SkySails Tethered Kites for Ship Propulsion and Power Generation: Modeling and System Identification

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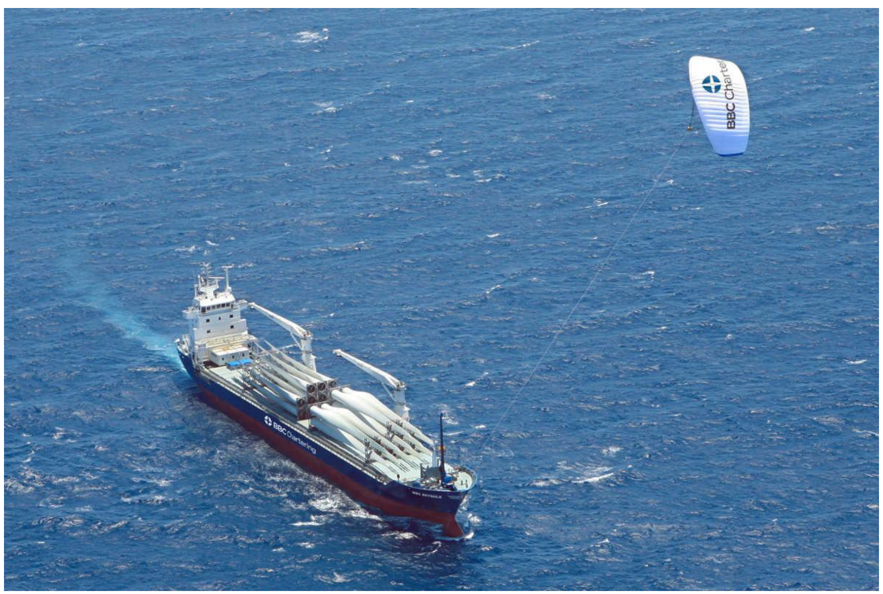
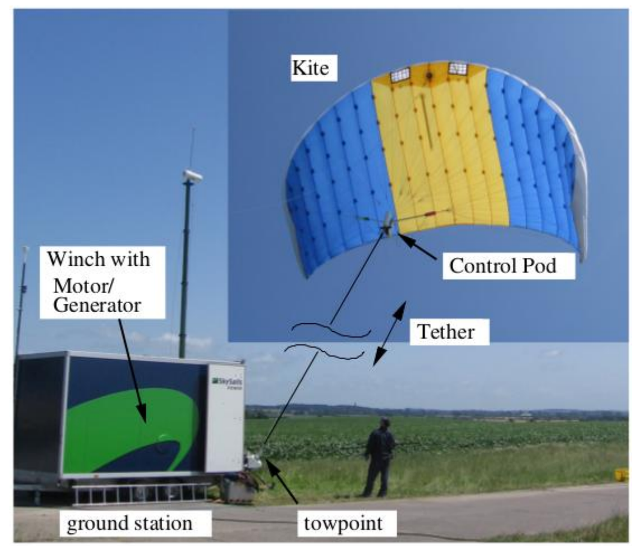




Small–Scale Functional Model (50kW peak power)

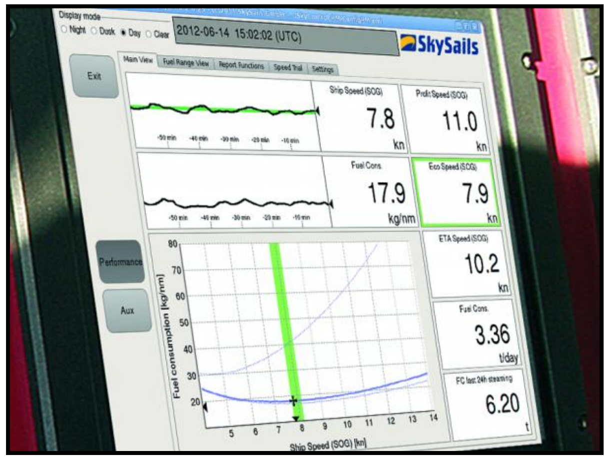
Contents

Business Segments

KITE PROPULSION

- aux. propulsion system
- up to 2000 kW engine equivalent power
- pilot customer operation since 2008
- autopilot controlled

PERFORMANCE MANAGER

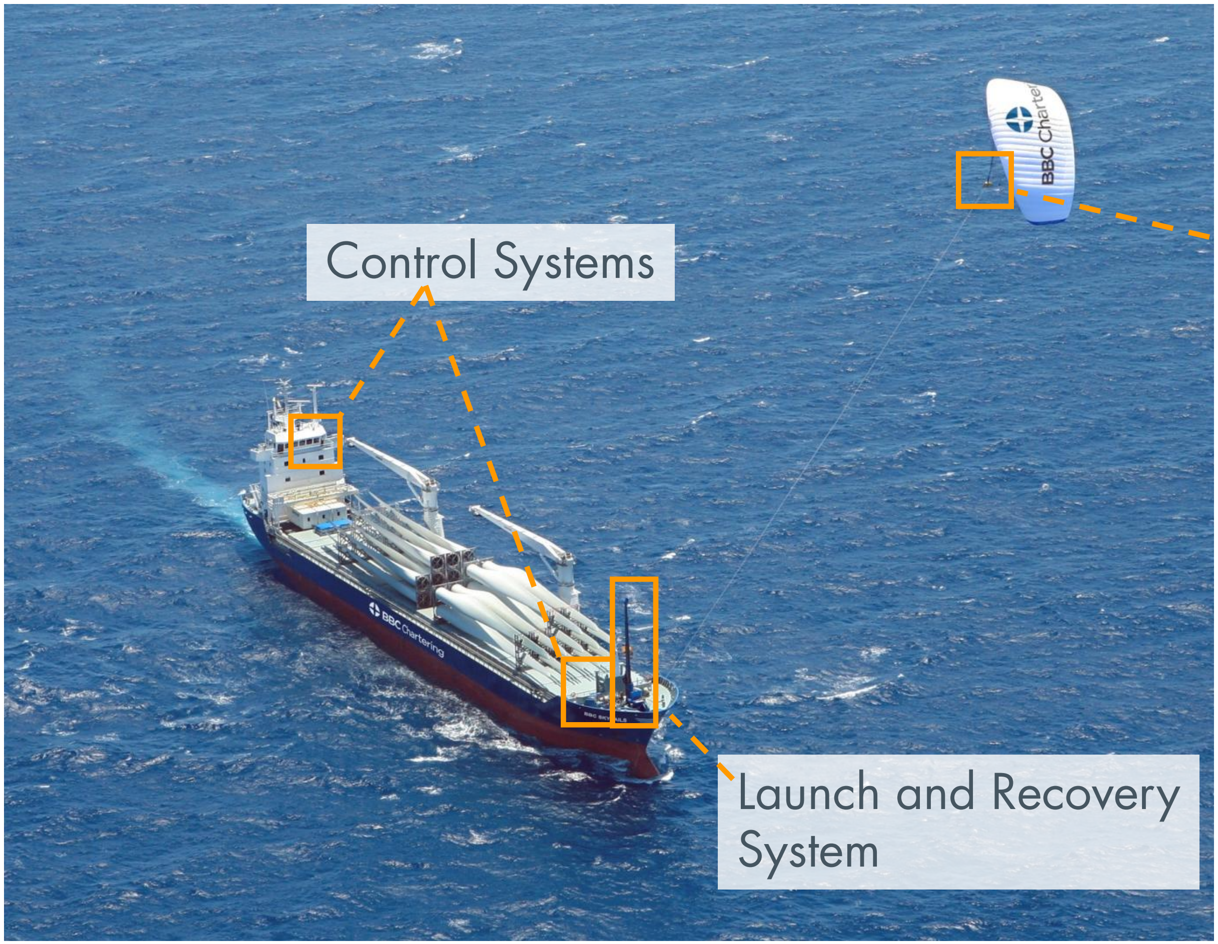


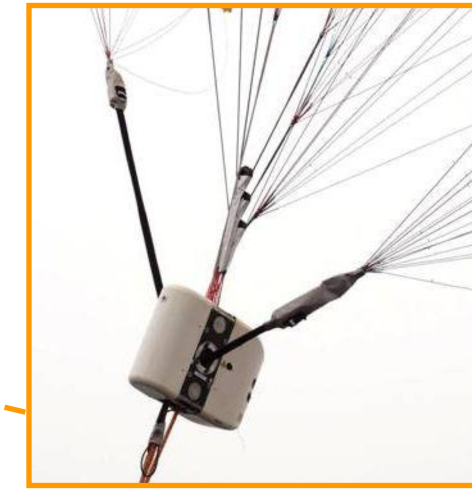
- improved communication ship to shore
- automatic fuel and condition monitoring
- in operation on 35+ ships

SKYSAILS POWER

- small scale model for airborne wind energy
- installed in a trailer
- kites up to 30 m^2
- autopilot controlled

