Design Challenges Towards Automated Flight Control for Tethered Kites

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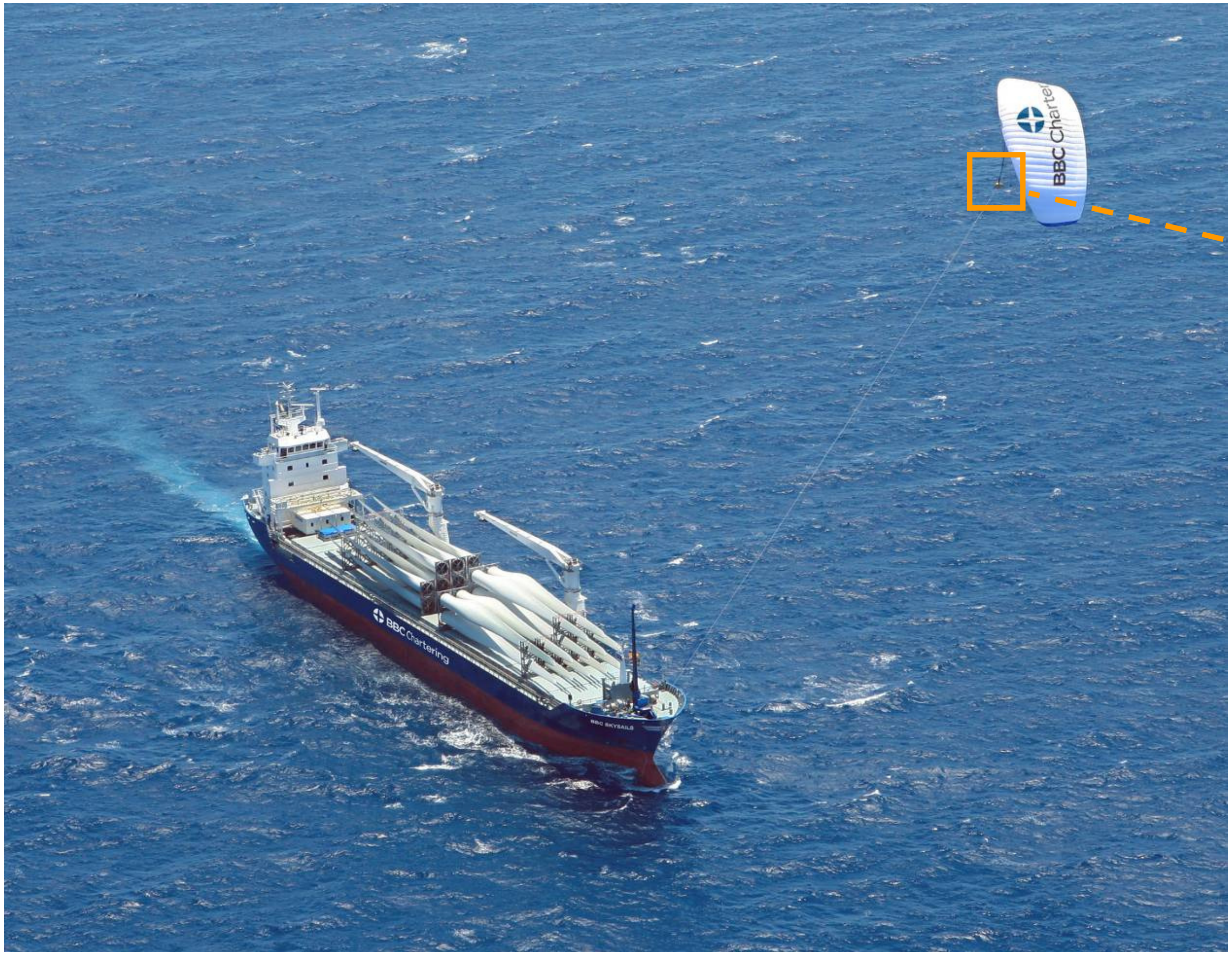
Hamburg, Germany

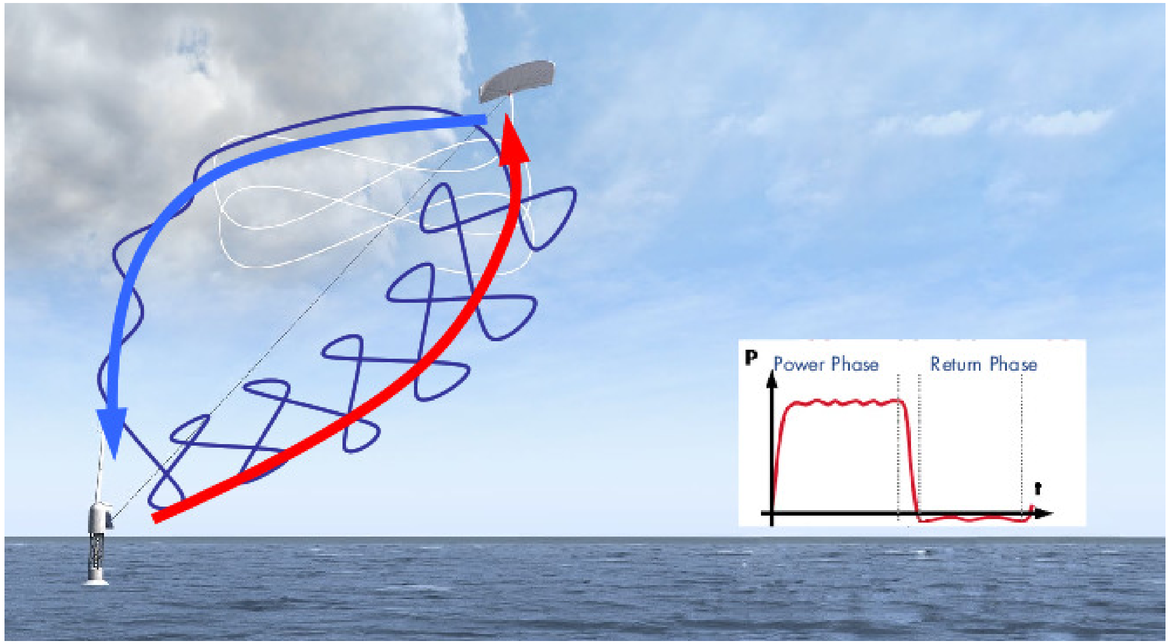
Airborne Wind Energy Conference Berlin, September 11, 2013

SkySails Marine – Towing Kite System



Airborne Control Pod

SkySails Power



Pumping Cycle

Functional Model
(Installed Generator Power 55kW)

Contents

- Introduction
- Model for Tethered Kite Dynamics
- Flight Controller Design
- Challenges
- Conclusions

Introduction

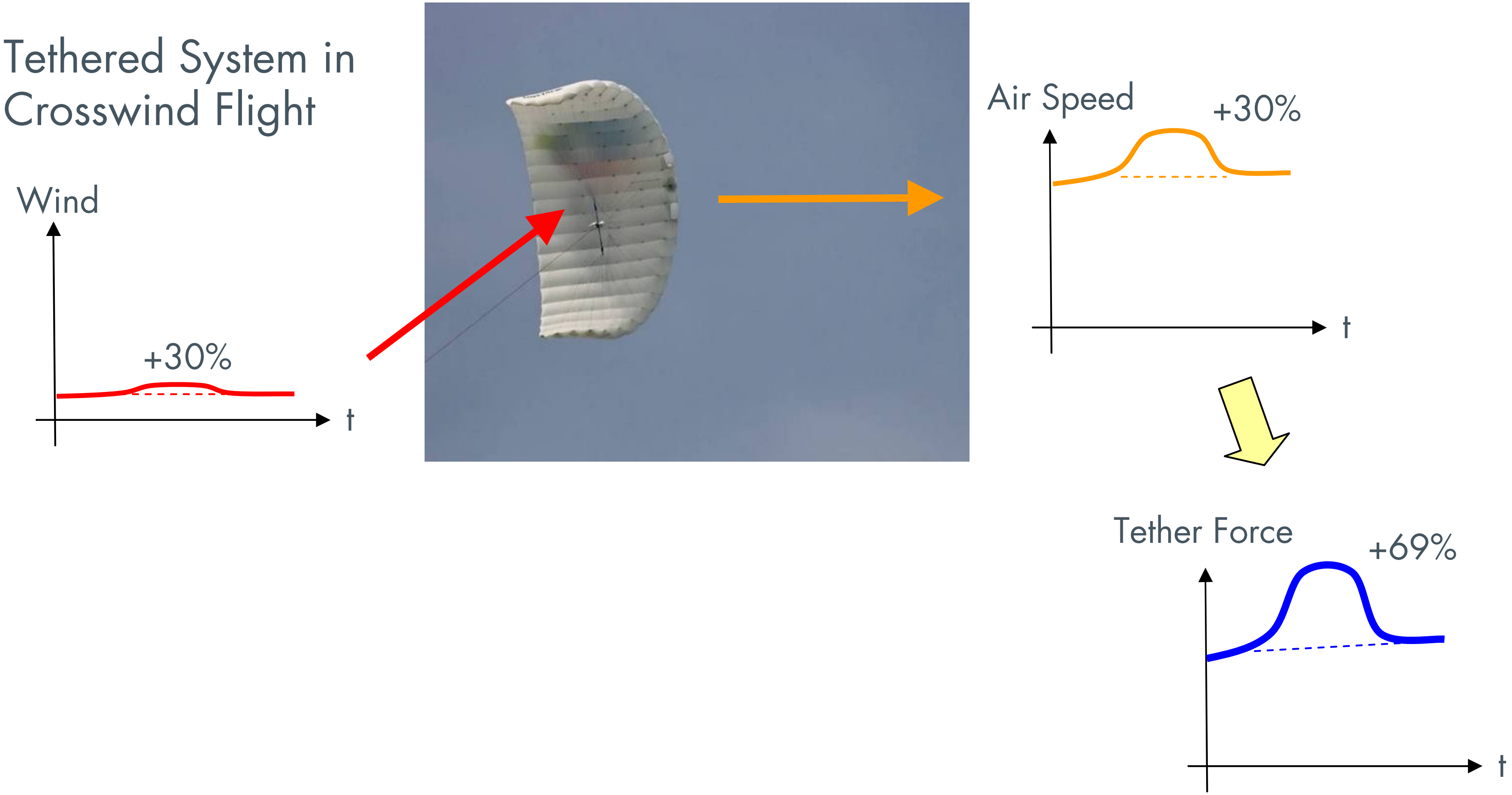
Economic energy generation ➔ Fully automated AWE plants

