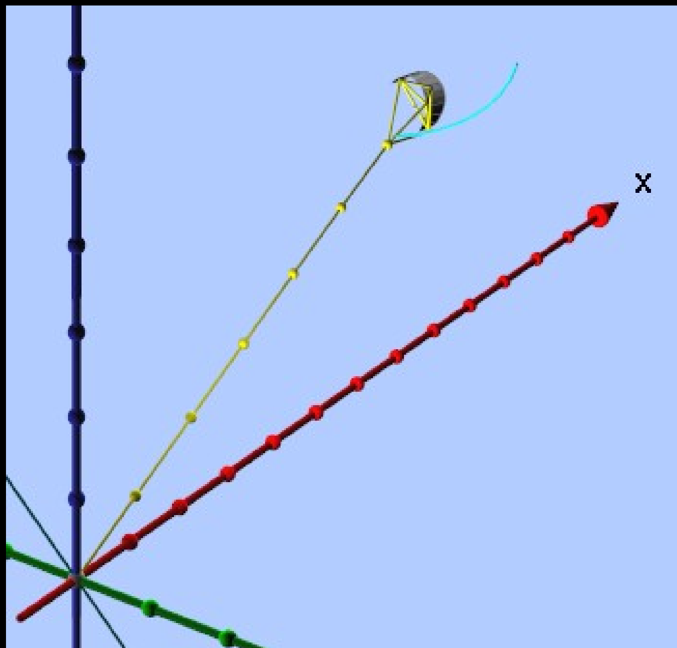

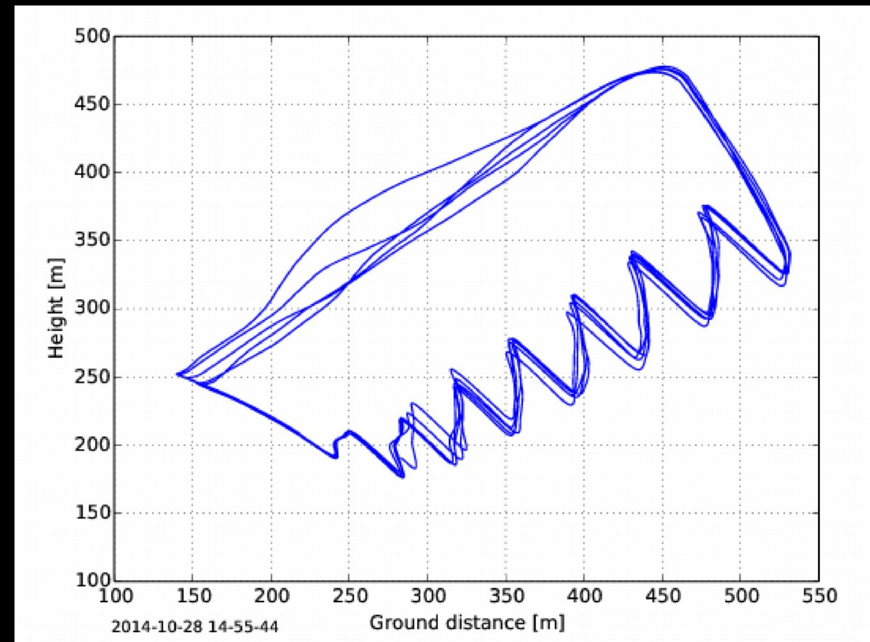

Flight Path Planning in a Turbulent Wind Environment

Airborne Wind Energy Conference 2015, June 15-16, Delft, The Netherlands

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TU Delft

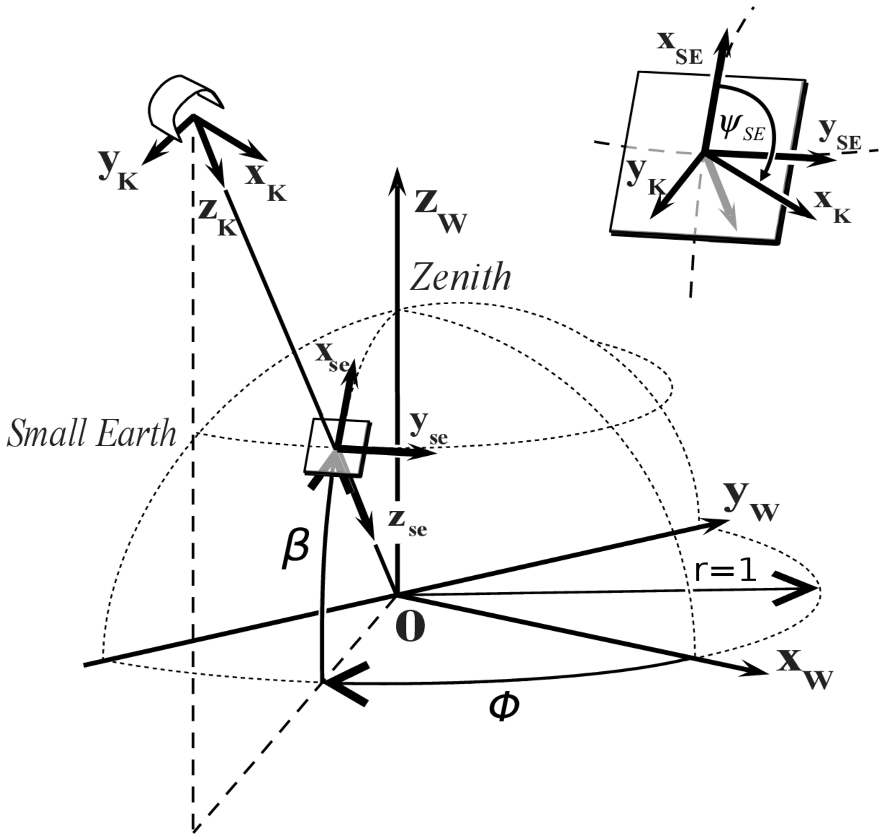
Outline

Flight Path Planning in a Turbulent Wind Environment

- *Background: Small earth reference frame*
- *Wind Environment*
  - Onshore location Cabau, The Netherlands