SkySails Marine – Towing Kite System



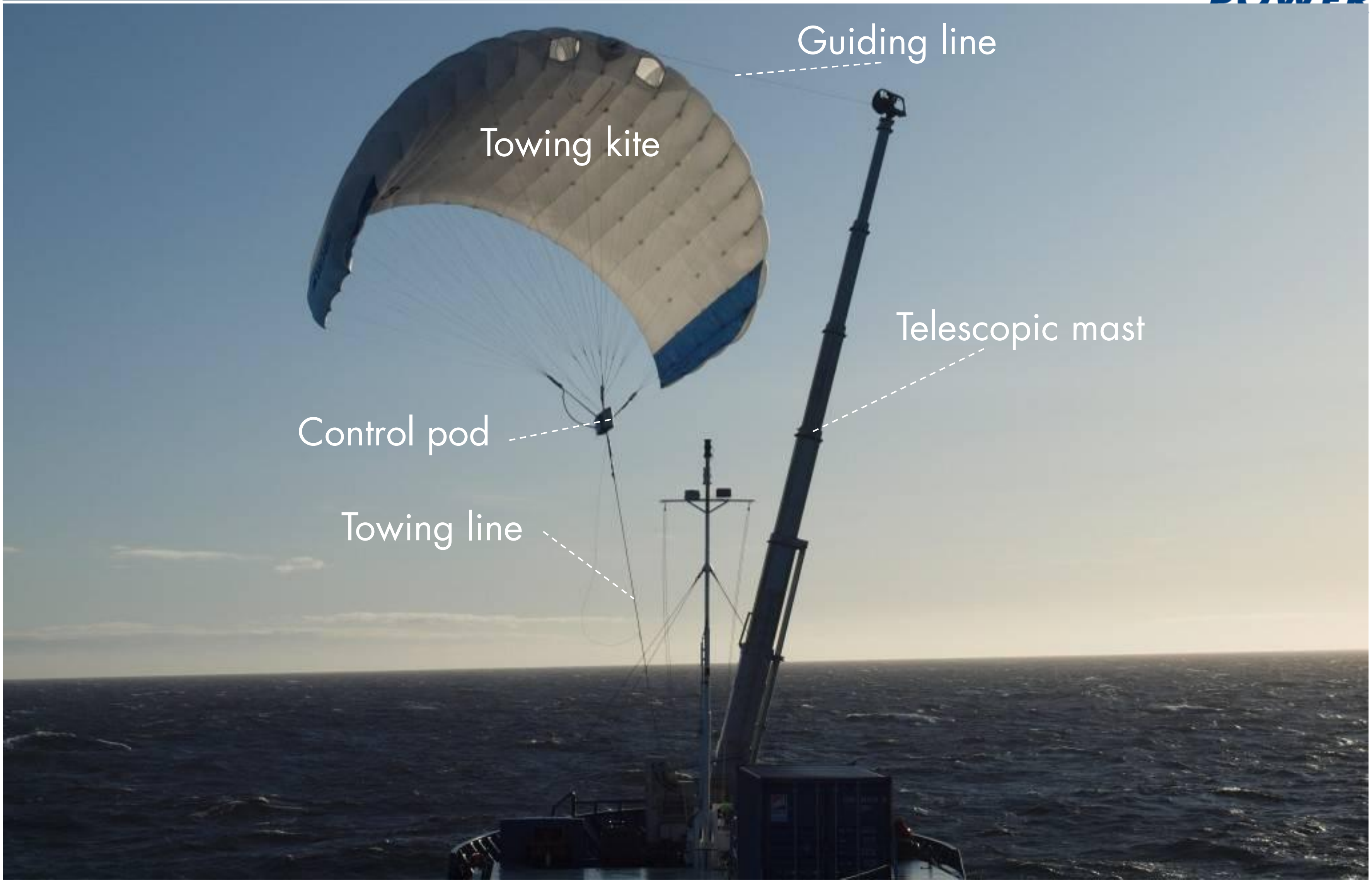


Airborne Control Pod

Kite sizes up to 320m²

Substitute 1-2 MW of main engine power

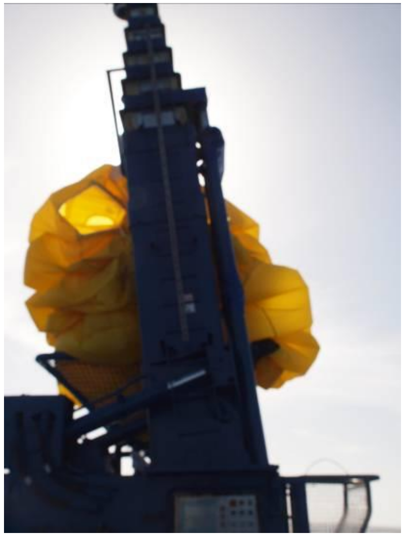
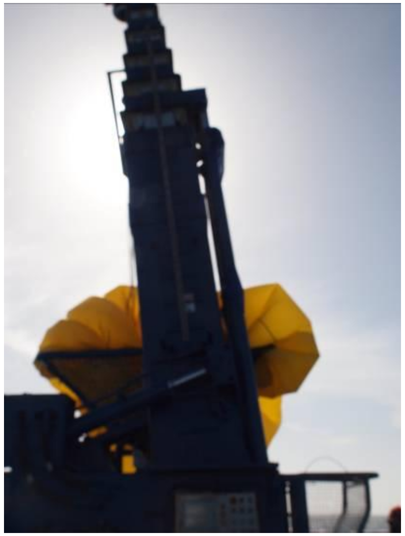
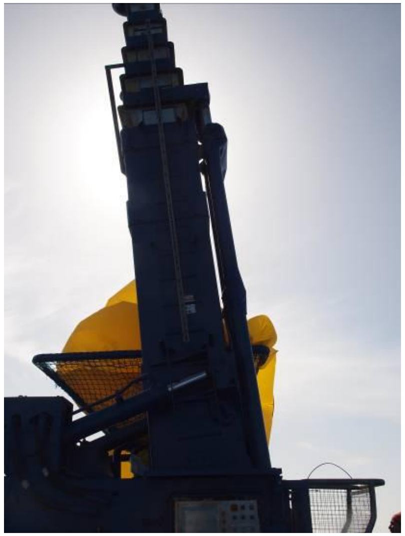
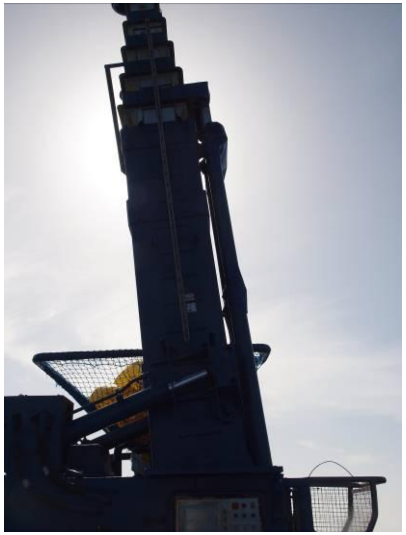
System Overview



Kite – Reefing

Machine Supported Ground Handling

SkySails POWER


Production and Installation

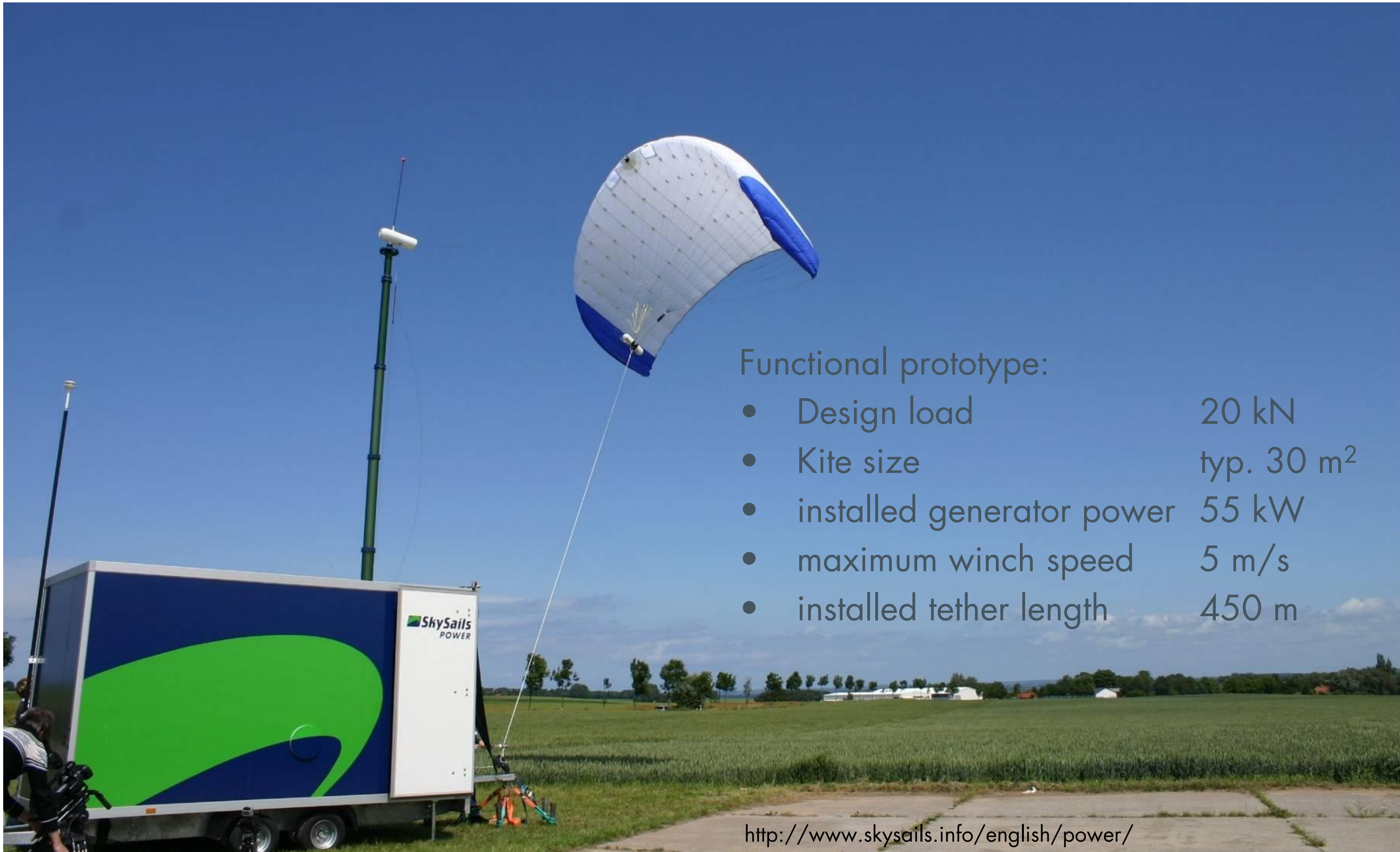
Impressions

(Marine Video)

See http://youtu.be/ckyHeizCAdk

SKYSAILS POWER Development

SkySails POWER



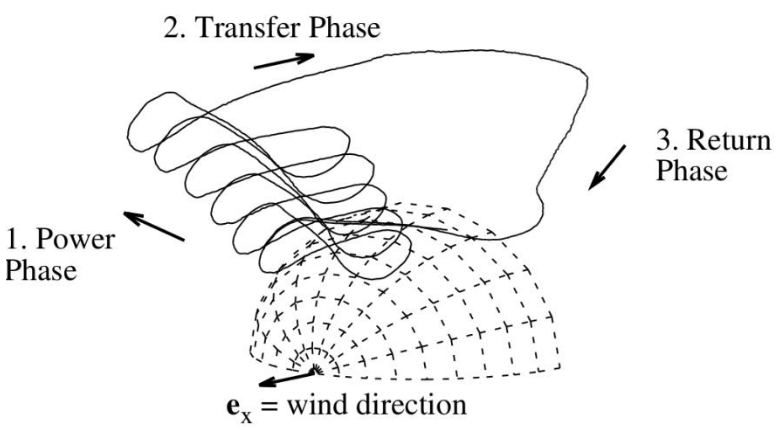
Functional prototype:

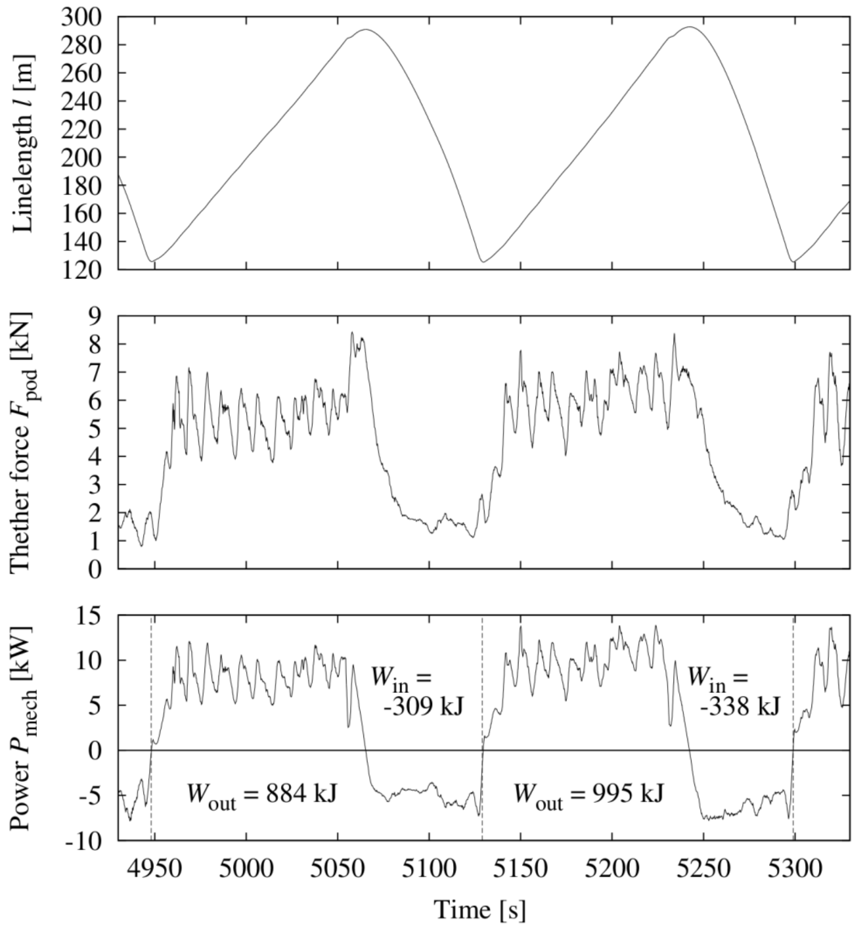
- Design load 20 kN
- Kite size typ. 30 m^2
- installed generator power 55 kW
- maximum winch speed 5 m/s
- installed tether length 450 m

http://www.skysails.info/english/power/

SkySails Power

- Pumping Cycle





M. Erhard, H. Strauch,
Flight control of tehered kites in autonomous pumping cycles for airborne wind energy,
to appear in Control Engineering Practice (2015)

SkySails Power

Economic energy generation ➔ Fully automated AWE plants

➔ Reliability of control system crucial

Impressions

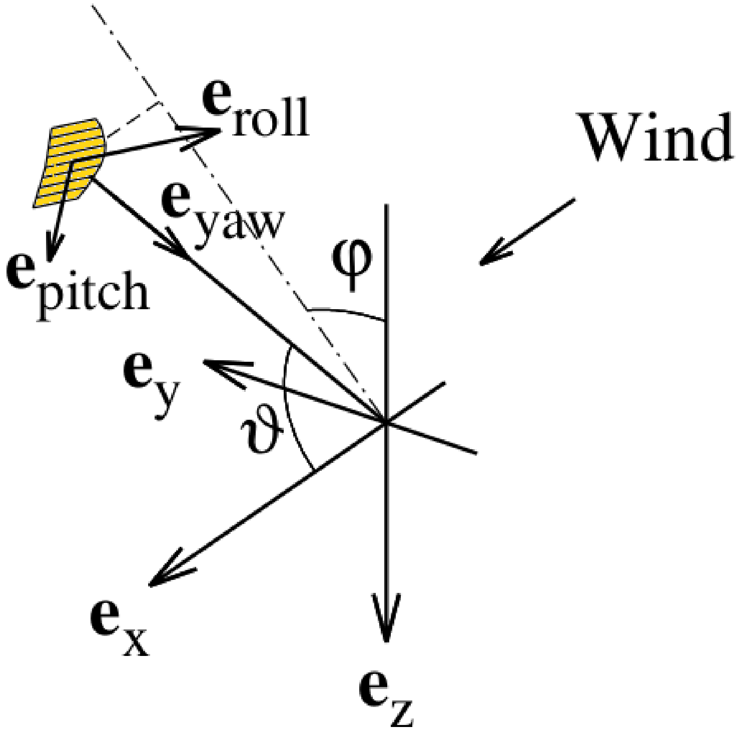
(Power Video)

Simple Model

Simple Model

Coordinate System

- Position φ, ϑ, l
- Orientation ψ

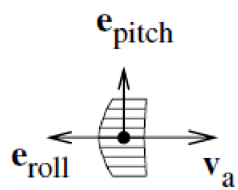


Simple Model

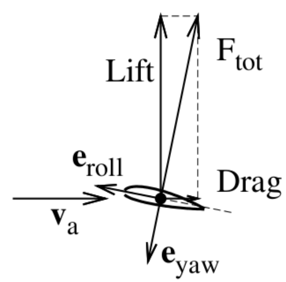
Model Assumptions

1.) Forces huge compared to masses ➔ Neglect Accelerations & Masses

2.) Airflow in Roll Direction



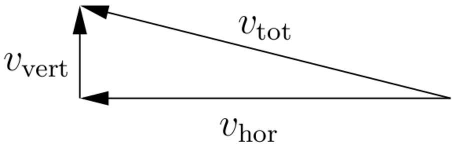
3.) Glide Ratio Condition



Side View

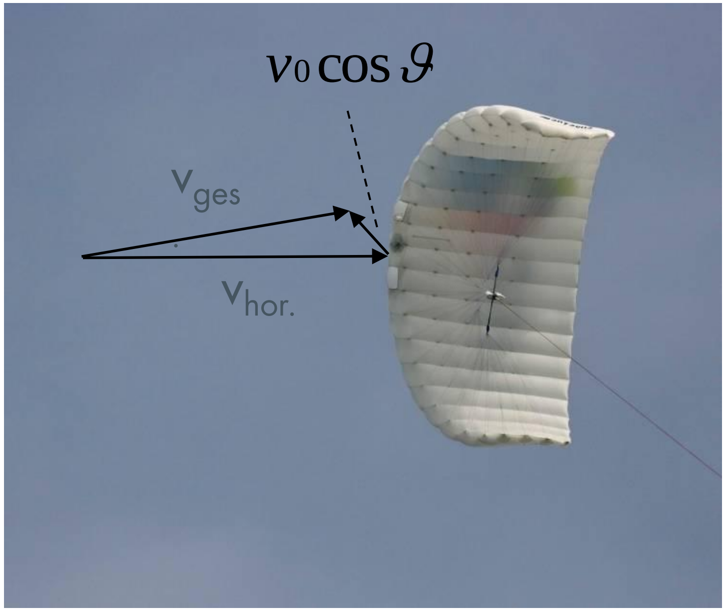
Aerodynamics of Tethered Kites

Paraglider (Free flight) : $v_{tot} = 10m/s$



$$E = \frac{v_{hor}}{v_{vert}}$$

Tethered Kite:



$v_{tot} = 1..E\, v_0$

$F_{tot} = 1..E^2\, F_0$

Wind $v_0 = 10m/s$ with E=5 yields

$v_{tot} = 10..50m/s$!