➔ Reliability of control system crucial

Introduction

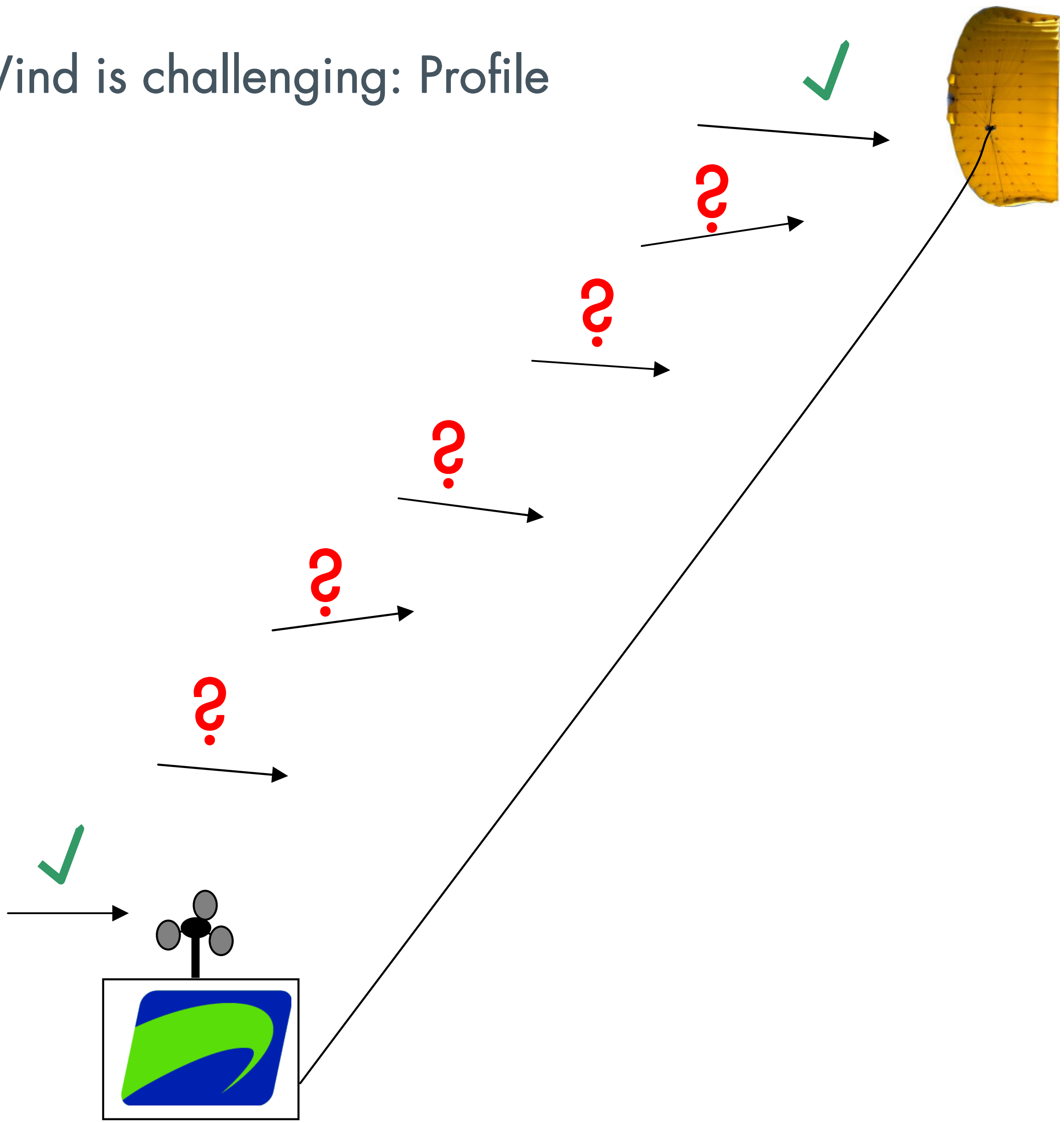
Wind is challenging: Perturbations due to Wind Gusts

Tethered System in Crosswind Flight



Introduction

Wind is challenging: Profile



How to model the wind field?

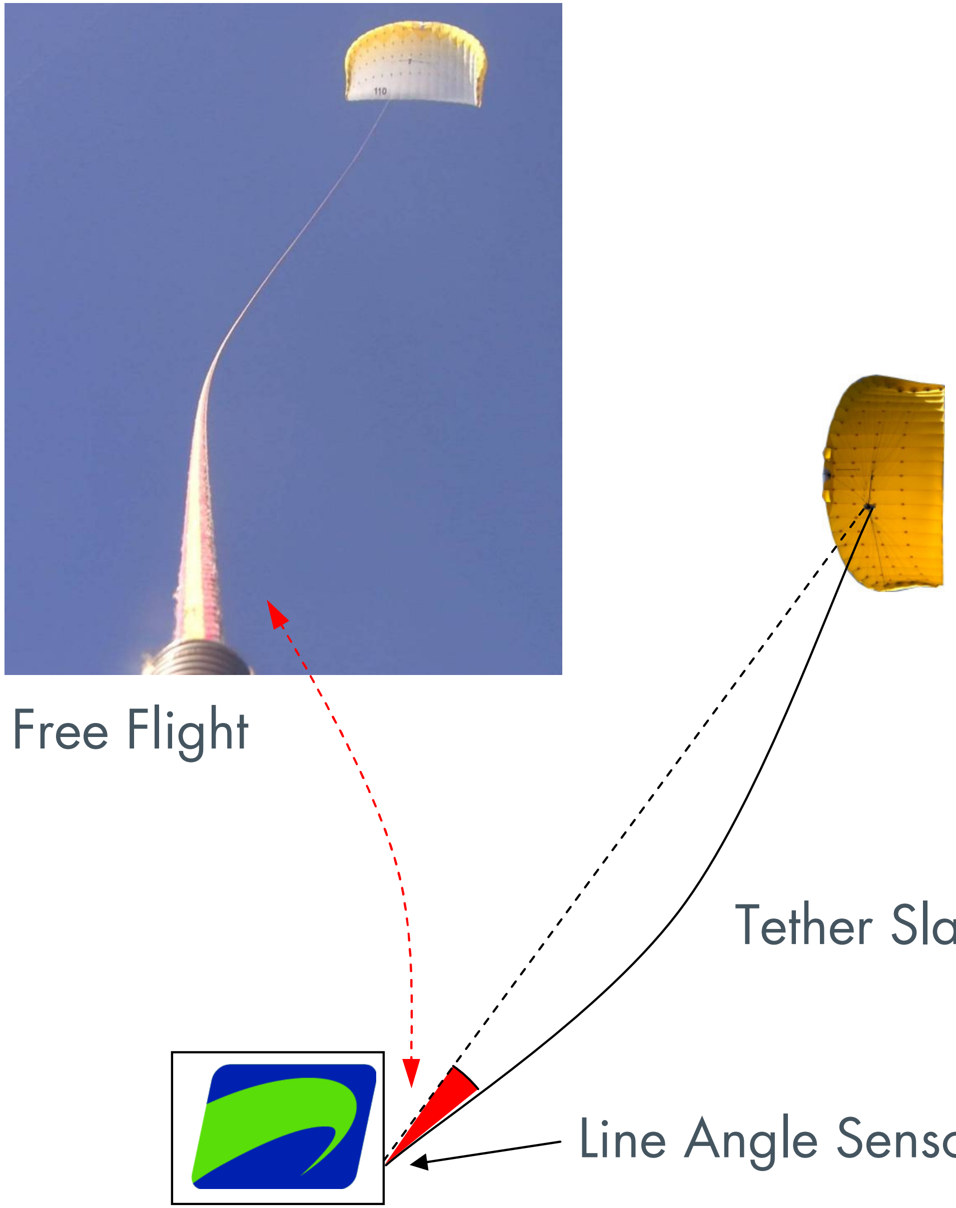
→ Profile?

→ Boundary layer?

→ ...

Introduction

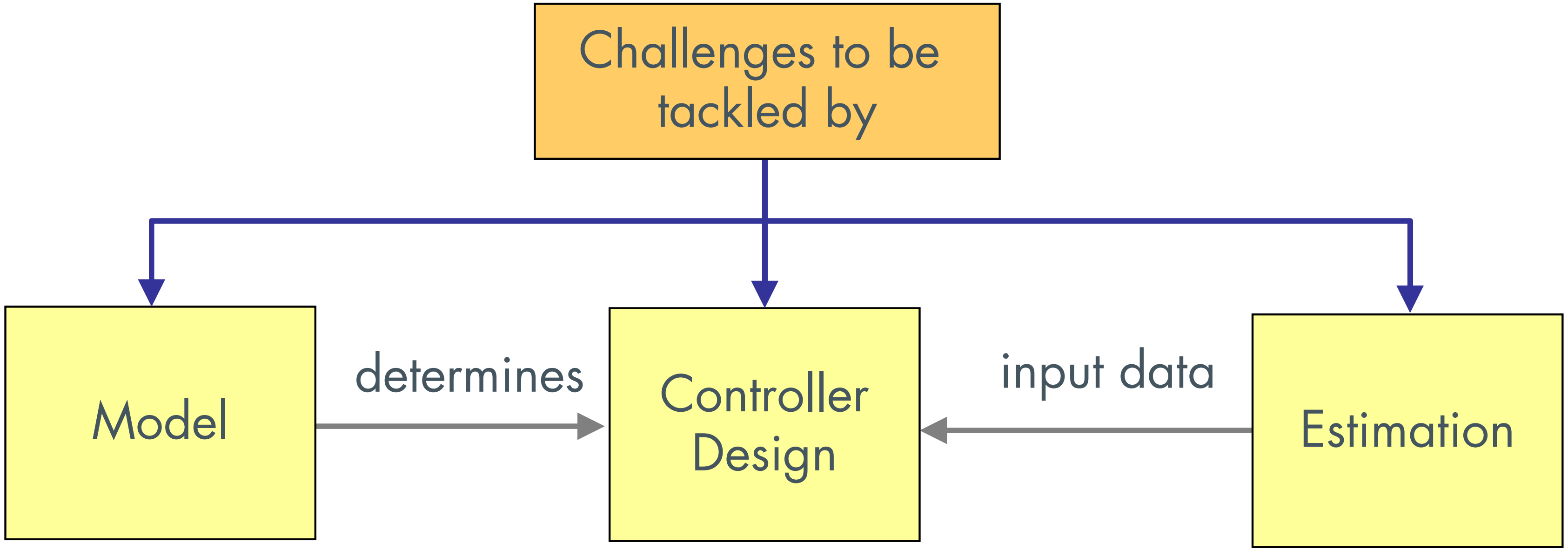
Soft Materials



Free Flight

- ➔ Modelling Accuracy is limited
- ➔ Limited Sensor `Accuracy´

Introduction



Challenges to be tackled by

Model

determines

Controller Design

input data

Estimation

`Keys´ to Success

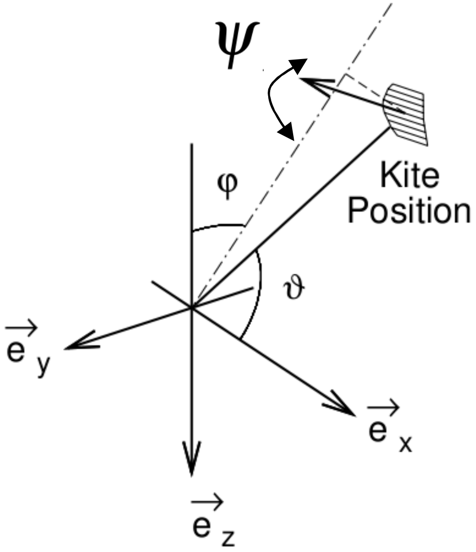
Keep it simple!

