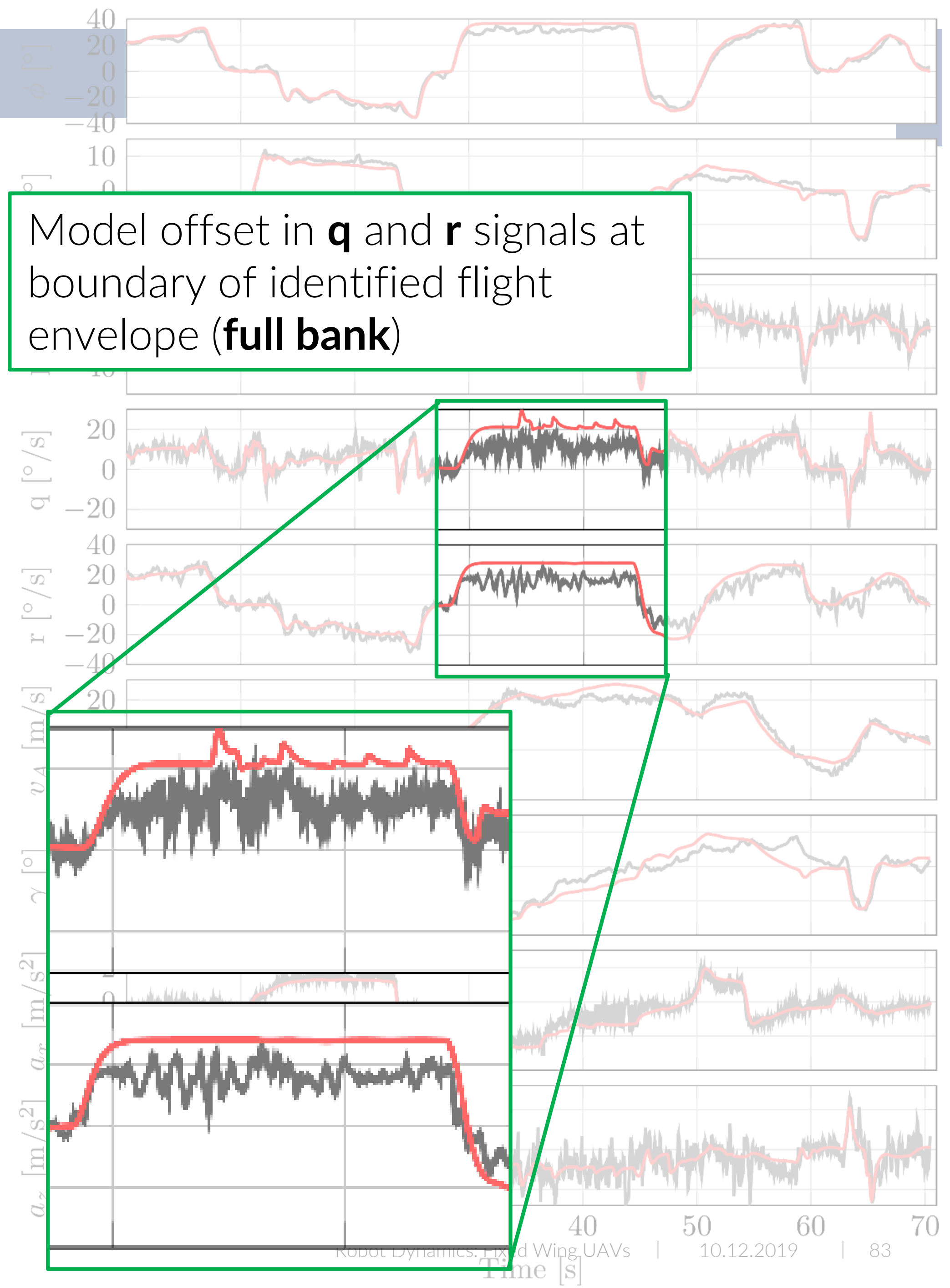
Model validation | free flight







Flight data
Control input
Model output

Stastny et. al. “Nonlinear Model Predictive Guidance for Small Fixed-wing UAVs Using Identified Control-augmented Dynamics”. International Conference on Unmanned Aerial Systems (ICUAS). 2018.

Nonlinear Model Predictive Control

- Finite horizon optimal control problem

$$\min_{\mathbf{x},\mathbf{u}} \int_{t=0}^{T} \Big((\mathbf{y}(t) - \mathbf{y}_{\text{ref}}(t))^T \mathbf{Q}_y (\mathbf{y}(t) - \mathbf{y}_{\text{ref}}(t))$$
$$+ (\mathbf{z}(t) - \mathbf{z}_{\text{ref}}(t))^T \mathbf{R}_z (\mathbf{z}(t) - \mathbf{z}_{\text{ref}}(t)) \Big) dt$$
$$+ (\mathbf{y}(T) - \mathbf{y}_{\text{ref}}(T))^T \mathbf{P} (\mathbf{y}(T) - \mathbf{y}_{\text{ref}}(T))$$

$$\text{subject to} \quad \begin{aligned} &\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u}), \\ &\mathbf{u}(t) \in \mathbb{U}, \\ &\mathbf{x}(0) = \mathbf{x}(t_0) \end{aligned}$$