Simple Model

- Equations of motion for φ, ϑ and l (3d kite position)

$$
\begin{aligned}
\dot{\vartheta} &= \frac{v_a}{l}\left(\cos\psi - \frac{\tan\vartheta}{E}\right) - \frac{\dot{l}}{l}\tan\vartheta \\
\dot{\varphi} &= -\frac{v_a}{l\sin\vartheta}\sin\psi \\
\dot{l} &= v_{\text{winch}}
\end{aligned}
$$

- orientation ψ
- winch speed v_{winch}

$$v_a = v_w E\cos\vartheta - \dot{l}E$$

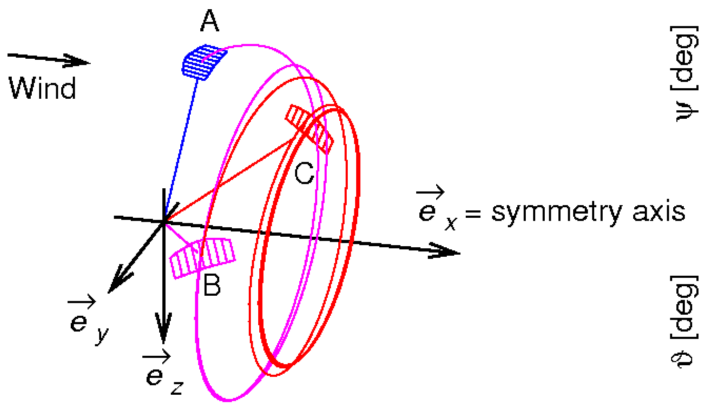
Parameters

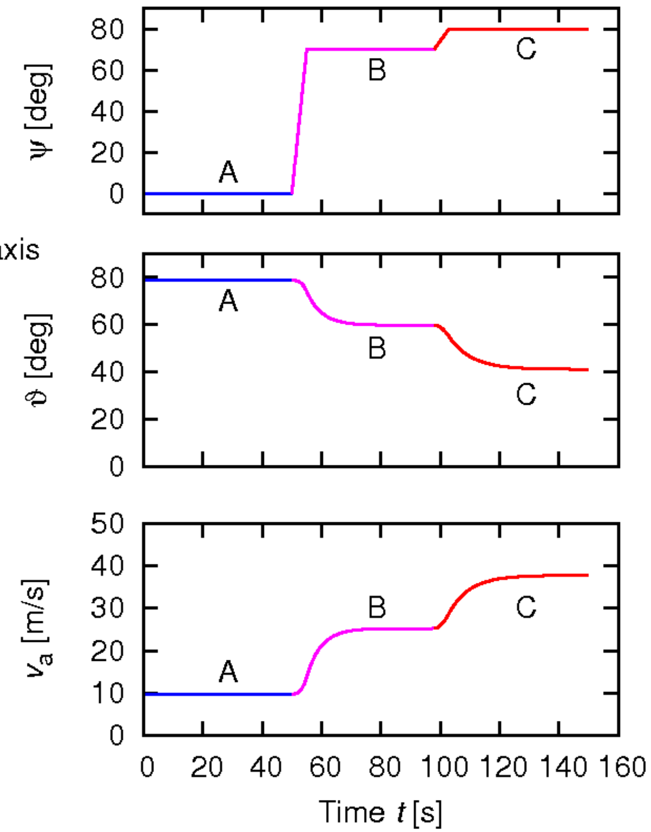
- glide ratio
- wind speed

Kinematic Equations of Motion

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

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





Model of Tethered Kites

Angle ψ is the central control variable:

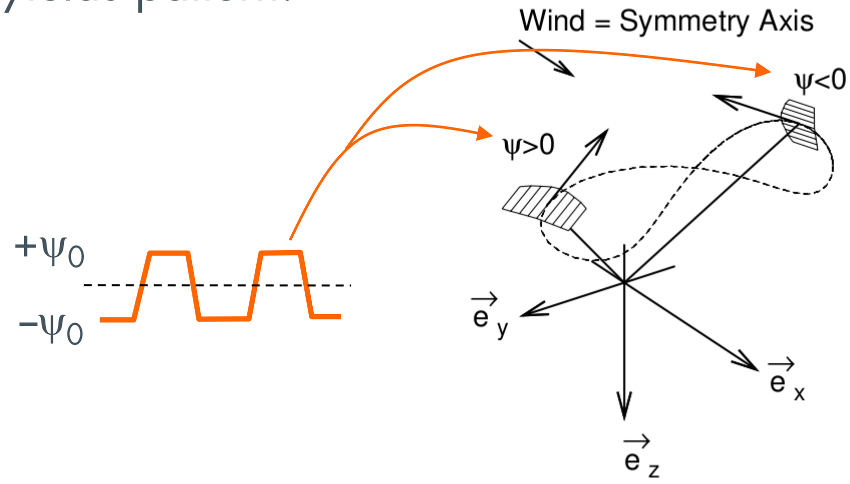
- Determines force $\vartheta_0(\psi) = \arctan(E \cos \psi)$

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

- Keep static zenith position (φ=const)

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

Periodic signal on ψ yields pattern:

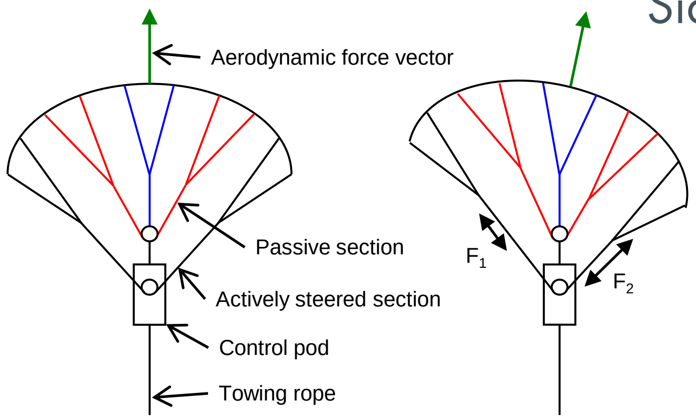


Control of Orientation ψ

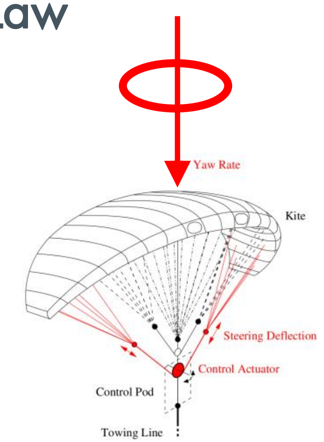
Steering

Steering by means of canopy (and force vector) rotation

Side Force



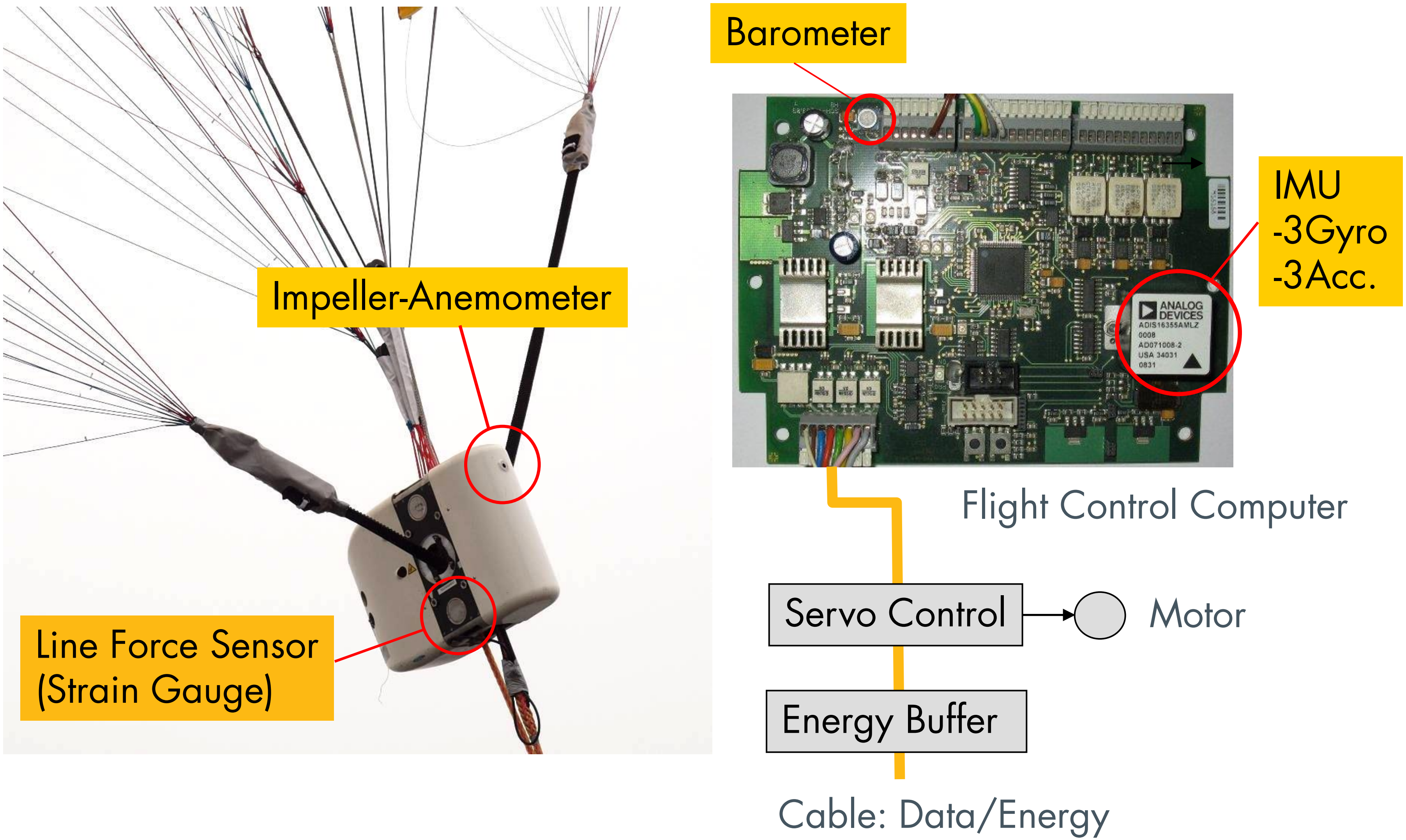
Turn Rate Law



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

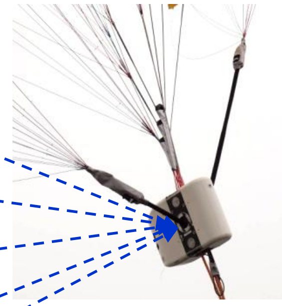
Sensors and Navigation

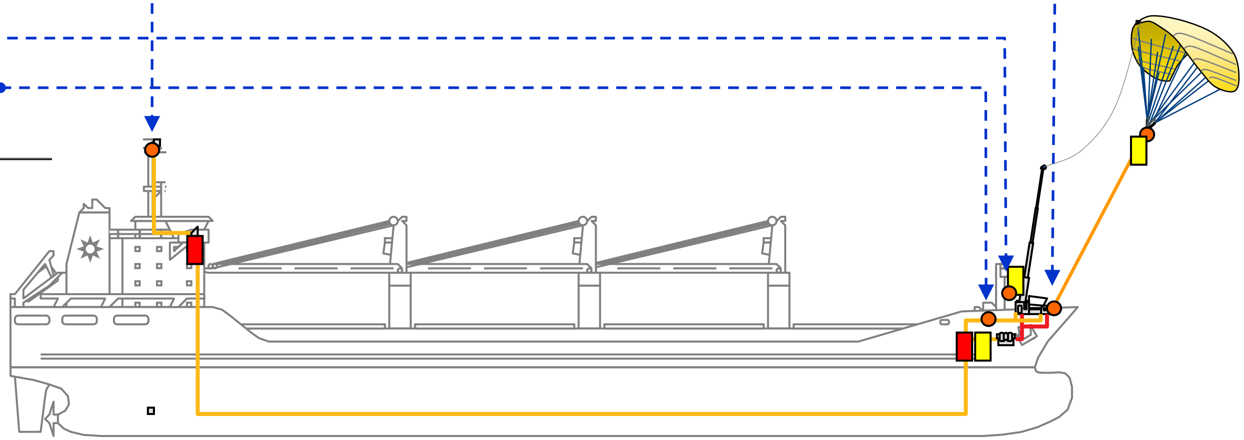
Control Pod Sensors



Sensor Overview

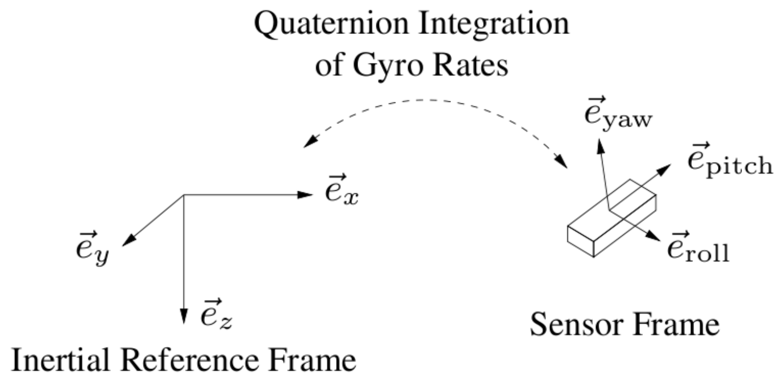
Sensor	Quantity
Inertial Measurement Unit (IMU)	$\vec{\omega}_{\mathrm{s}}$
	$\vec{a}_{\mathrm{s}}$
Impeller Anemometer	v_{a}
Strain Gauge Pod	F
Barometer	h
Tow Point	$\phi_{\mathrm{s}}, \theta_{\mathrm{s}}$
Ship Anemometer	$v_{\mathrm{w}}, \phi_{\mathrm{w}}$
Ship IMU	
Line length	L