Explicit Understanding of Dynamics

Transparent and Deterministic Design

MODEL

Simple Model



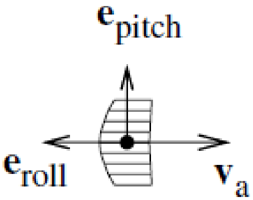
Position φ, ϑ

Orientation ψ

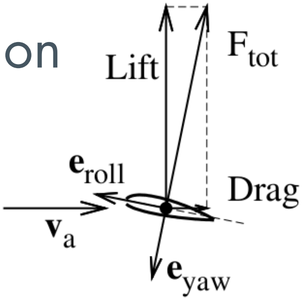
Model Assumptions

1.) Neglect Accelerations & Masses

2.) Airflow in Roll Direction



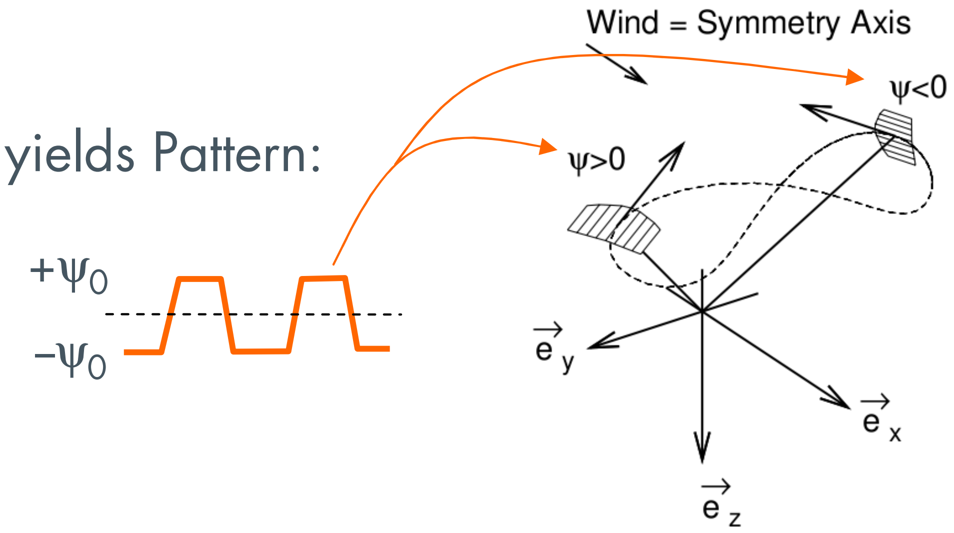
3.) Glide Ratio Condition



Side View

Model of Tethered Kites

Periodic Signal on ψ yields Pattern:



Equations of Motion:

$$\dot\vartheta = \frac{v_a}{L}\left(\cos\psi - \frac{\tan\vartheta}{E}\right)$$

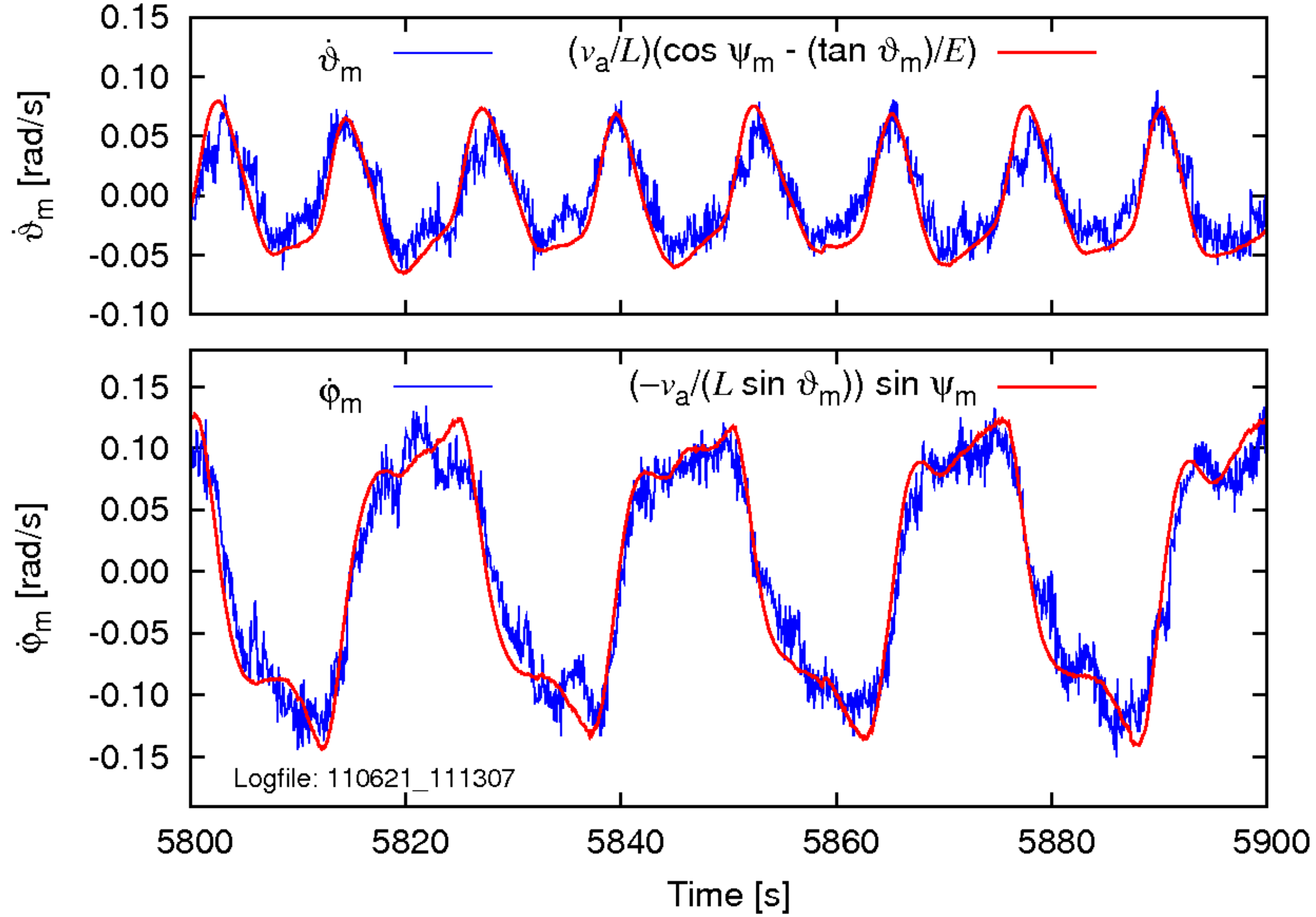
➔ Control Force: $\vartheta_0(\psi) = \arctan(E\cos\psi)$

$$\dot\varphi = -\frac{v_a}{L\sin\vartheta}\sin\psi.$$

➔ Control Position (static φ=const)

➔ Angle ψ is the Central Control Variable

Validation of Kinematics



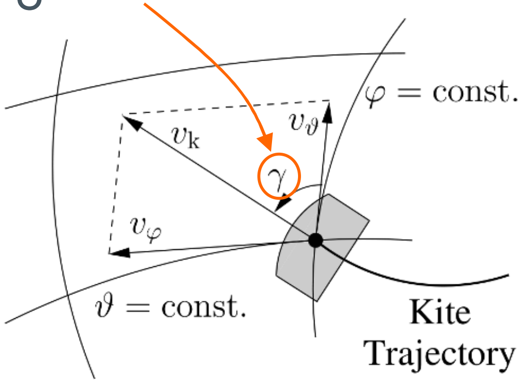
$$\dot{\vartheta} = \frac{v_a}{L}\left(\cos\psi - \frac{\tan\vartheta}{E}\right)$$

$$\dot{\varphi} = -\frac{v_a}{L\sin\vartheta}\sin\psi.$$

M. Erhard, H. Strauch, *Theory and Experimental Validation of a Simple Comprehensible Model of Tethered Kite Dynamics Used for Controller Design*, in: Airborne Wind Energy, Springer, DOI 10.1007/978-3-642-39965-7_8 (2013)

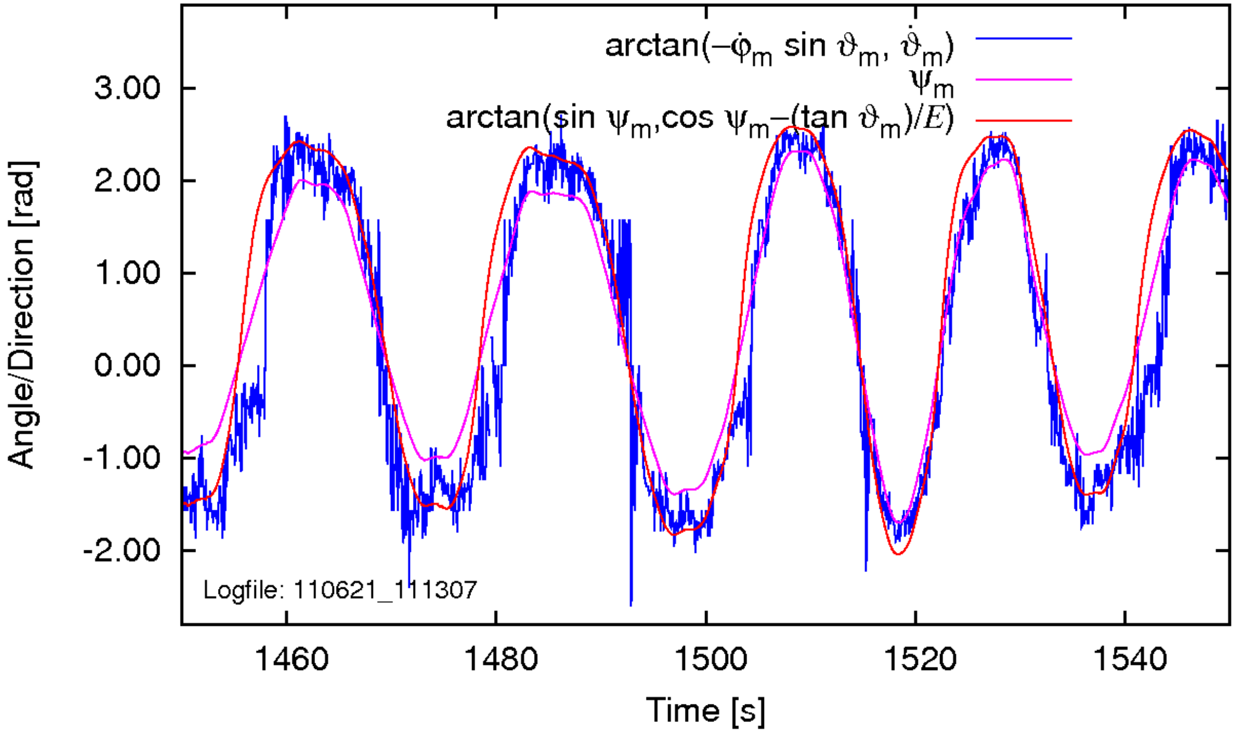
Experimental Results

Flight Direction



$$\gamma \doteq \arctan(-\dot{\varphi}\sin\vartheta, \dot{\vartheta})$$

$$\gamma = \arctan(\sin\psi, \cos\psi - \frac{\tan\vartheta}{E})$$



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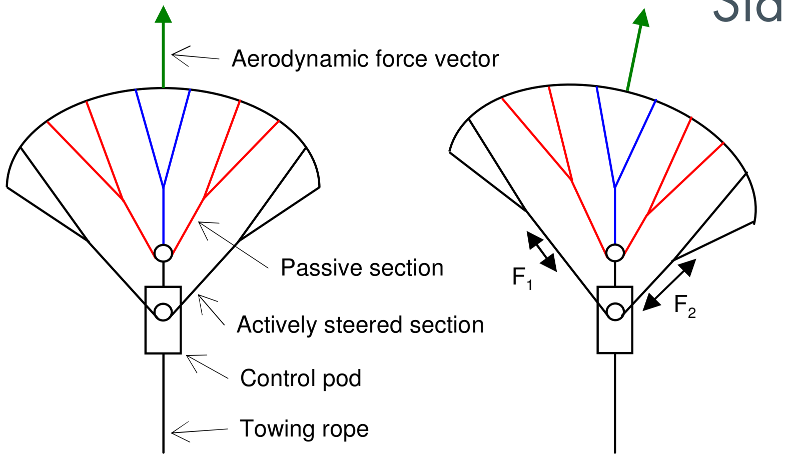
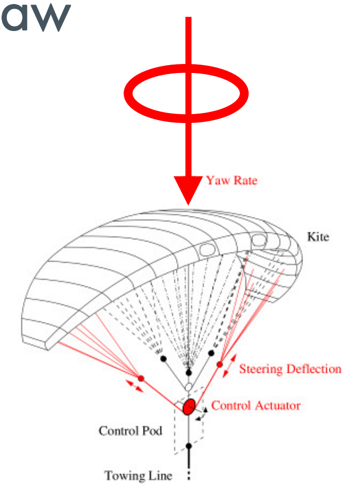
Steering