  - Wind speed distribution
  - Vertical wind profile
  - Turbulence intensity
- *Flight path planner*
  - Design goals
  - Implementation
  - Parameters
- *Simulation Results*
  - Nominal wind speed
  - High wind speed
- *Summary and Conclusion*

Background

Small Earth Reference Frame



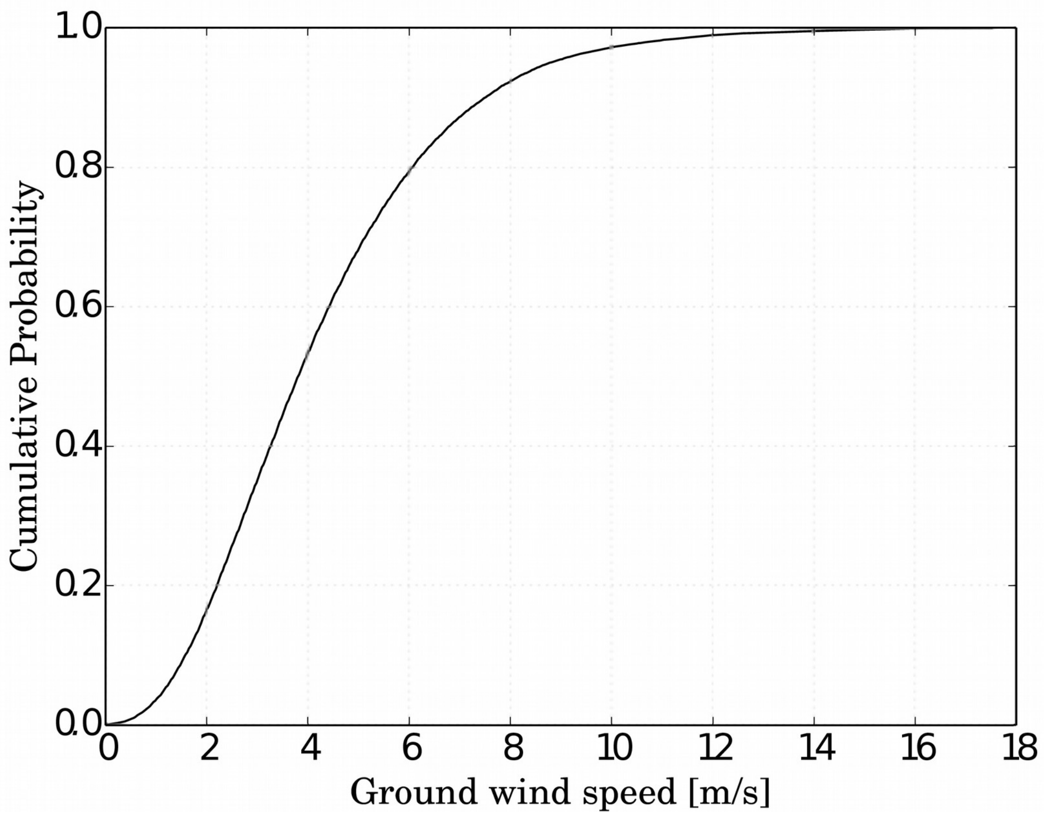
The position of the kite as projected on the unit sphere can be described with two angles: The elevation angle β and the azimuth angle ϕ.