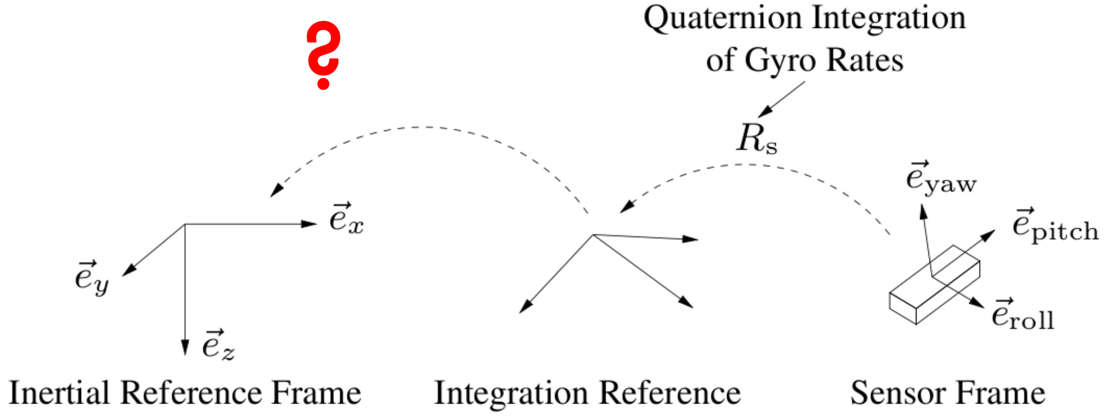


Inertial Navigation

- Quaternion integration…

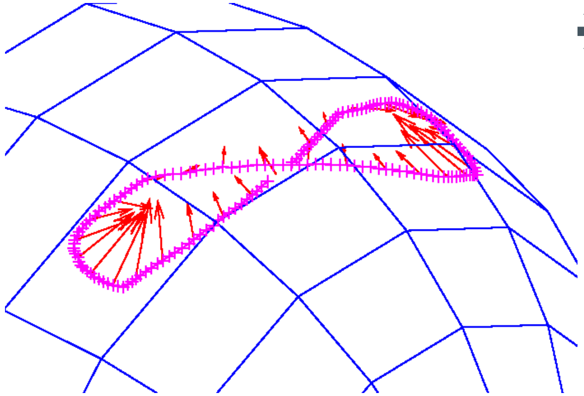


- Problem: drift of turn rate sensors

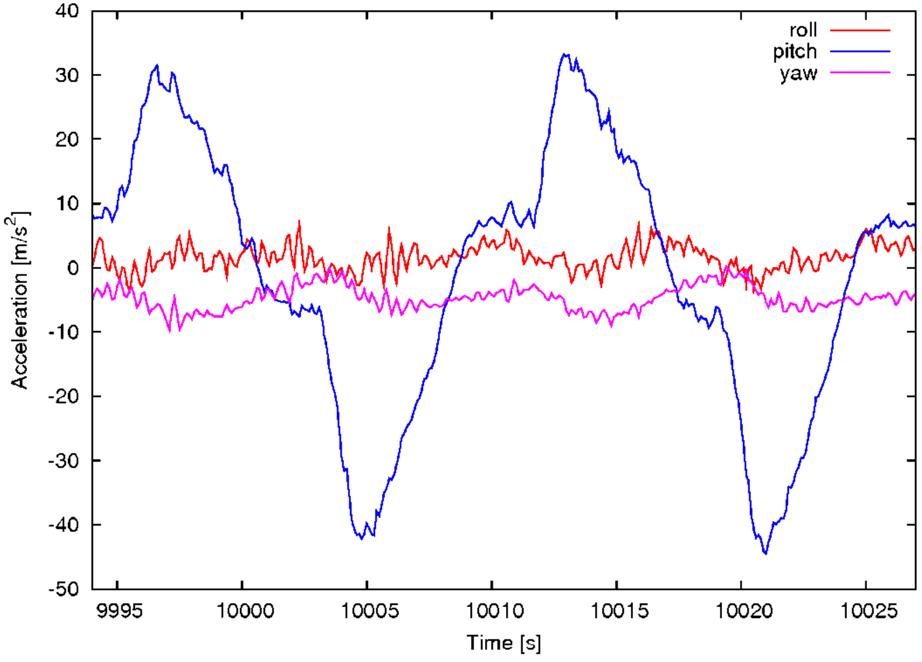


Inertial Navigation

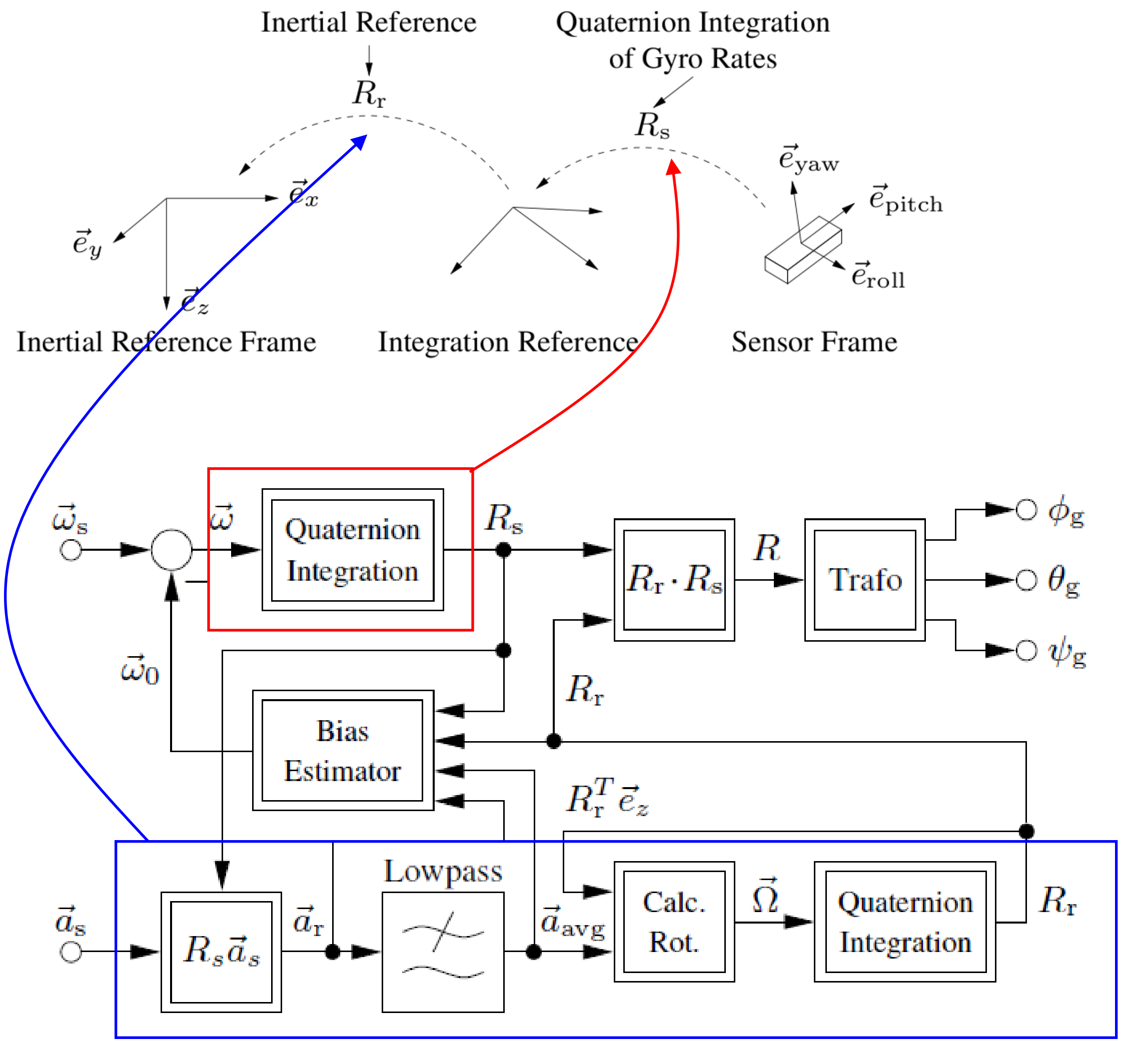
Reference to ‚Down'-Direction



➔Average Accelerations $\langle \vec{a}_s \rangle \approx -|g|\,\vec{e}_z$

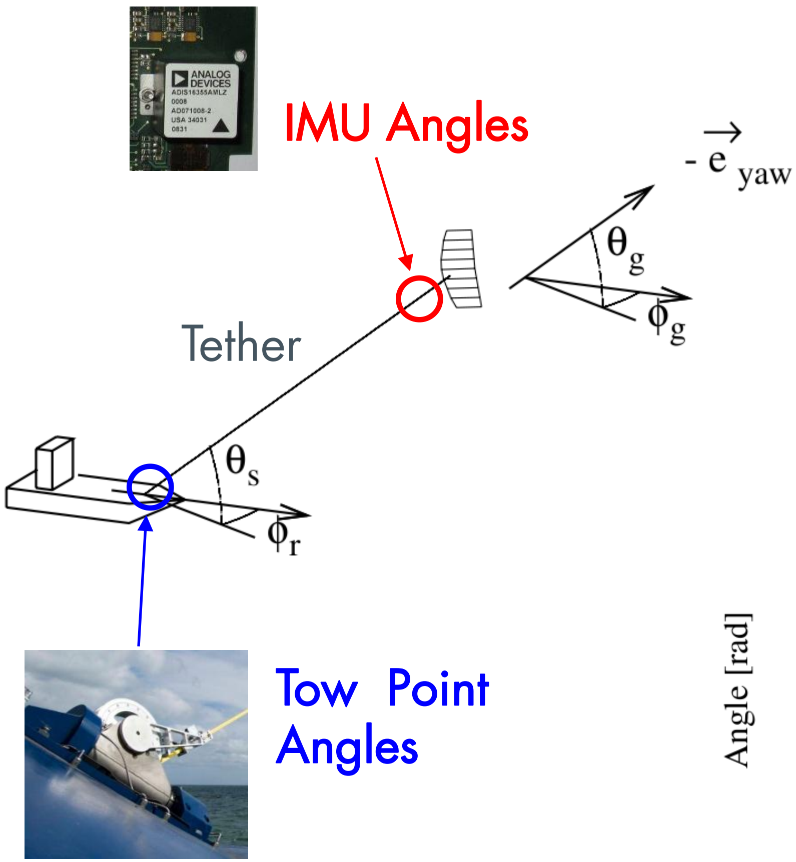


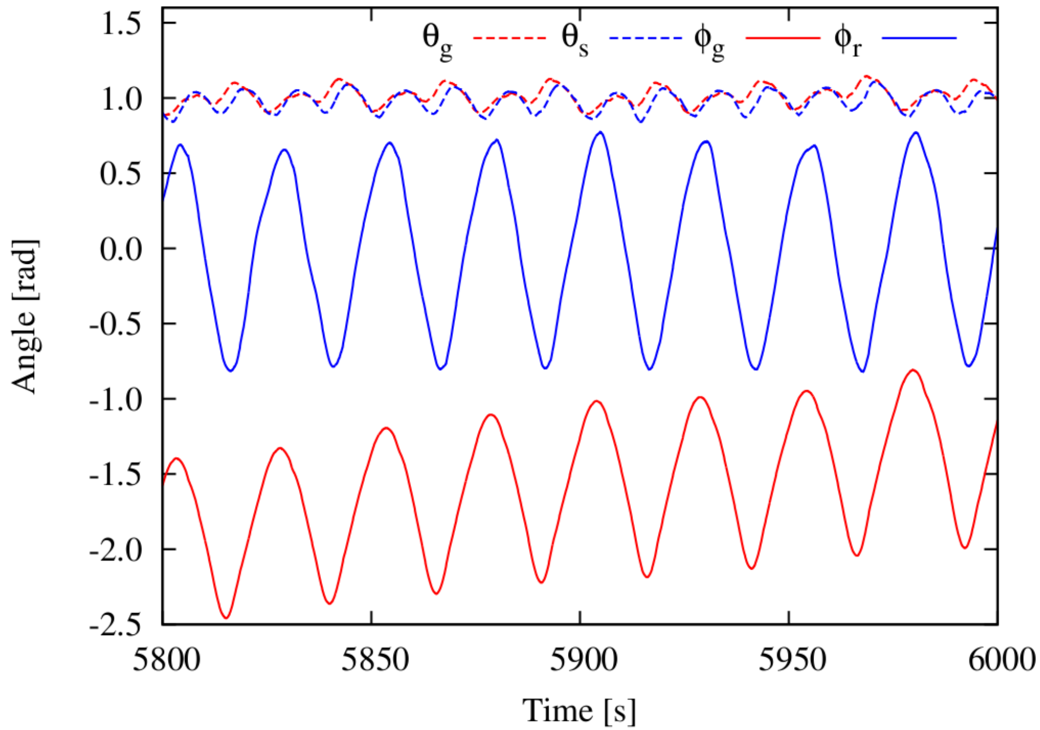
Yaw Angle Estimator



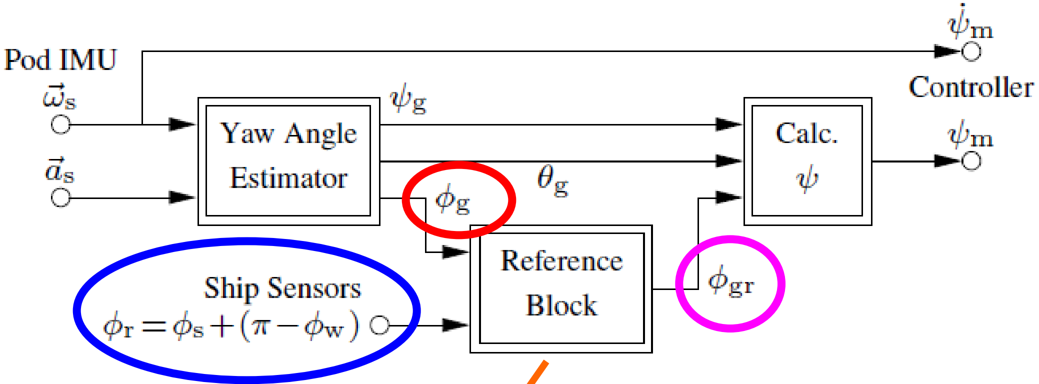
M. Erhard, H. Strauch, *Sensors and Navigation Algorithms for Flight Control of Tethered Kites*, Proc. European Control Conf., 2013

Experimental Results



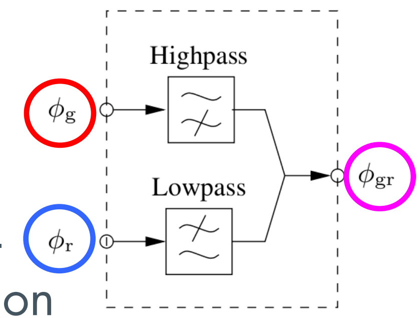


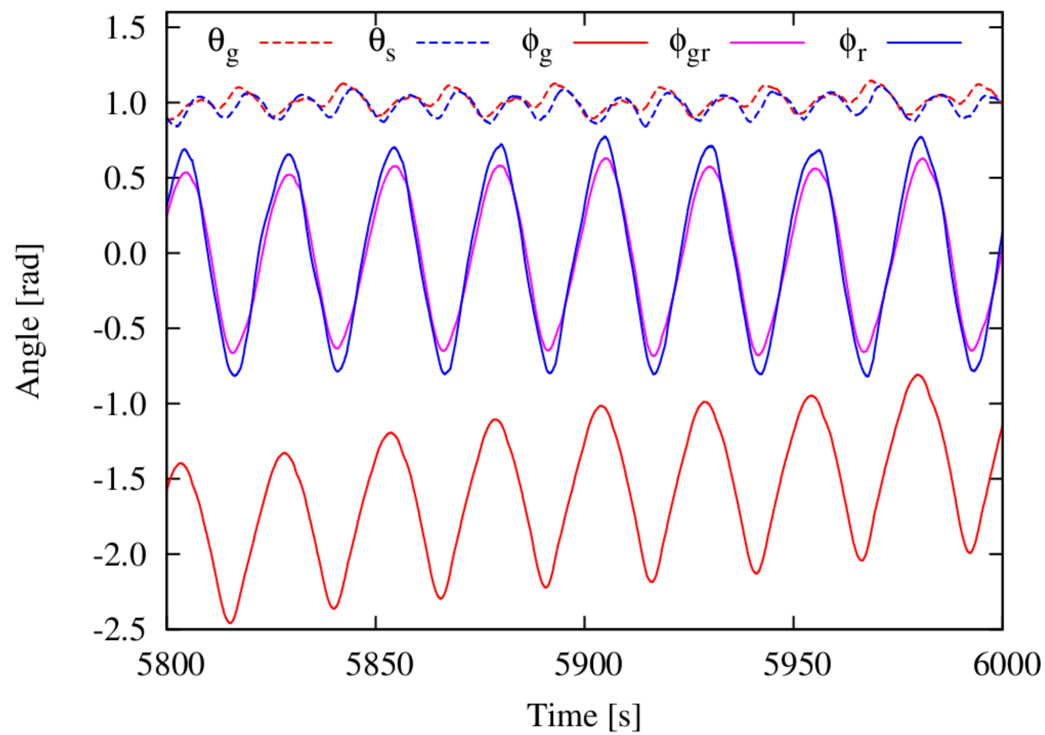
Wind Referencing



IMU

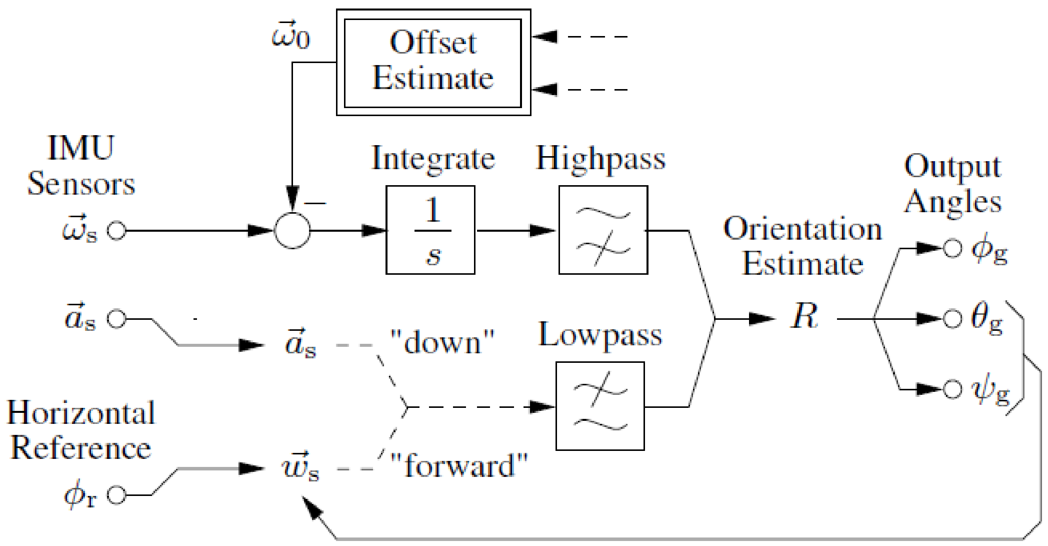
Wind-direction





Merging of Algorithms

Complementary Filter



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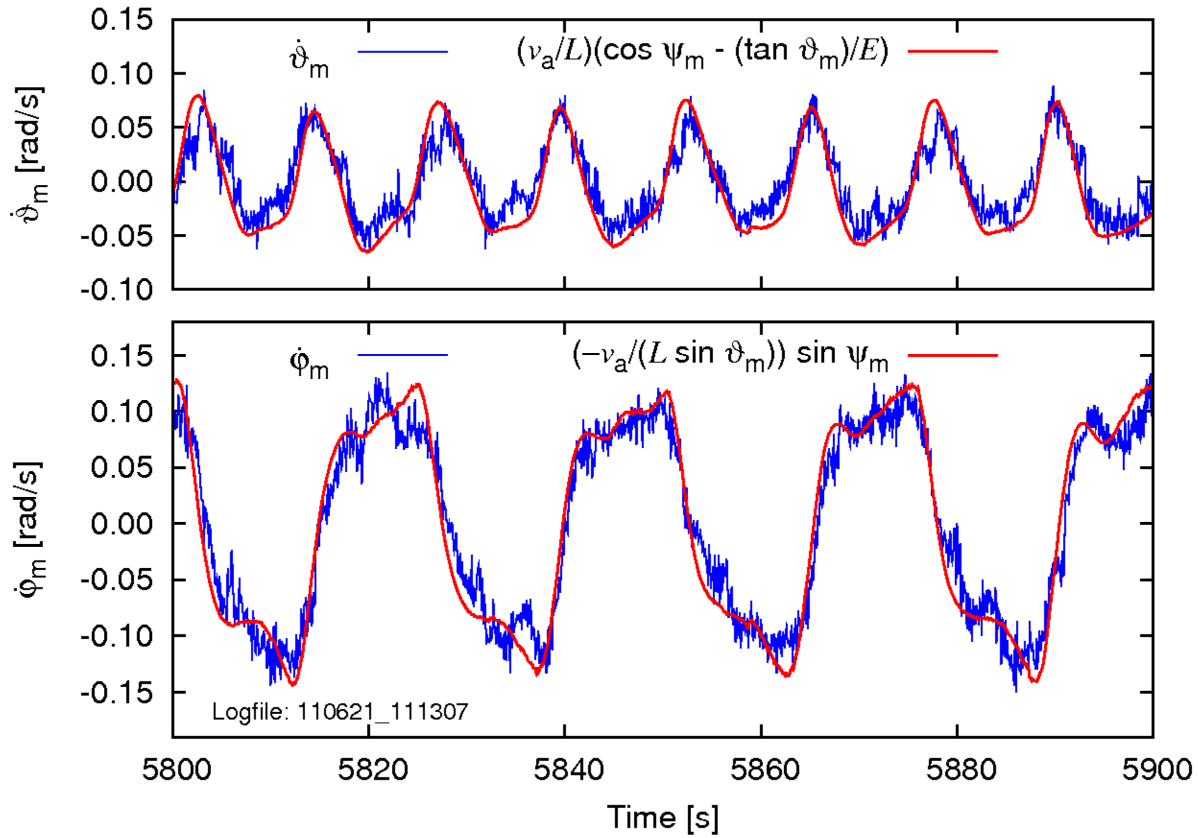
Validation of kinematics

Validation of Kinematics

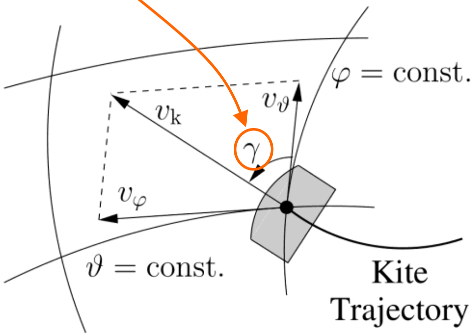


$$\dot{\vartheta} = \frac{v_a}{l}\left(\cos\psi - \frac{\tan\vartheta}{E}\right)$$