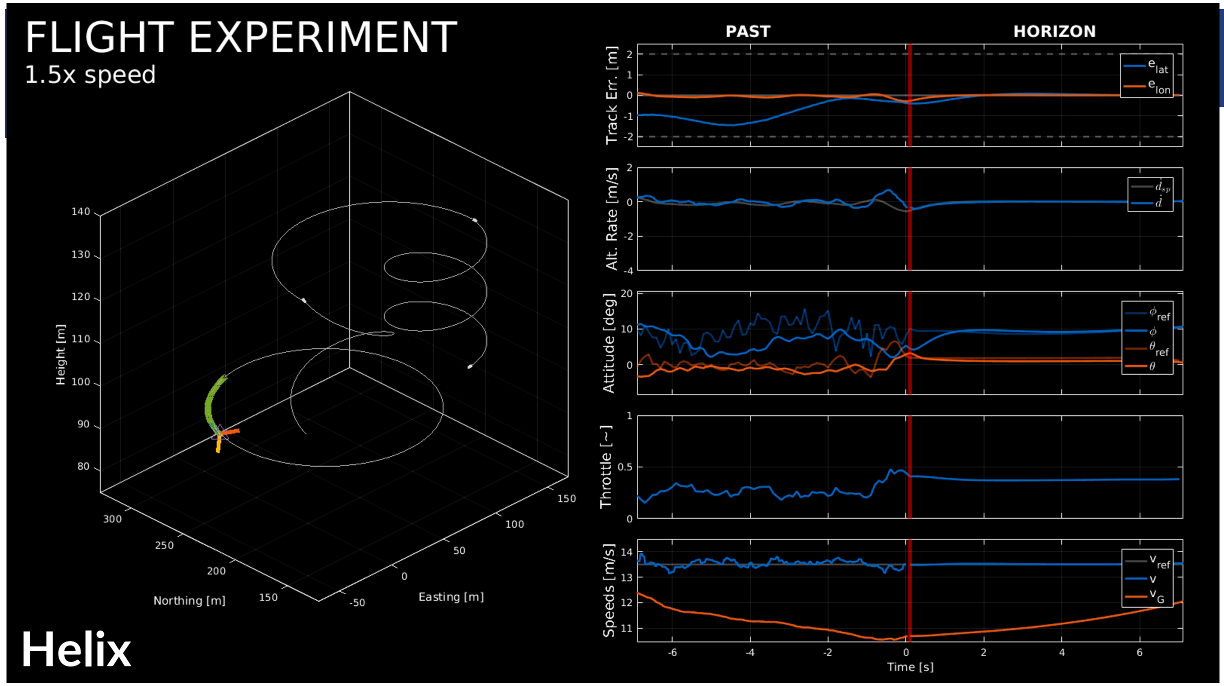
States / controls:

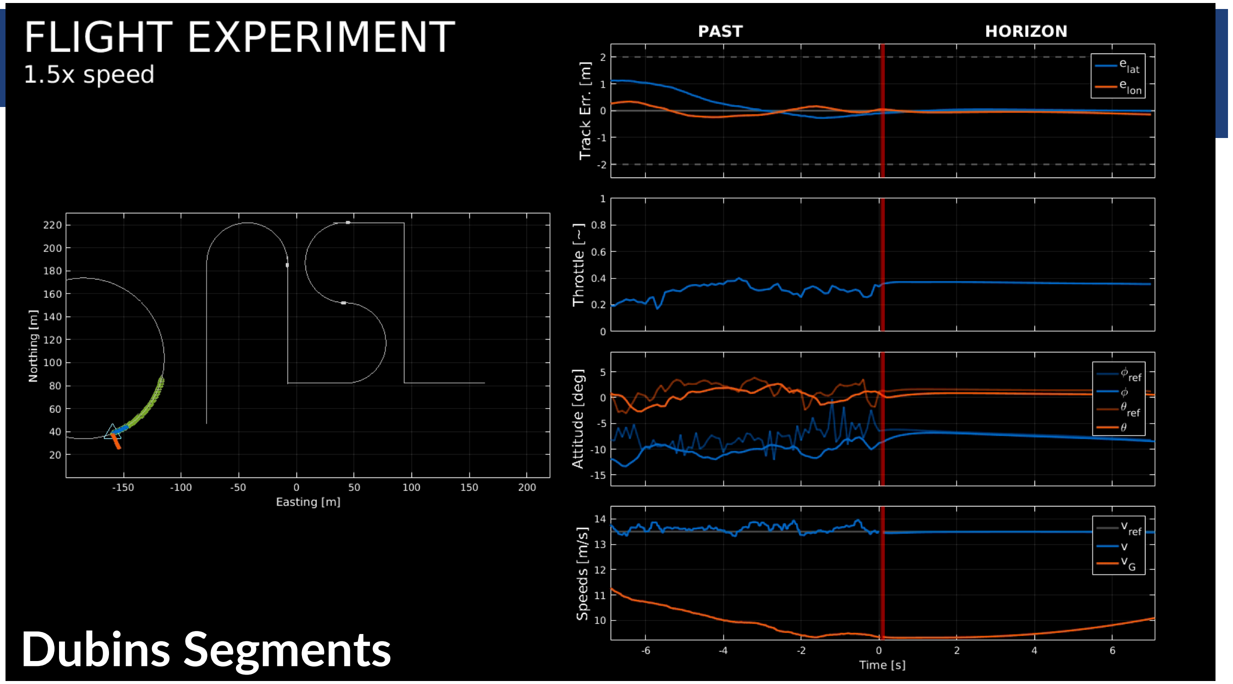
$$\mathbf{x} = \left[\mathbf{r}^T, \mathbf{v}_V^T, \boldsymbol{\Theta}^T, \boldsymbol{\omega}^T, \delta_T, x_{sw}\right]^T$$
$$\mathbf{u} = [u_T, \phi_{\text{ref}}, \theta_{\text{ref}}]^T$$