Steering by means of canopy (and force vector) rotation



Side Force

Turn Rate Law

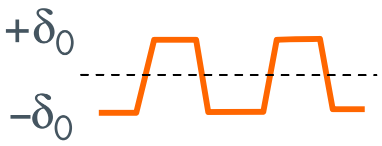


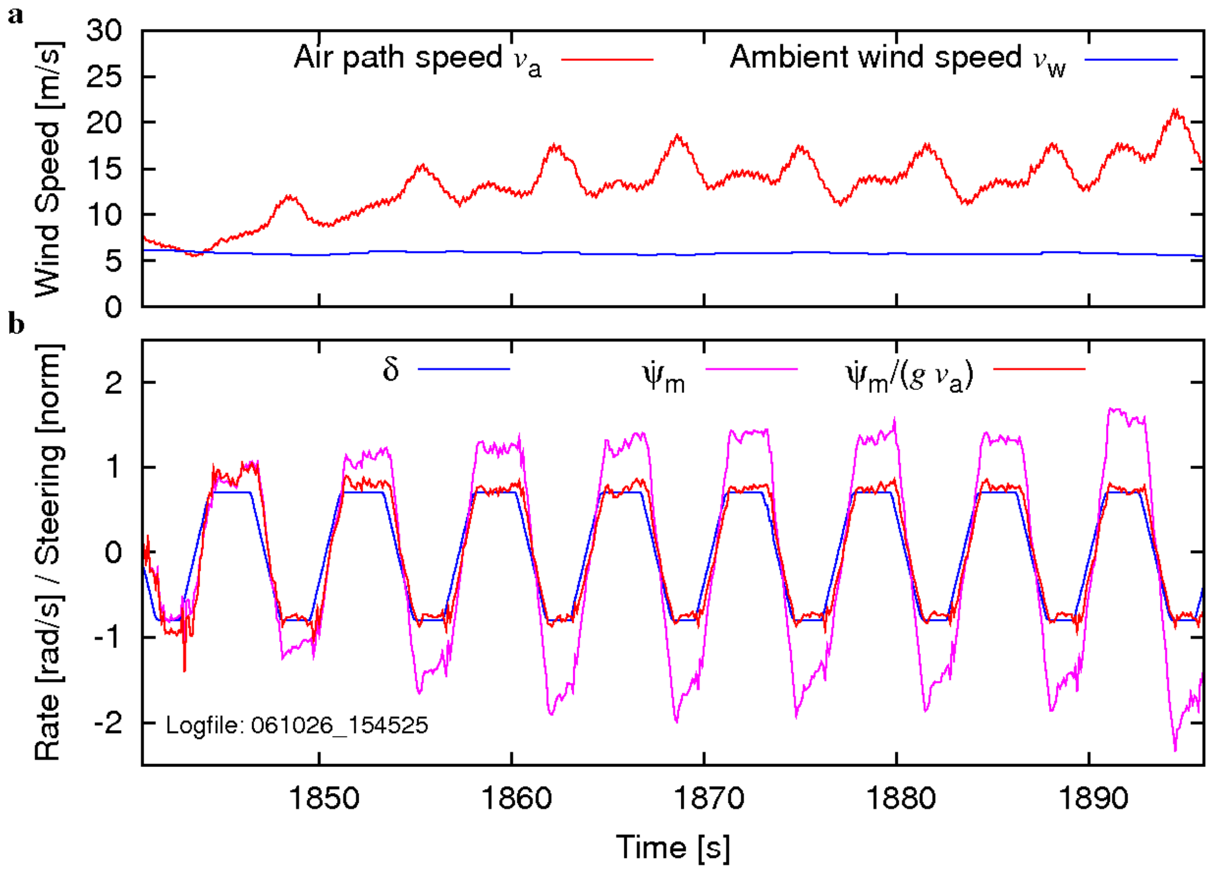
$$\boxed{\dot{\psi}_{\mathrm{m}} = g_{\mathrm{k}}\, v_{\mathrm{a}}\, \delta}$$

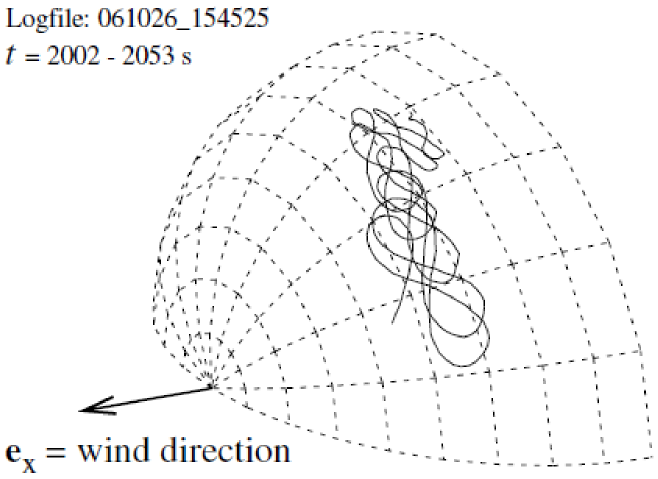
System Identification

Test Turn Rate Law?

Bang-Bang-Experiment





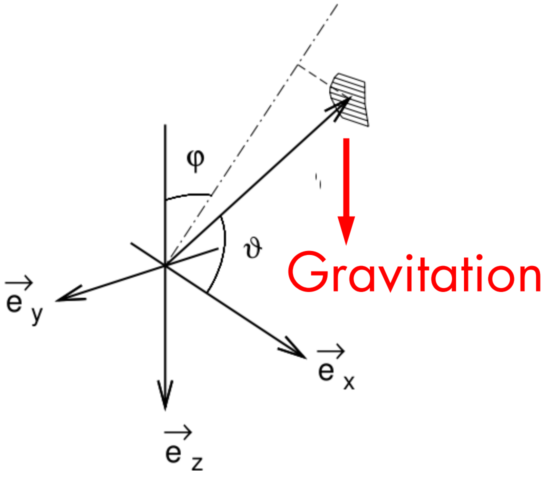


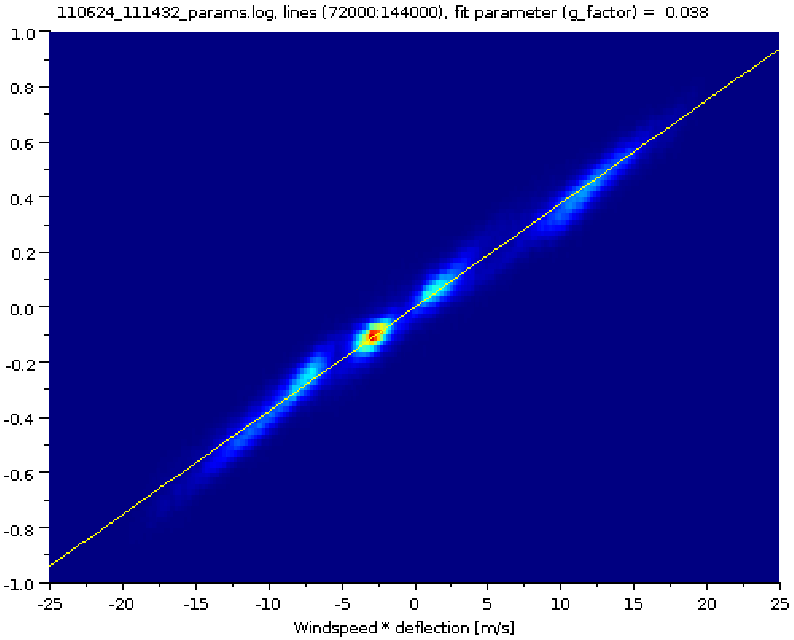
$$\boxed{\dot\psi_m = g_k\, v_a\, \delta}$$

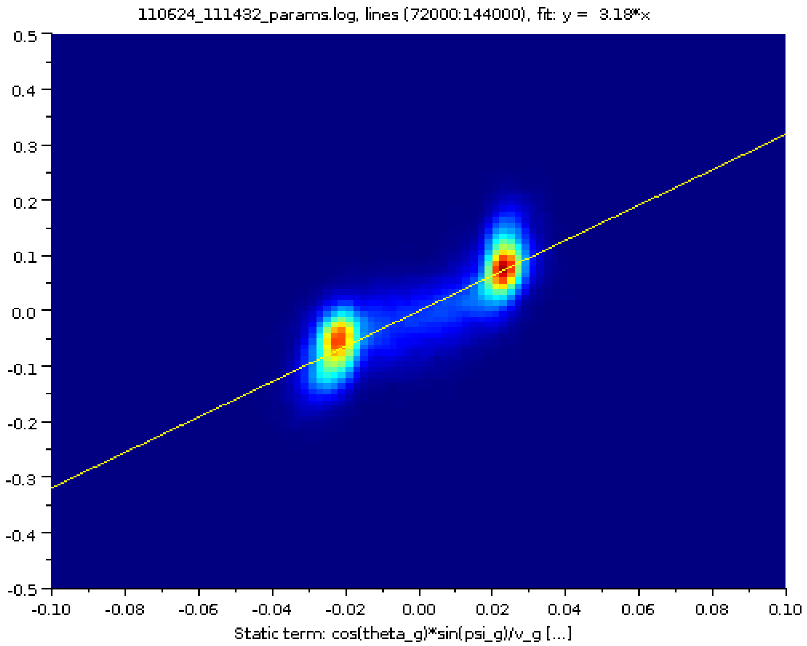
Extended Turn Rate Law

$$\dot{\psi}_{\mathrm{m}} = \boxed{g_{\mathrm{k}}}\, v_{\mathrm{a}}\, \delta + \boxed{M}\, \frac{\cos\theta_{\mathrm{k}} \sin\psi_{\mathrm{k}}}{v_{\mathrm{a}}}$$