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

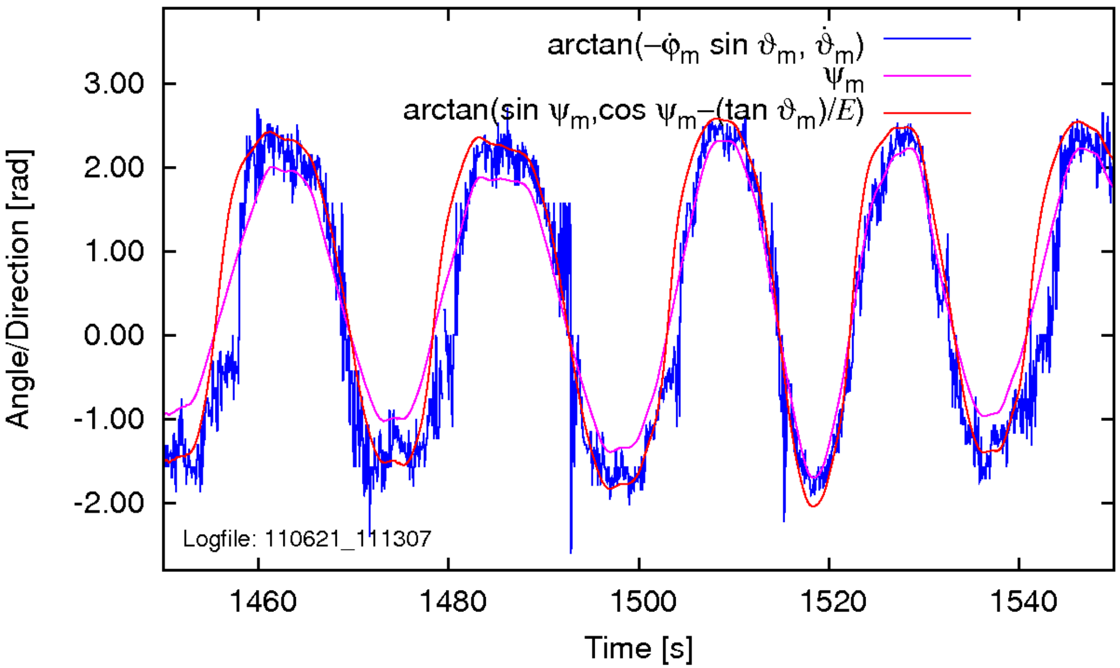
Validation of Kinematics

Flight Direction



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

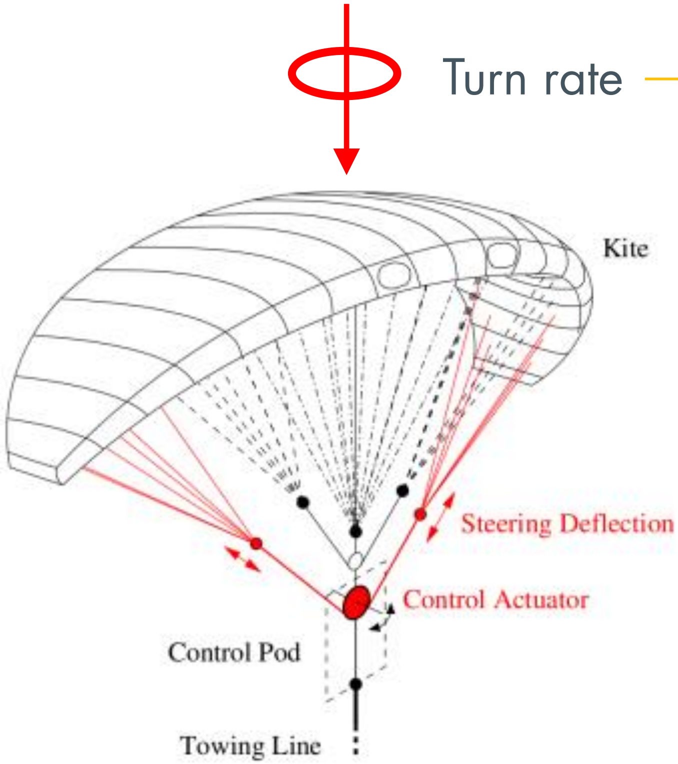
$$= \arctan\left(\sin\psi, \cos\psi - \frac{\tan\vartheta}{E}\right)$$



Validation of Turn Rate Law

Turn Rate Law

SkySails POWER



Turn rate

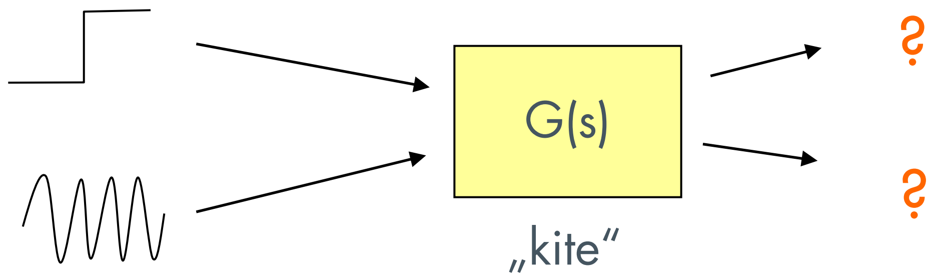
Parameter

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

Air path speed

Steering deflection

System Identification



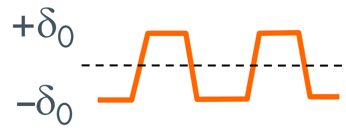
Challenges:

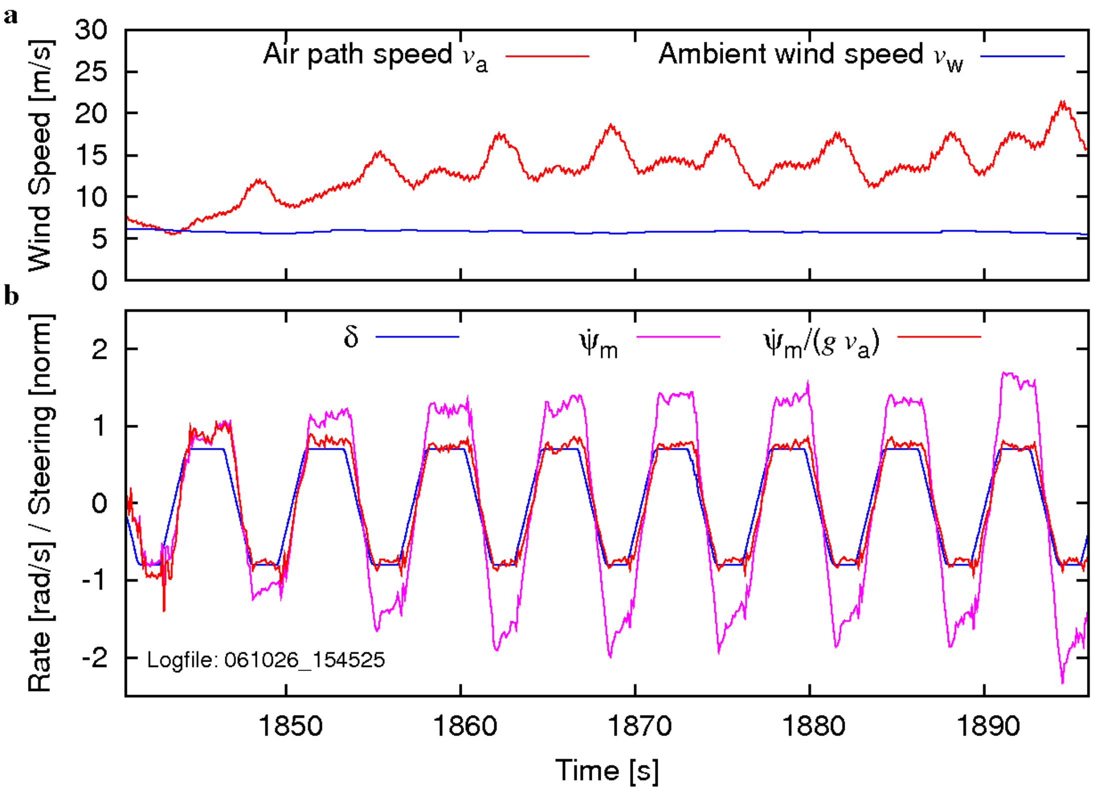
- How to fly open loop and not crash ?
- Flight pattern ?
- Operational point ? (Flight speed, wind window position, …)

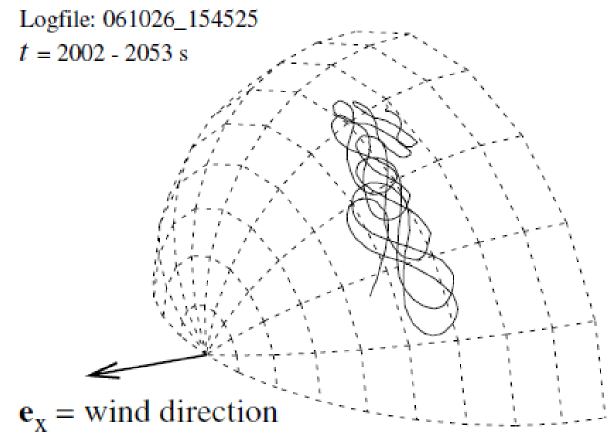
System Identification

Test Turn Rate Law?

Bang-Bang-Experiment





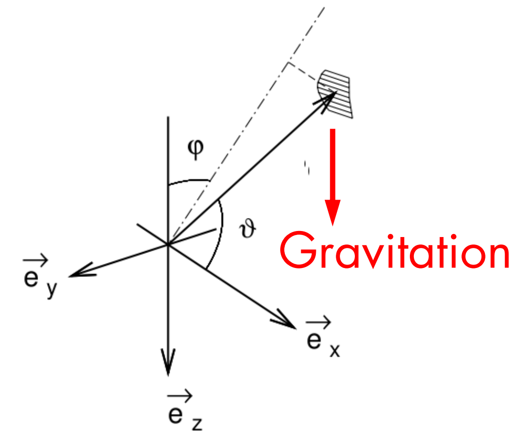


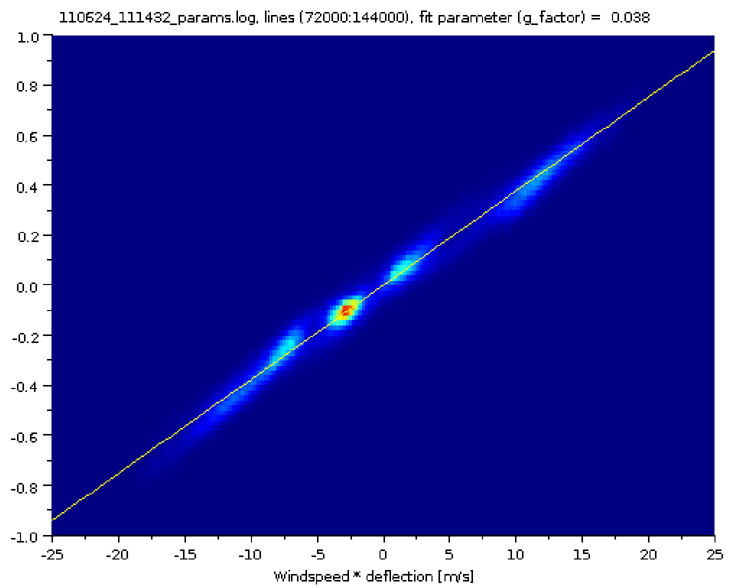
$$\dot{\psi}_{\mathrm{m}} = g_{\mathrm{k}}\, v_{\mathrm{a}}\, \delta$$

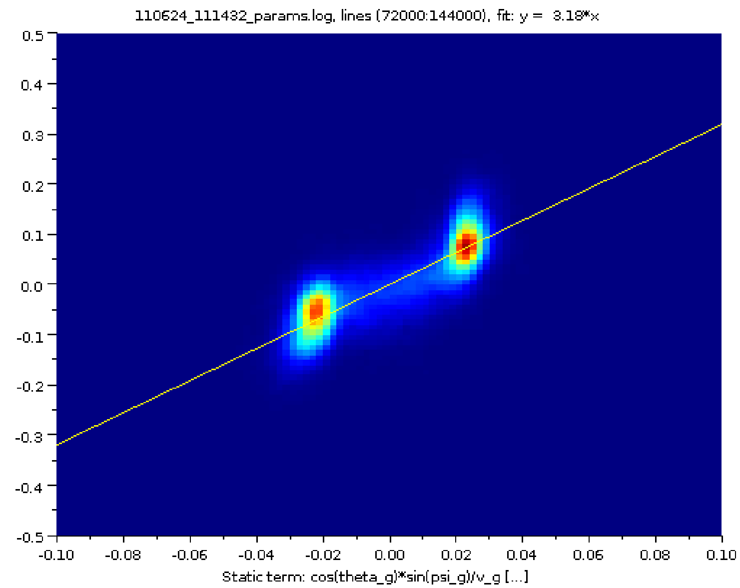
Extended Turn Rate Law

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

2 Fit Parameter







Online Parameter Estimation

Weighted least-square

$$\hat{\theta}_t = \arg\min_{\theta} \sum_{k=1}^{t} \beta(t,k)\left[y(k) - \varphi^T(k)\theta\right]^2$$

$$\hat{\theta}_t = \bar{R}^{-1}(t) f(t)$$

$$\bar{R}(t) = \sum_{k=1}^{t} \beta(t,k)\varphi(k)\varphi^T(k)$$

$$f(t) = \sum_{k=1}^{t} \beta(t,k)\varphi(k)y(k)$$

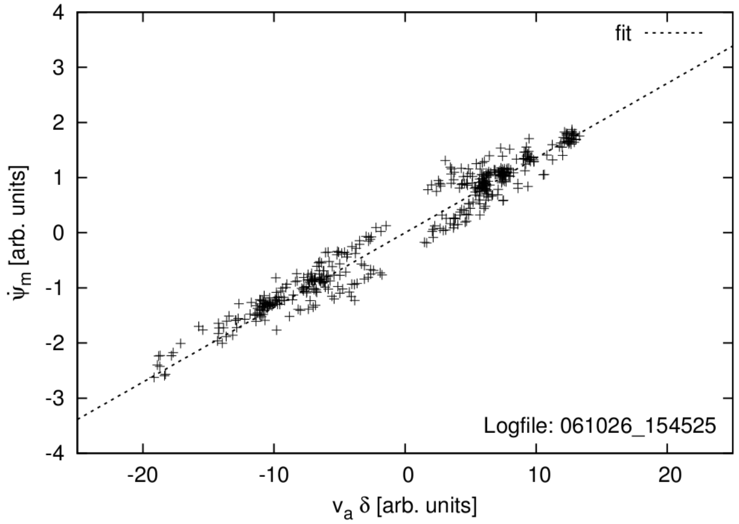
See e.g.:
Ljung, *System identification*