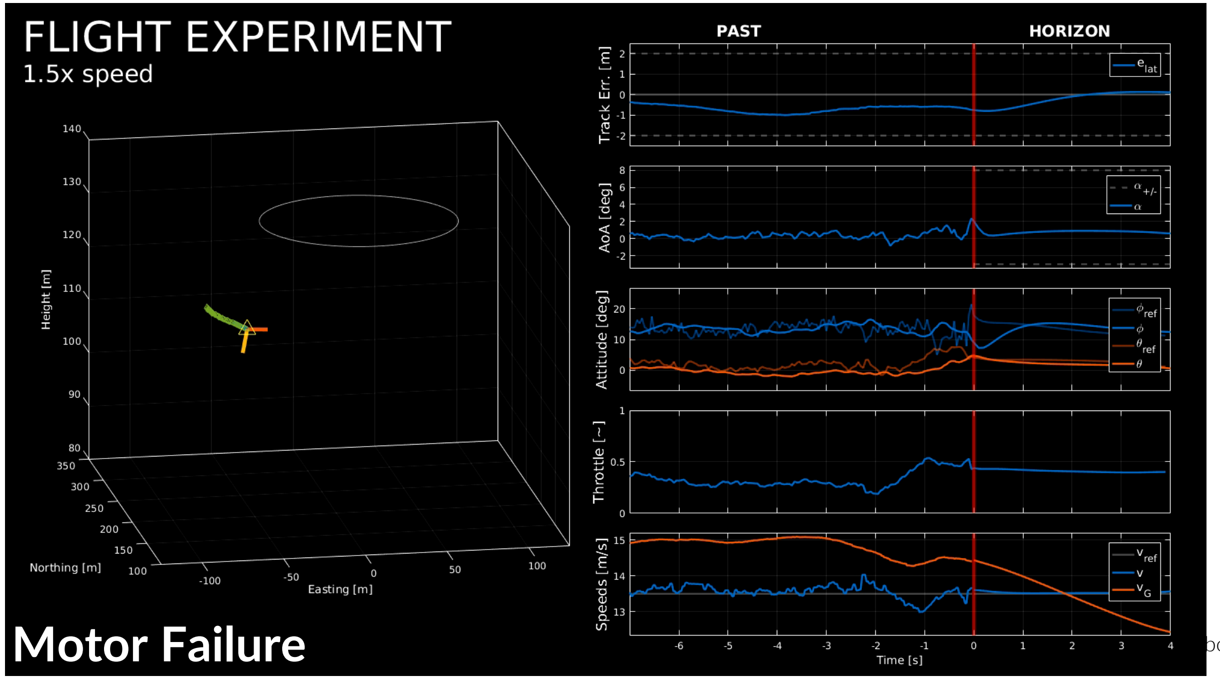
State / control dependent outputs:

$$\mathbf{y} = \left[\boldsymbol{\eta}^T, v_A, \boldsymbol{\omega}^T, \alpha_{\text{soft}}\right]^T$$
$$\mathbf{z} = \left[\delta_T, \mathbf{u}^T\right]^T$$

Augmented objectives / constraints


FLIGHT EXPERIMENT
1.5x speed
PAST
HORIZON
Track Err. [m]
Alt. Rate [m/s]
Attitude [deg]
Throttle [~]
Speeds [m/s]
Time [s]
Height [m]
Northing [m]
Easting [m]
Helix


FLIGHT EXPERIMENT
1.5x speed
PAST
HORIZON
Track Err. [m]
Throttle [~]
Attitude [deg]
Speeds [m/s]
Time [s]
Northing [m]
Easting [m]
Dubins Segments


FLIGHT EXPERIMENT
1.5x speed
PAST
HORIZON
Track Err. [m]
AoA [deg]
Attitude [deg]
Throttle [~]
Speeds [m/s]
Time [s]
Height [m]
Northing [m]
Easting [m]
Motor Failure

Questions?