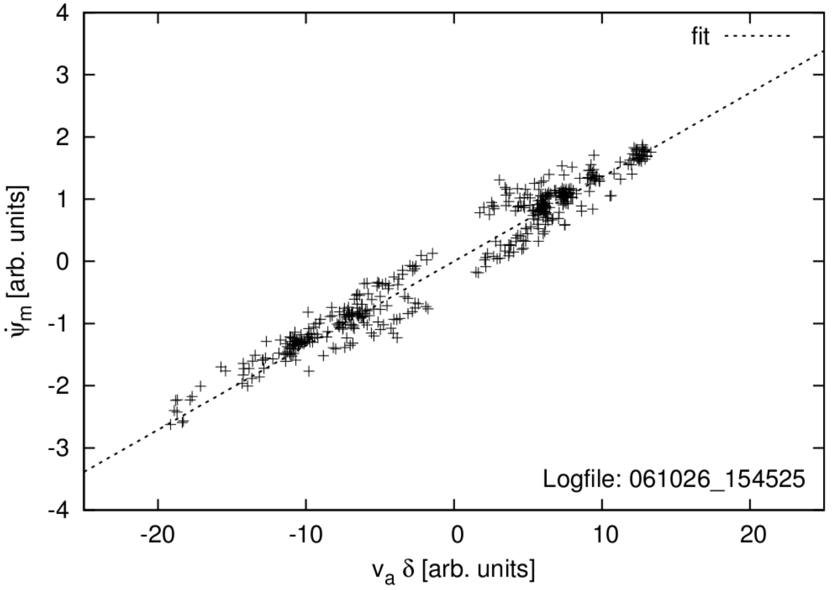
2 Fit Parameter




110624_111432_params.log, lines (72000:144000), fit parameter (g_factor) = 0.038

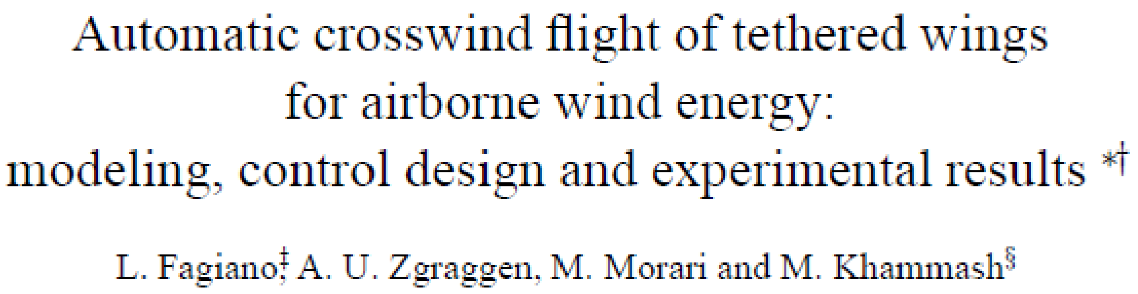

110624_111432_params.log, lines (72000:144000), fit: y = 3.18*x

Turn Rate Law



M. Erhard, H. Strauch,
Control of Towing Kites for Seagoing Vessels,
IEEE Trans. Control Syst. Technol.,
DOI 10.1109/TCST.2012.2221093 (2012)

Theoretical derivation and experiment



Automatic crosswind flight of tethered wings
for airborne wind energy:
modeling, control design and experimental results *†

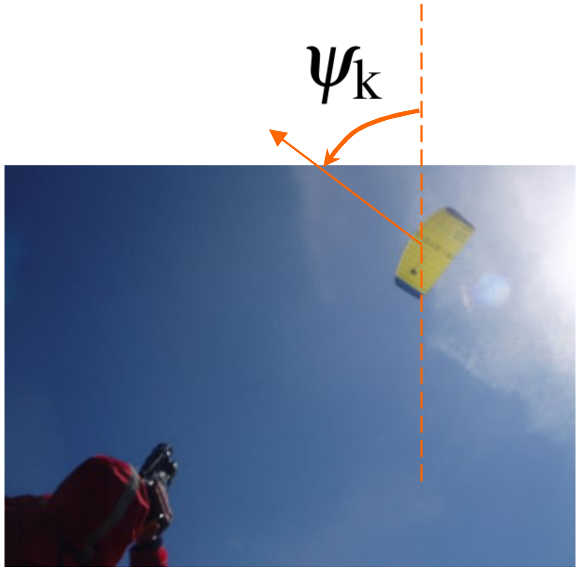
L. Fagiano‡, A. U. Zgraggen, M. Morari and M. Khammash§

arXiv:1301.1064,
submitted to
IEEE Trans. Control Syst. Technol. (2013)

FLIGHT CONTROL

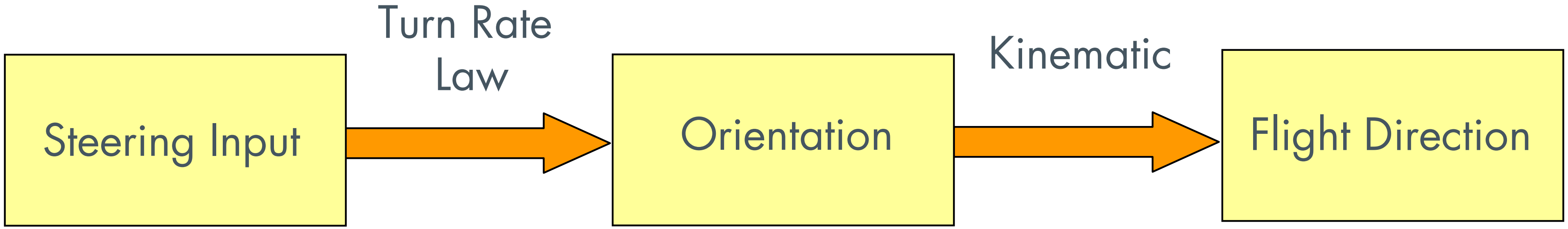
Flight control

Human Control Strategy?



➔ Use Angle w.r.t horizon (or wind)
Orientation determines flight direction

Controlled System (Plant)