Example: turn rate law

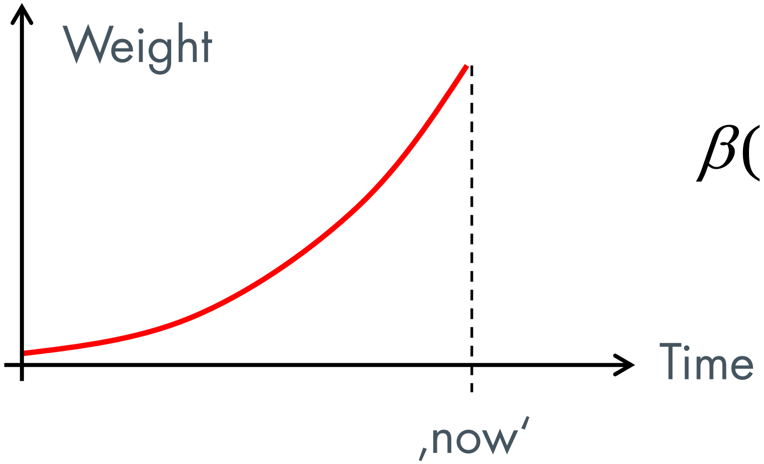
$$\dot{\psi}_{\mathrm{m}} = g_{\dot{\psi}}\, v_{\mathrm{a}}\delta$$

$y(k)$ $\hat{\theta}_t$ $\varphi(k)$

result



Online Parameter Estimation



$$\beta(t,k) = e^{-\gamma(t-k)} = \lambda^{(t-k)}$$

Recursive algorithm:

$$\hat{\theta}_t = \overline{R}^{-1}(t) f(t)$$

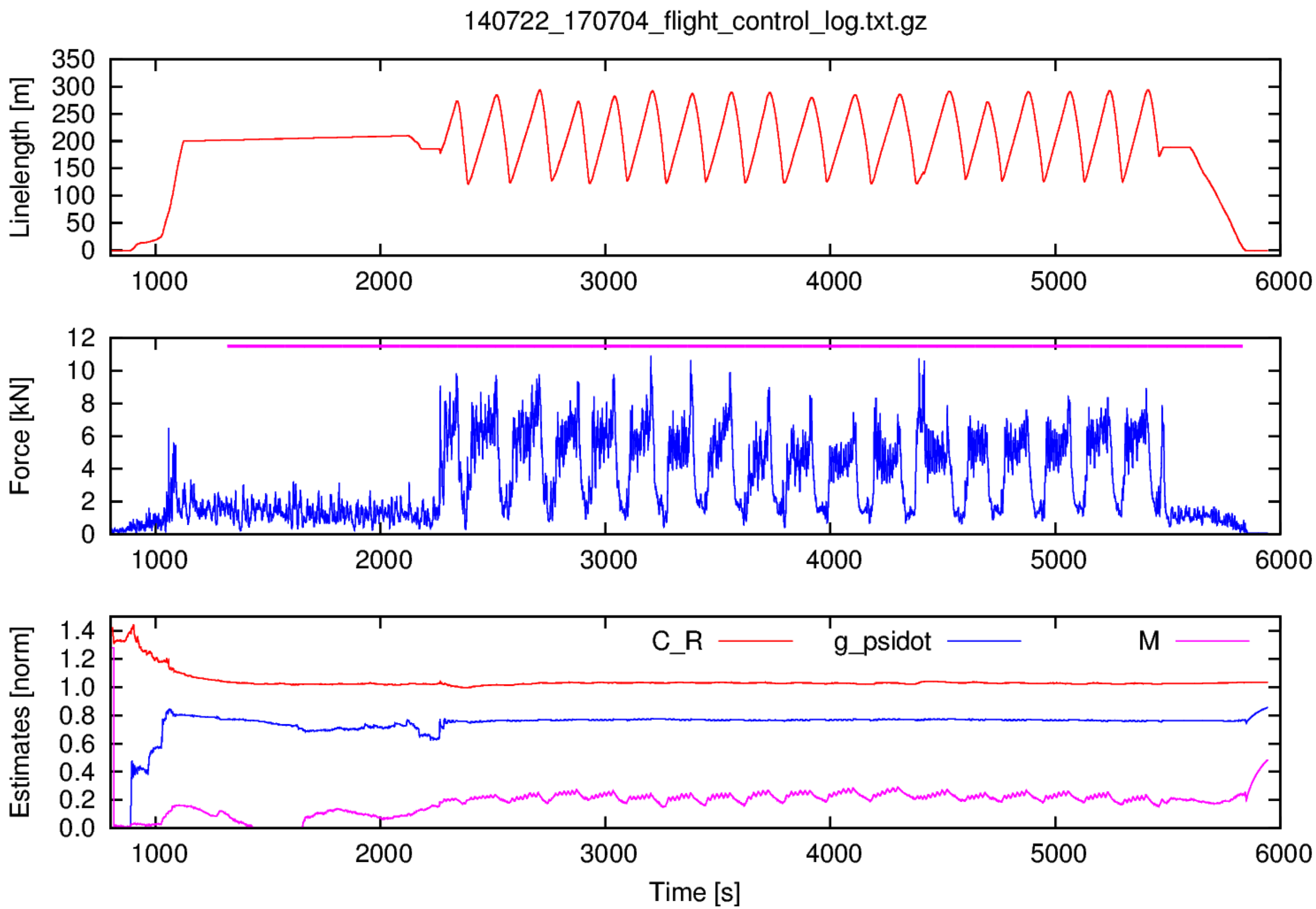
$$\overline{R}(t) = \lambda \overline{R}(t-1) + \varphi(t)\varphi^T(t)$$

$$f(t) = \lambda f(t-1) + \varphi(t) y(t)$$

Applications:

- ➢ System monitoring (degrading, damage, …)
- ➢ Adaption of controller

Online Parameter Estimation

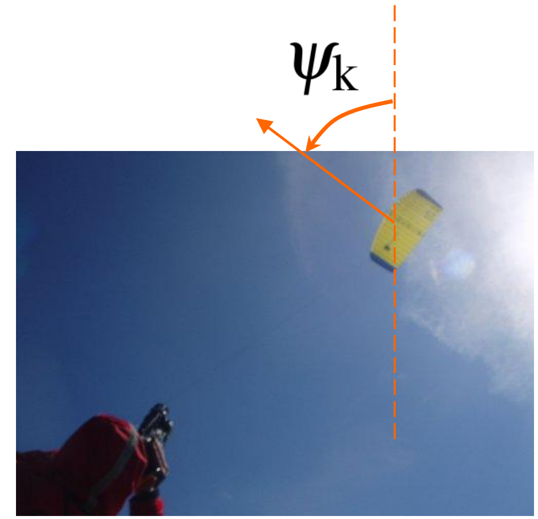


Control System

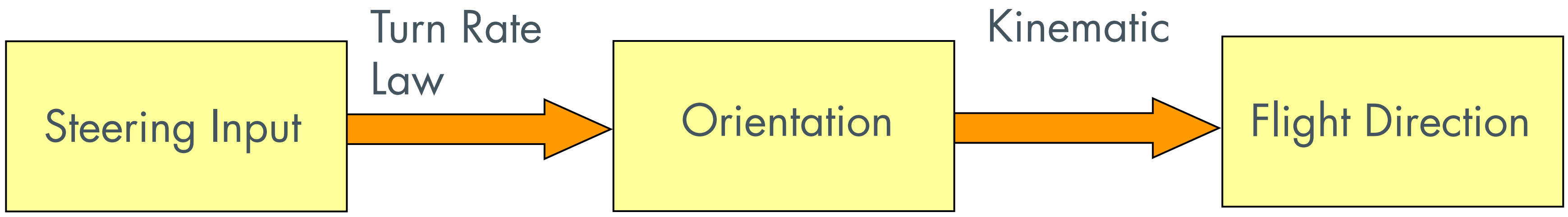
Flight control

Human Control Strategy?

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

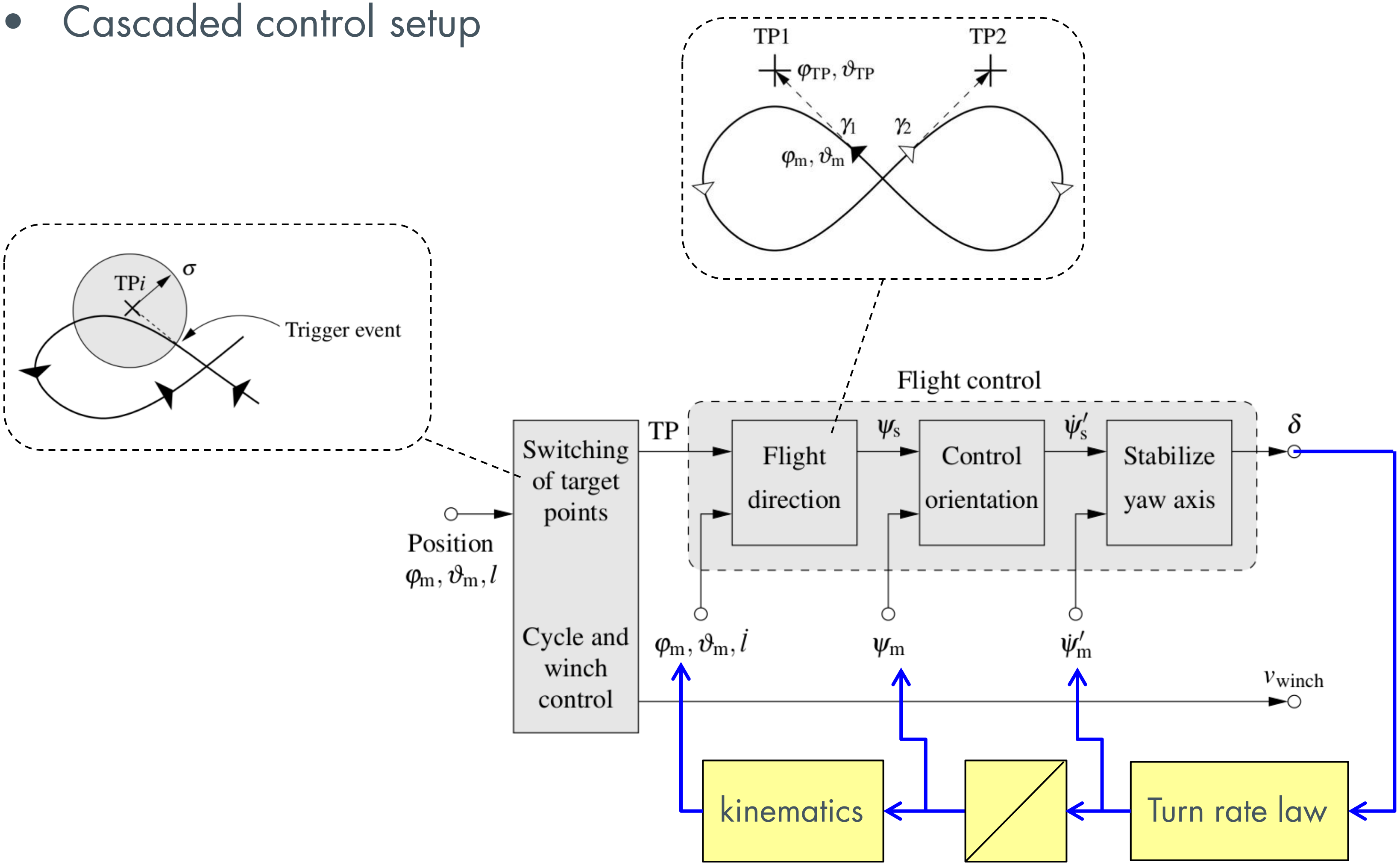


Controlled System (Plant)