Steering Input

Turn Rate Law

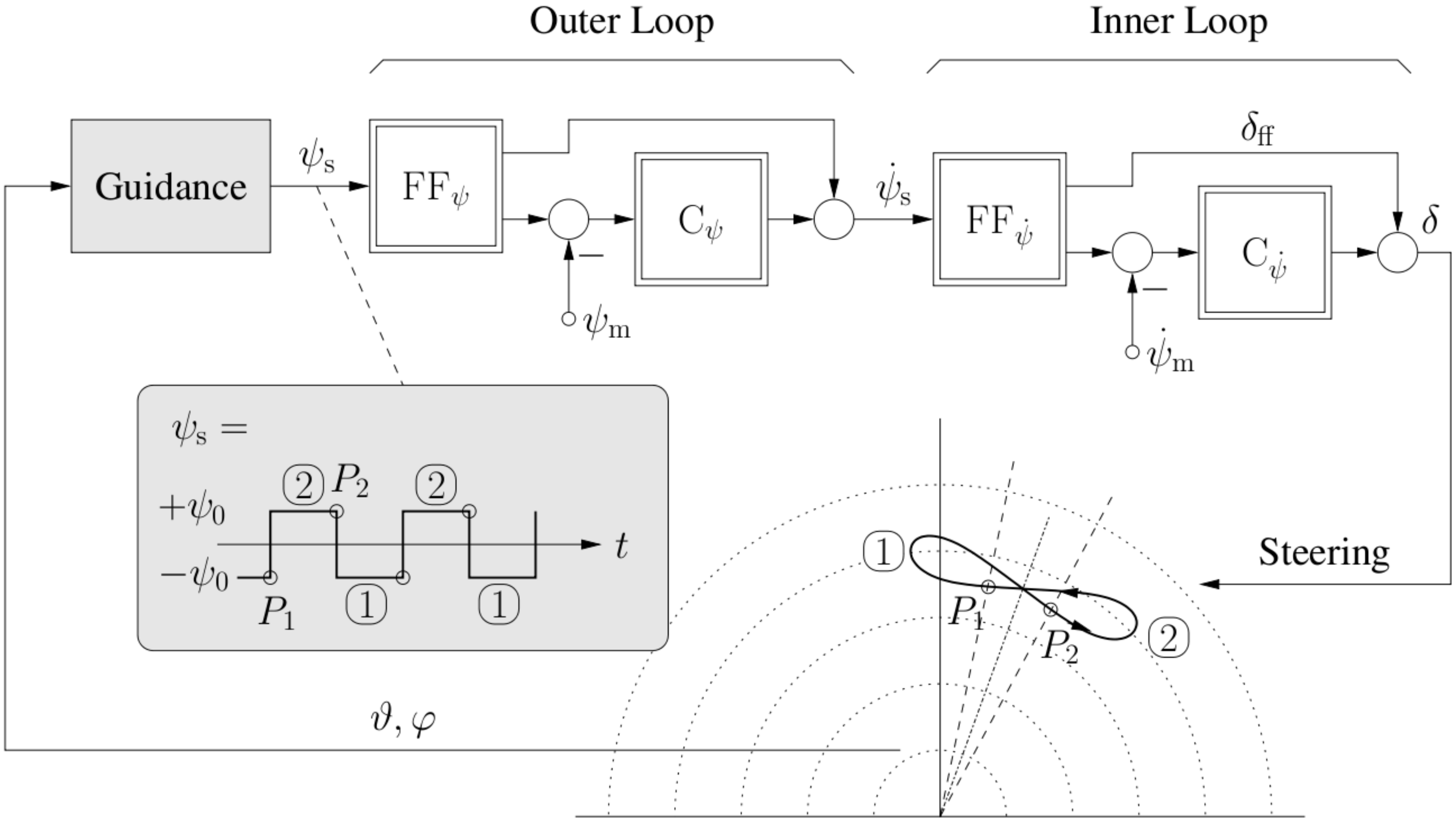
Orientation

Kinematic

Flight Direction

Flight Control

Cascaded Structure



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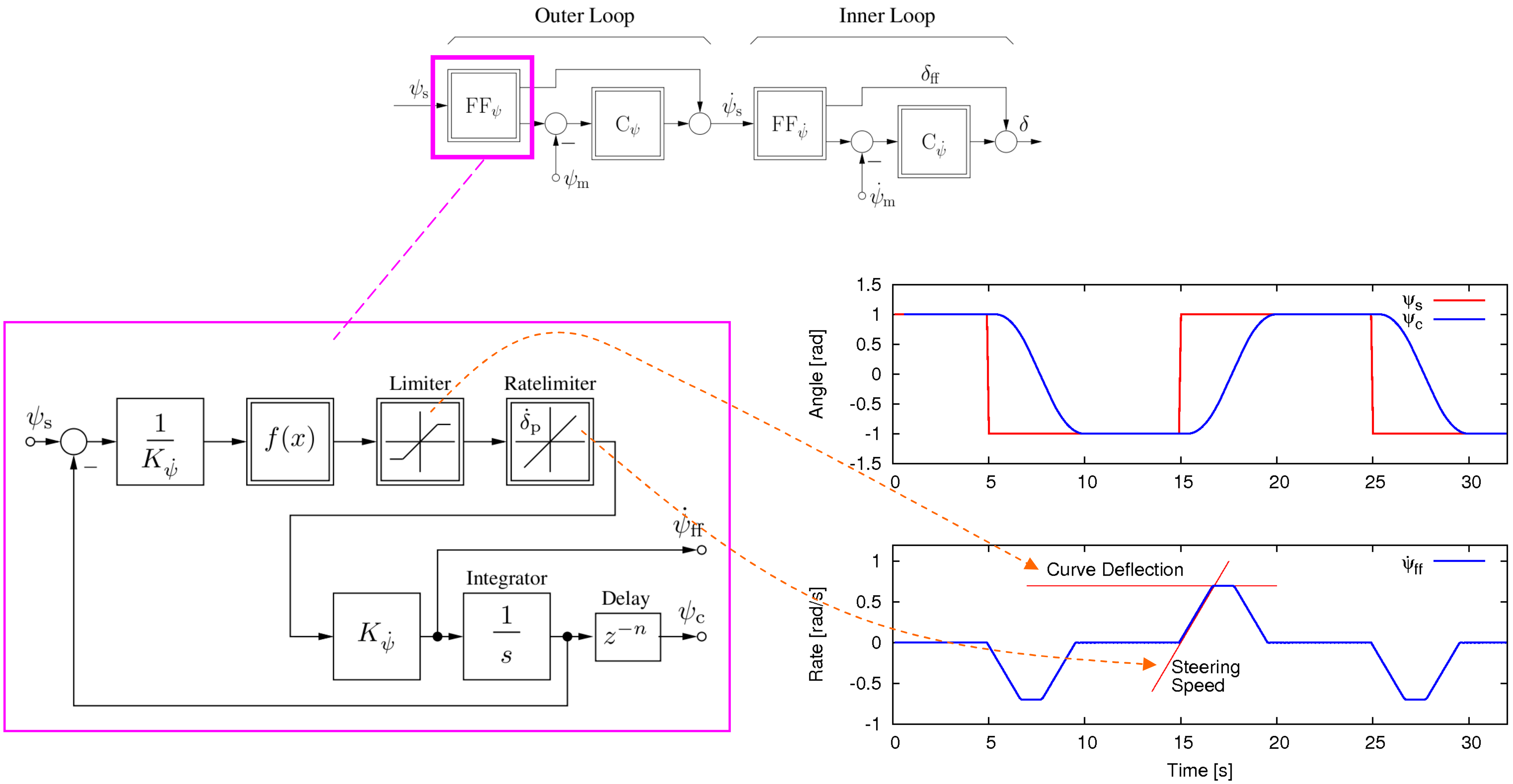
Model Based Feedforward



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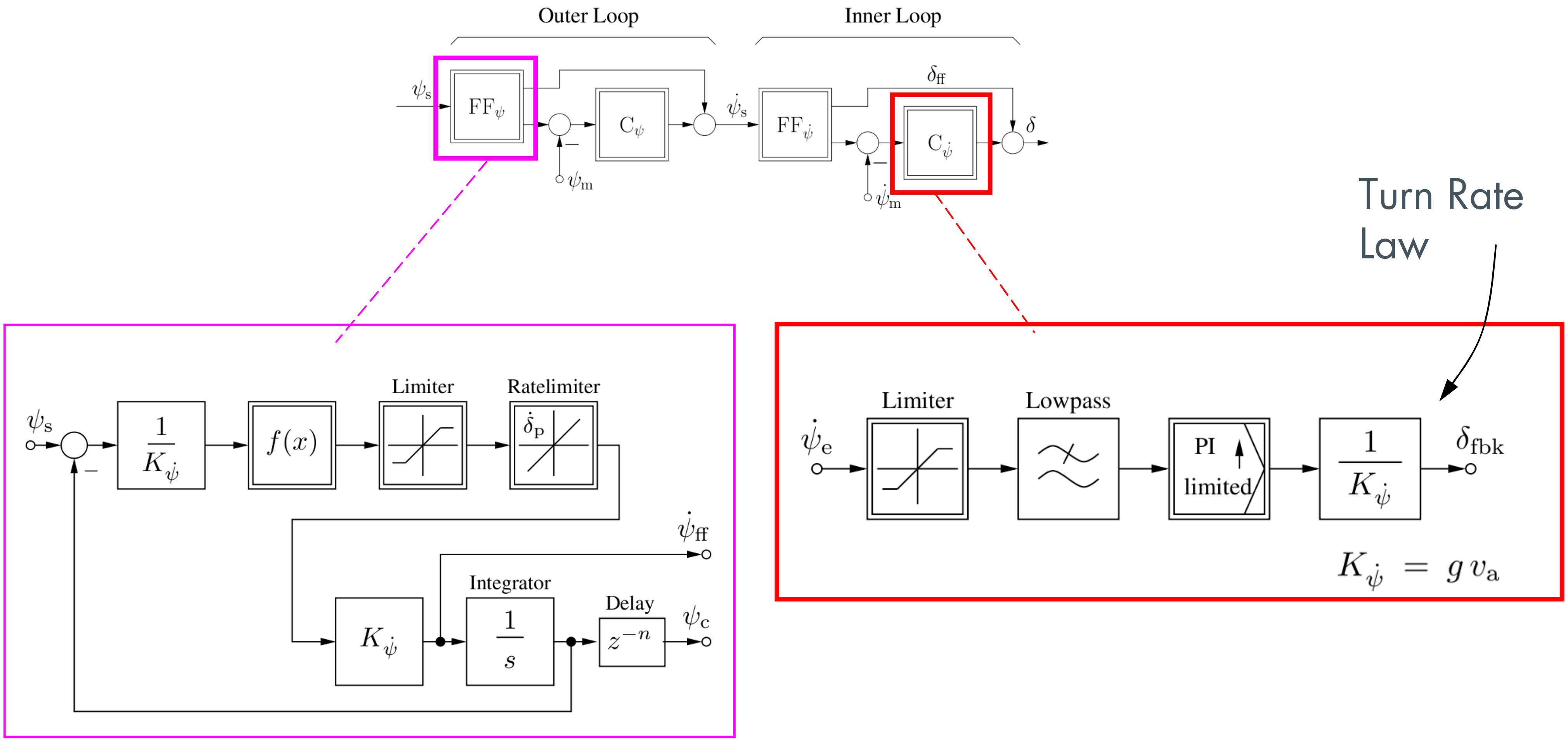
Linearization of plant



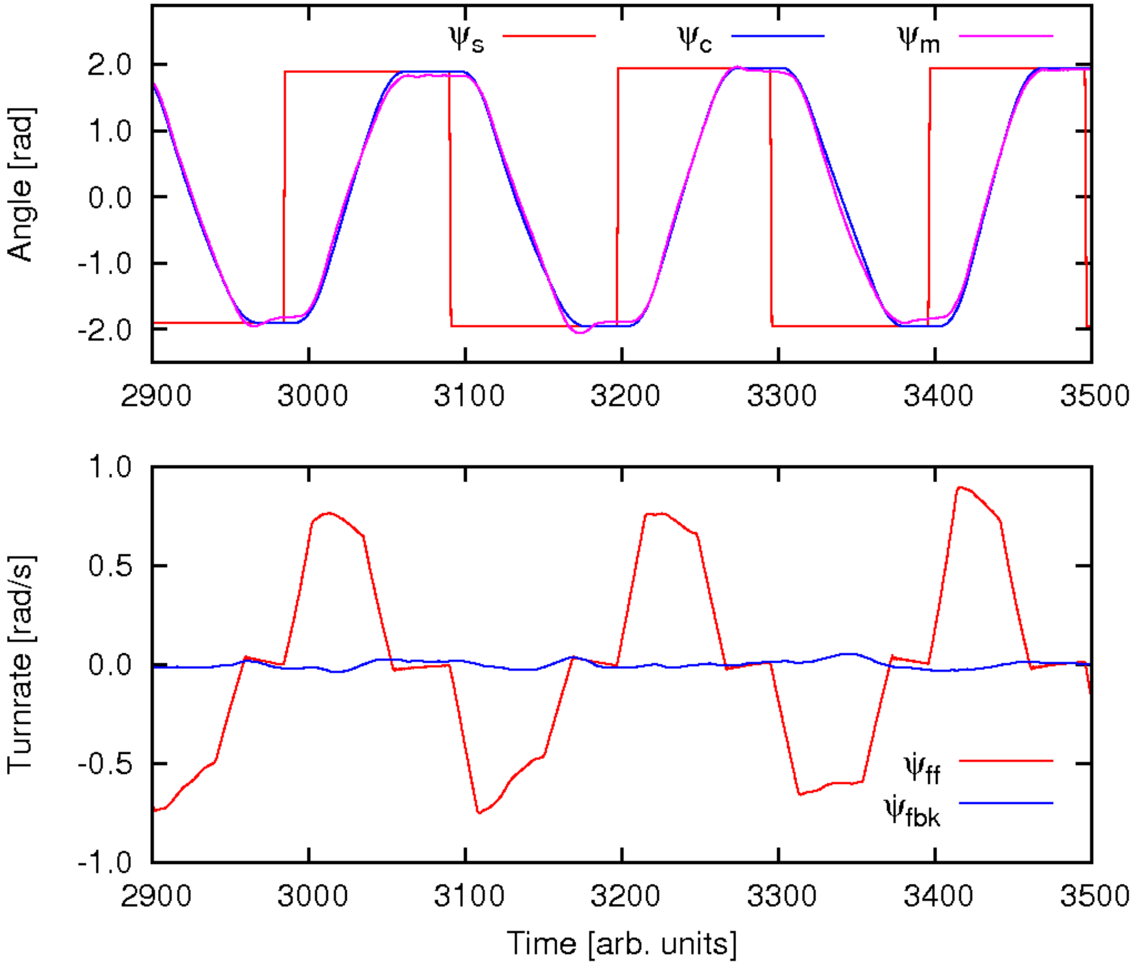
$$K_{\dot\psi} = g\, v_a$$

Turn Rate Law

M. Erhard, H. Strauch, *Control of Towing Kites for Seagoing Vessels*, IEEE Trans. Control Syst. Technol., DOI 10.1109/TCST.2012.2221093