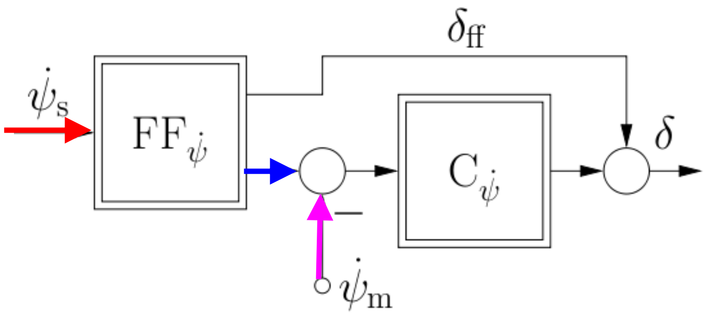
Control System

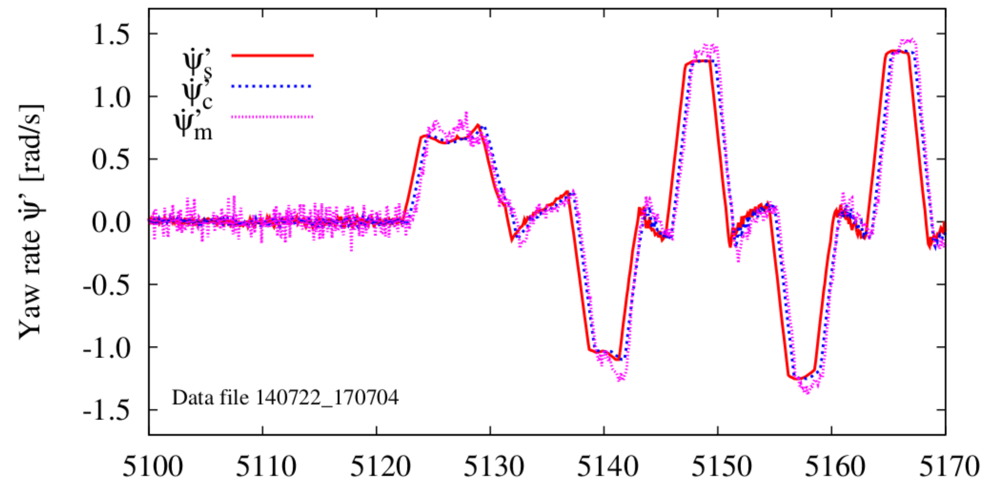
- Cascaded control setup

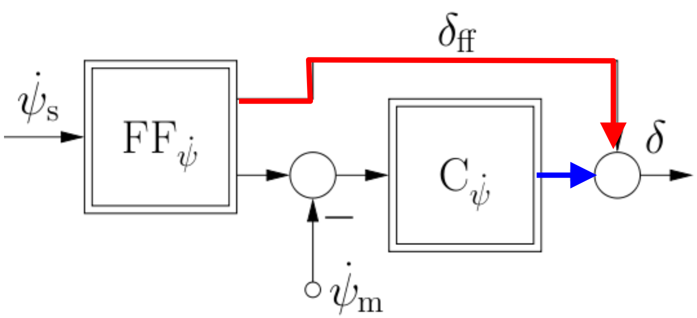


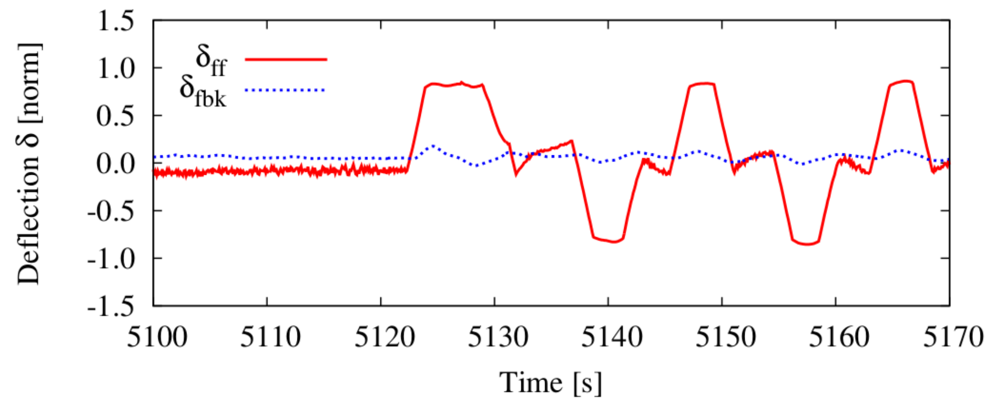
Controller Performance

Turn rate control loop









(FBK << FF) ➔ ‚Indirect' system identification

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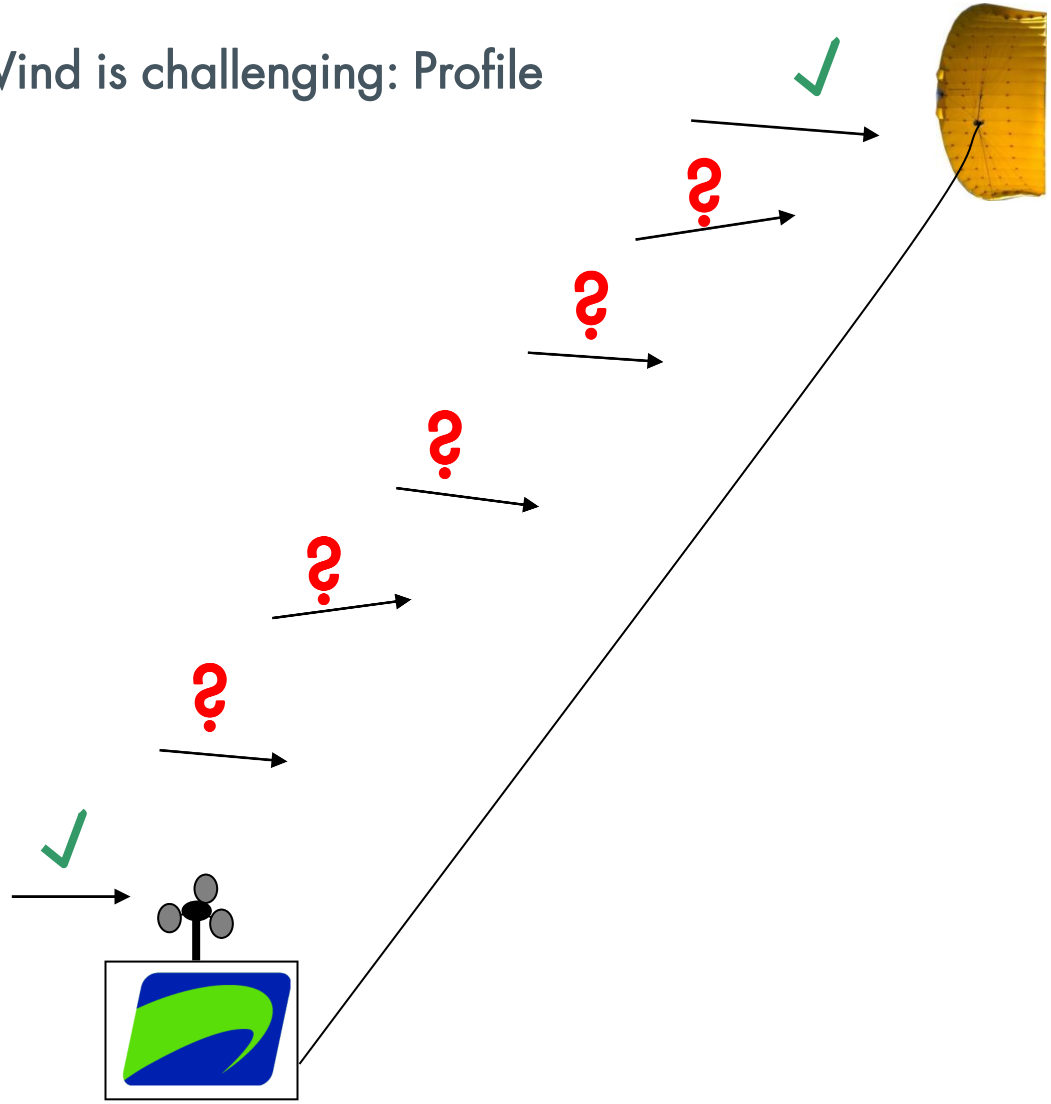
Limits and challenges

Challenges and limits

Wind is challenging: Profile



How to model the wind field?

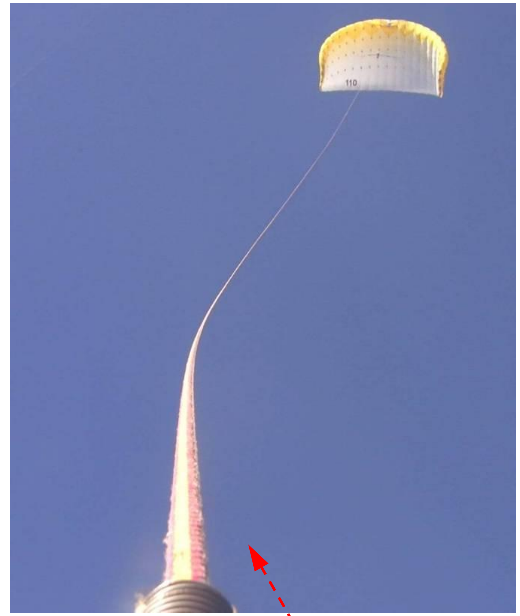
→ Profile?

→ Boundary layer?

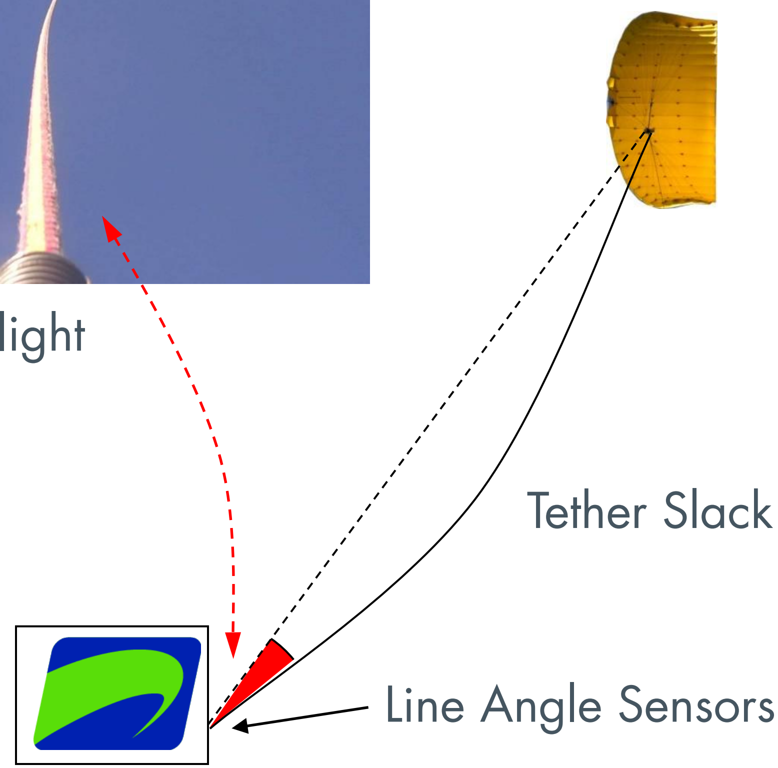
→ ...

Challenges and limits

Soft Materials



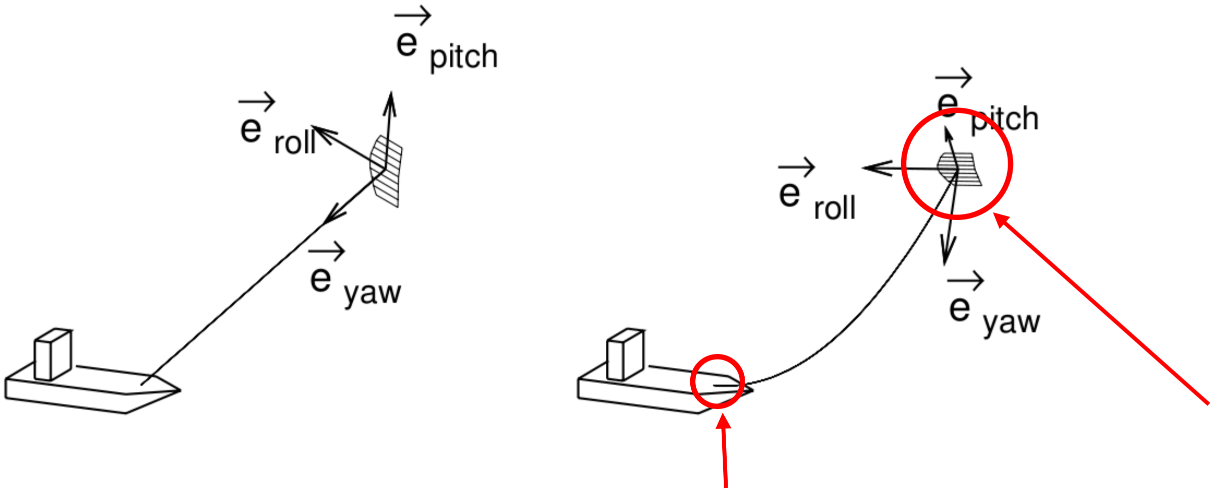
Free Flight



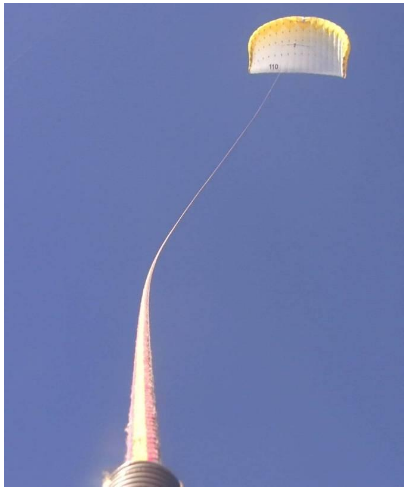
- ➔ Modelling Accuracy is limited
- ➔ Limited Sensor `Accuracy´

Free flight

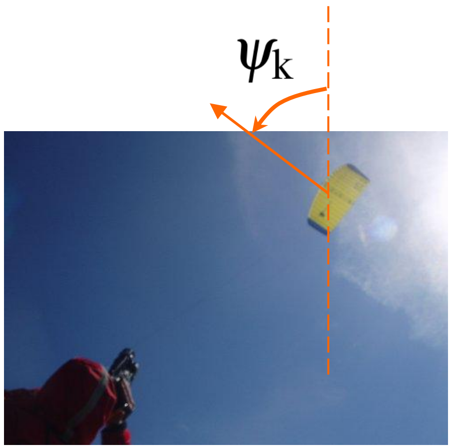
Due to gusts or wave induced motion: temporarily **untethered** system



Angle w.r.t. Horizon
`undefined´



Line Angle
Sensor



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Thank you for your Attention!

Questions?