Controller Performance

Outer Loop



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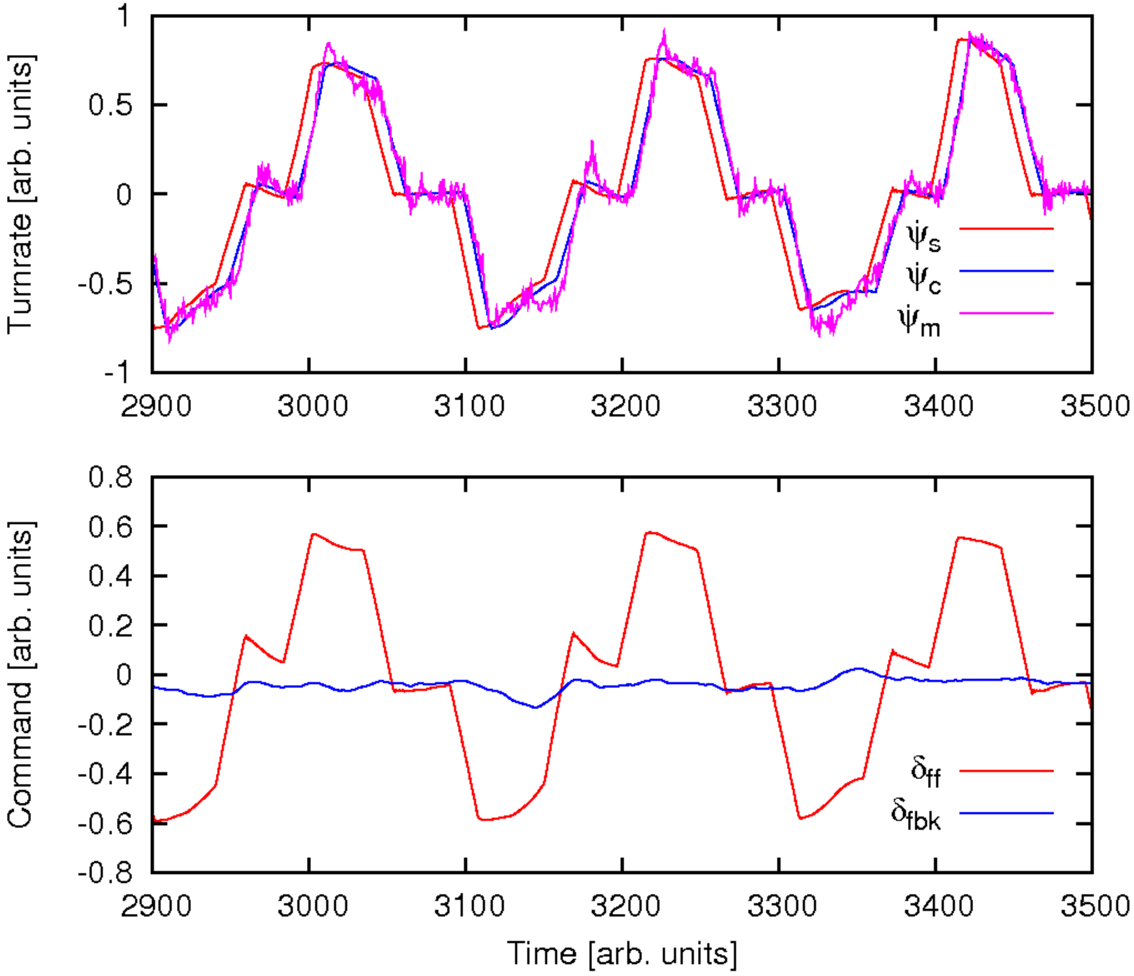
Controller Performance

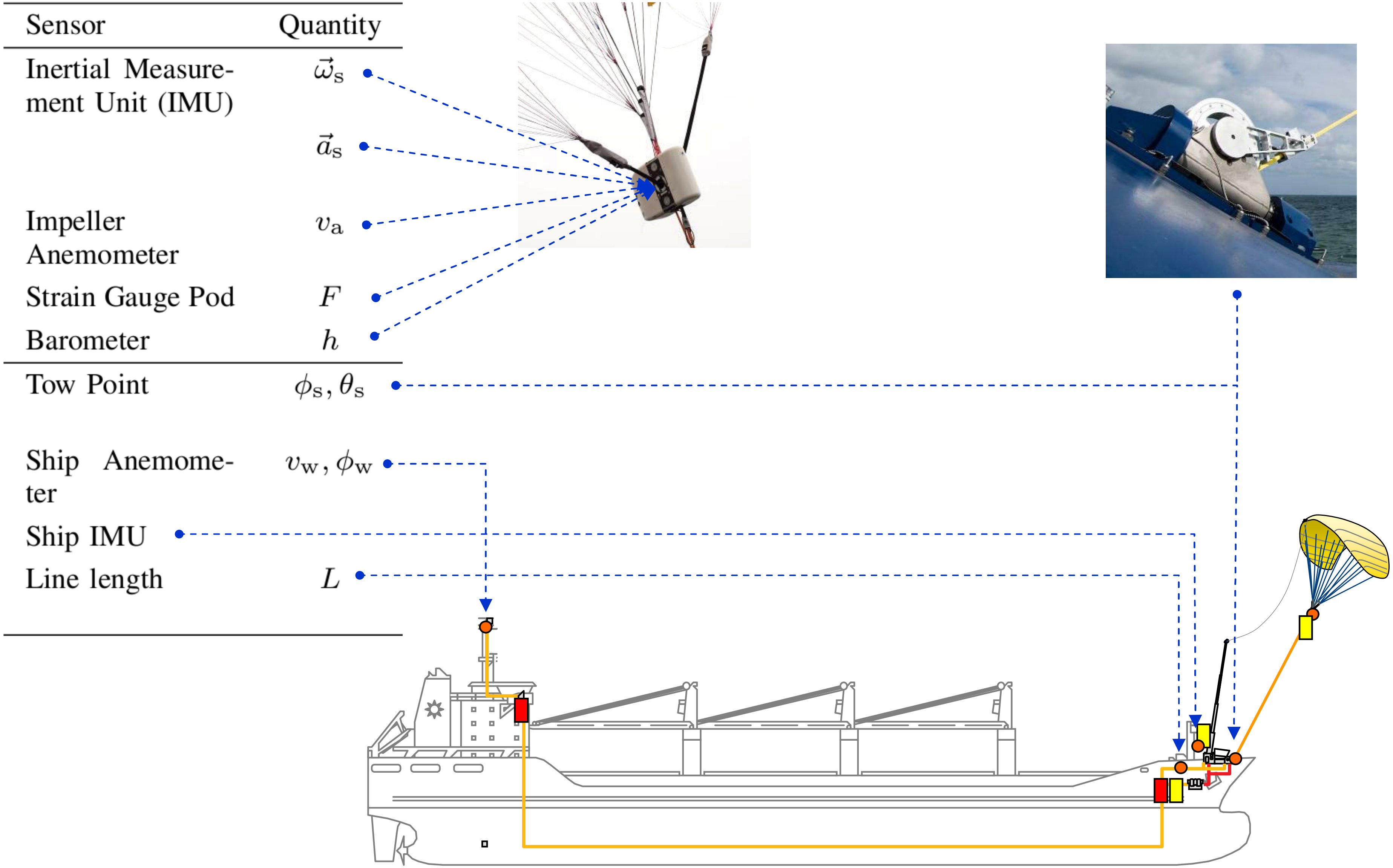
Inner Loop



M. Erhard, H. Strauch, *Control of Towing Kites for Seagoing Vessels*, IEEE Trans. Control Syst. Technol., DOI 10.1109/TCST.2012.2221093

CHALLENGES

Sensor Overview



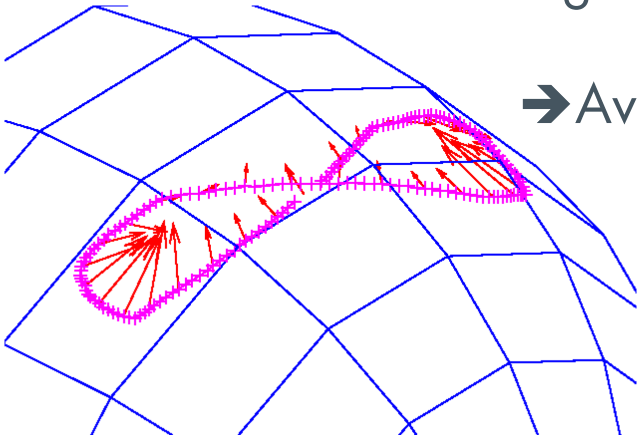
Sensor	Quantity
Inertial Measurement Unit (IMU)	$\vec{\omega}_\mathrm{s}$ $\vec{a}_\mathrm{s}$
Impeller Anemometer	v_a
Strain Gauge Pod	F
Barometer	h
Tow Point	$\phi_\mathrm{s}, \theta_\mathrm{s}$
Ship Anemometer	$v_\mathrm{W}, \phi_\mathrm{W}$
Ship IMU	
Line length	L

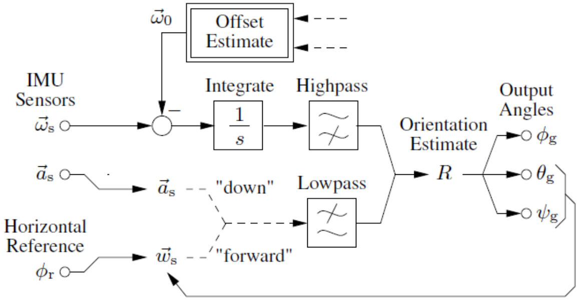
Inertial Navigation

Measured effects small compared to dynamics

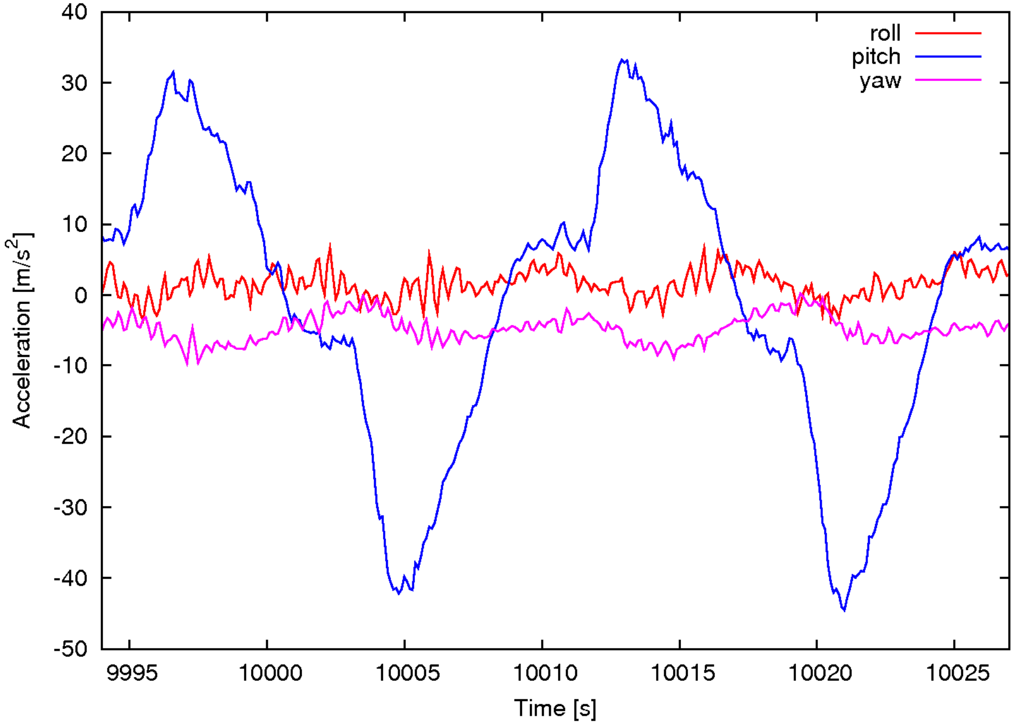
e.g. Reference to `down´-direction

➔Average accelerations $\langle \vec{a}_\mathrm{s} \rangle \approx -\,|g|\,\vec{e}_z$



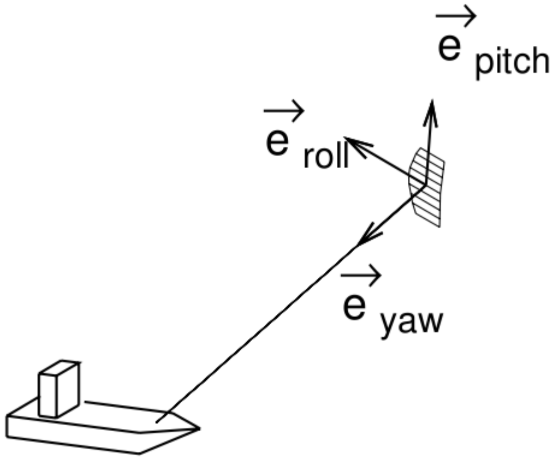


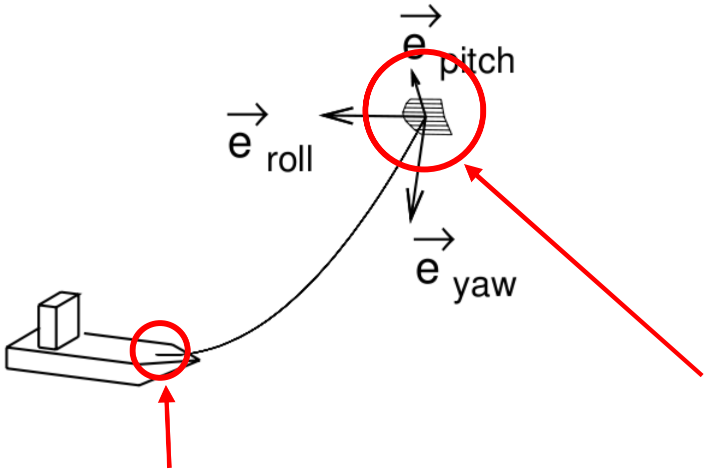
M. Erhard, H. Strauch, *Sensors and Navigation Algorithms for Flight Control of Tethered Kites*, Proc. European Control Conf., arXiv:1304.2233 (2013)



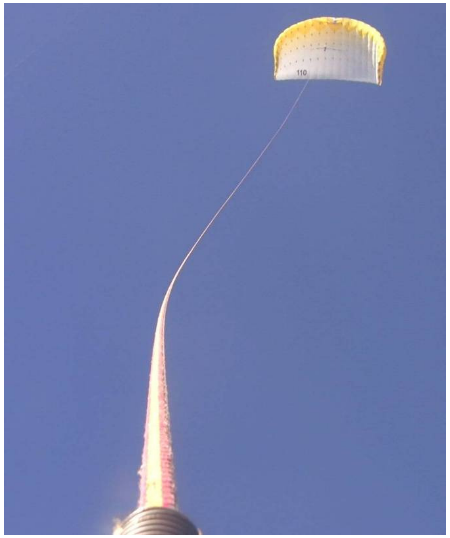
Free flight

Due to Gusts or wave induced motion: temporarily **untethered** system

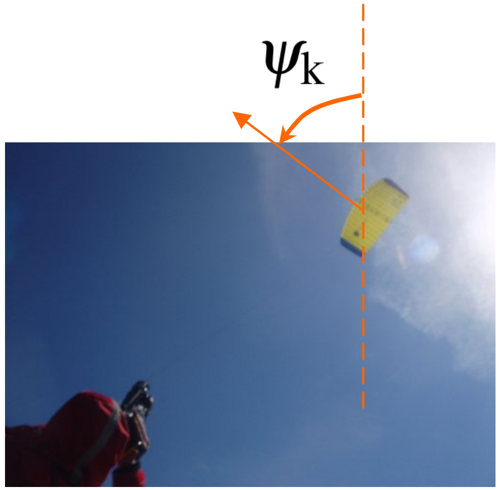




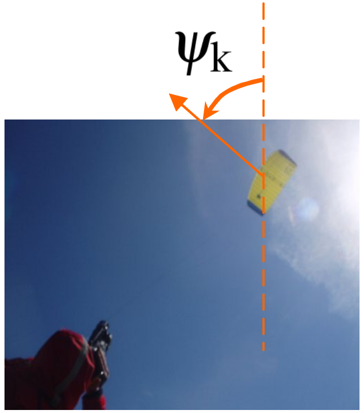
Angle w.r.t. Horizon
`undefined´

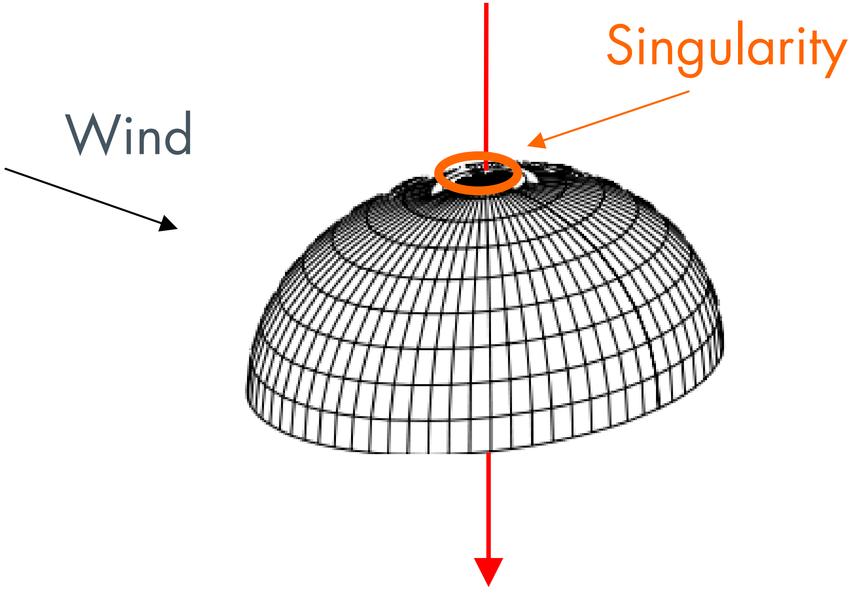


Line Angle
Sensor

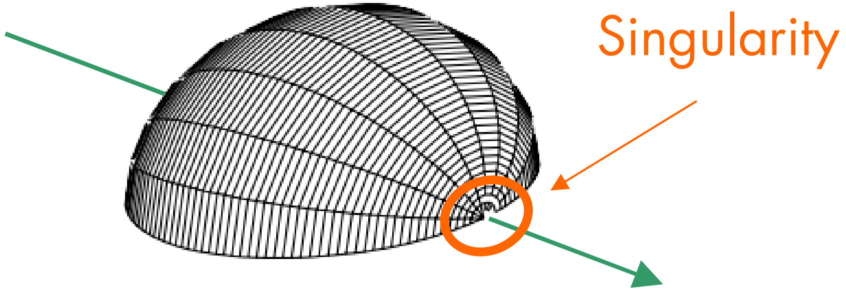


Solution: Consider Symmetry



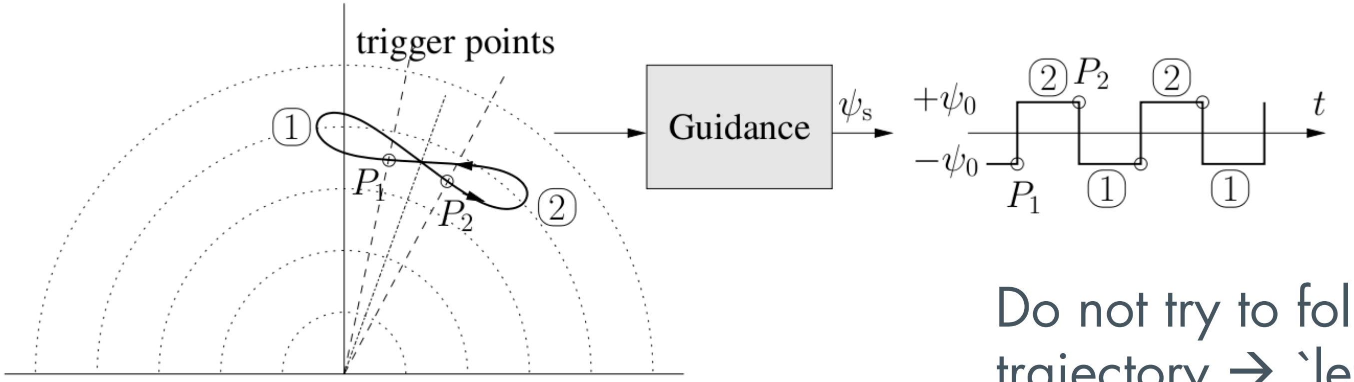


Symmetry w.r.t. Gravity



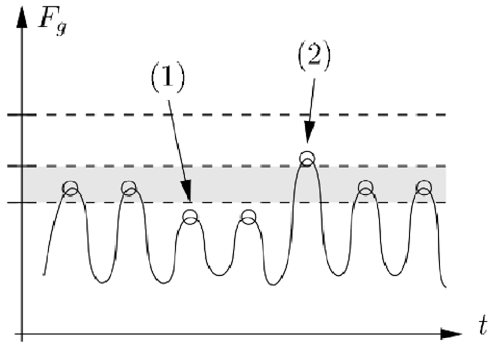
Symmetry w.r.t. Wind

Trajectory Generation



Do not try to follow an exact trajectory → `let the pattern evolve´

Force Control



Step-Controller on ψ –Amplitude

Controller quite efficient w.r.t. wind uncertainties, but room for improvement…

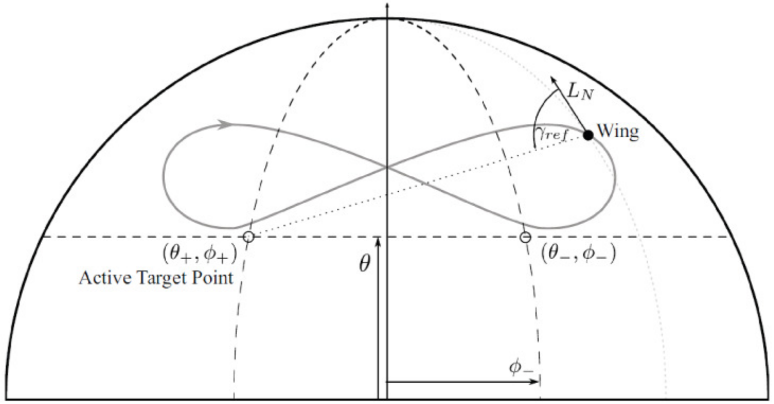
Trajectory Generation

Unknown Wind distribution

➔ Use local Measurement for Control (Turn Rate Law)

➔ Try to estimate Wind Speed and Direction at Flight Altitude

Guidance by using Target Points



L. Fagiano, A.U. Zgraggen, M. Morari, M. Khammash, *Automatic crosswind flight of tethered wings for airborne wind energy: modeling, control design and experimental results*, arXiv: 1301.1064 (2013)

Future Work

➔ Extended Wind Models (profile, ...), in particular for force control and optimization of Power

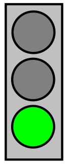
➔ Take into Account `short time´ Effects (Gusts)

➔ NMPC??? ...

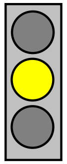
Conclusions

Control of Airborne Wind Energy Systems → Challenging!

Status



Standard Flight Situations



`Special´ Situations

➔ Work to be done to increase reliability

Design Concepts

Model

Simple Model Describes Dynamics

Controller

Architecture reflects Plant Structure

Estimation

Must be Robust against Exceptional Situations

Acknowledgements

Hans Strauch
Consultant since 2004

Thank you for your attention!

Questions?