In addition, the heading angle Ψ and the angular speed ω are needed.

$$\omega = \sqrt{\dot{\beta}^2 + \dot{\phi}^2}$$

Wind Environment I

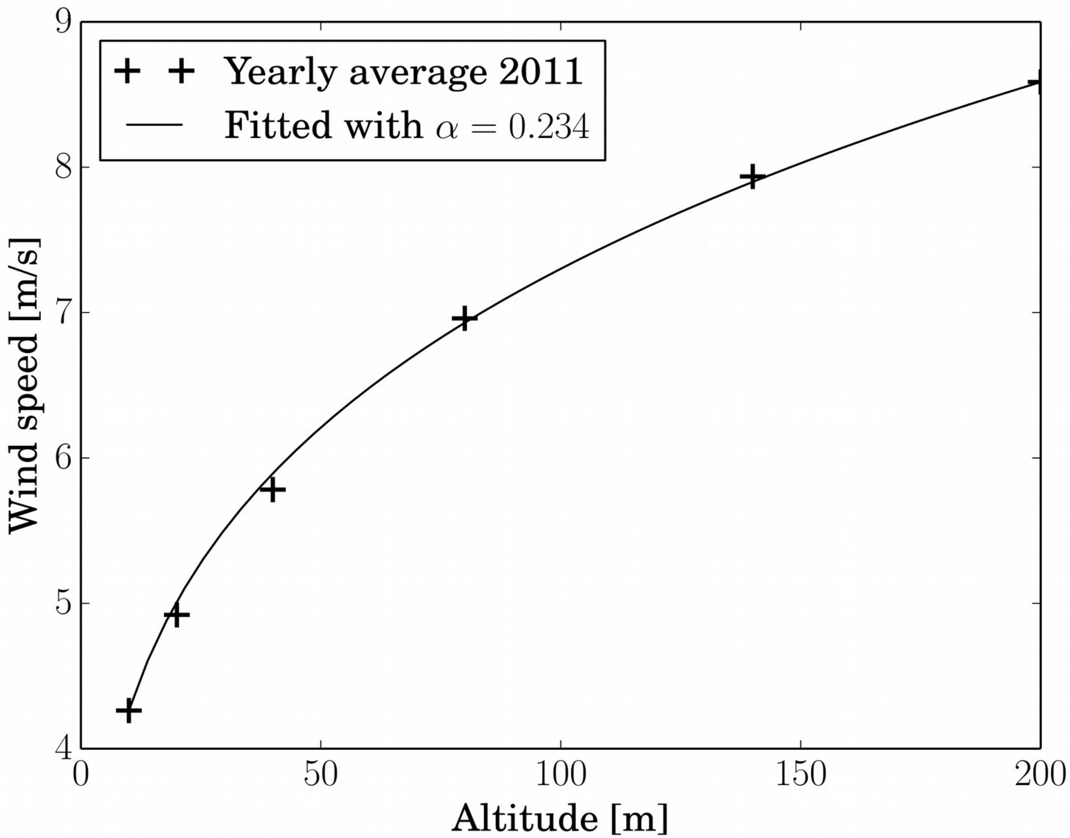
Onshore location Cabauw, The Netherlands



- *Average wind speed:* **4.26 m/s** *at 10 m height;*
- *Nominal wind speed, exceeded 20% of the time:* **6 m/s***;*
- *High wind speed, exceeded 4.1% of the time:* **9.2 m/s***.*

Wind Environment II

Onshore location Cabauw, The Netherlands



Average wind speed: **8.56 m/s** *at 197 m height;*

Nominal wind speed, exceeded 20% of the time: **12.1 m/s** *at the same height.*

High wind speed, exceeded 4.1% of the time: **18.5 m/s.**

Wind Environment III

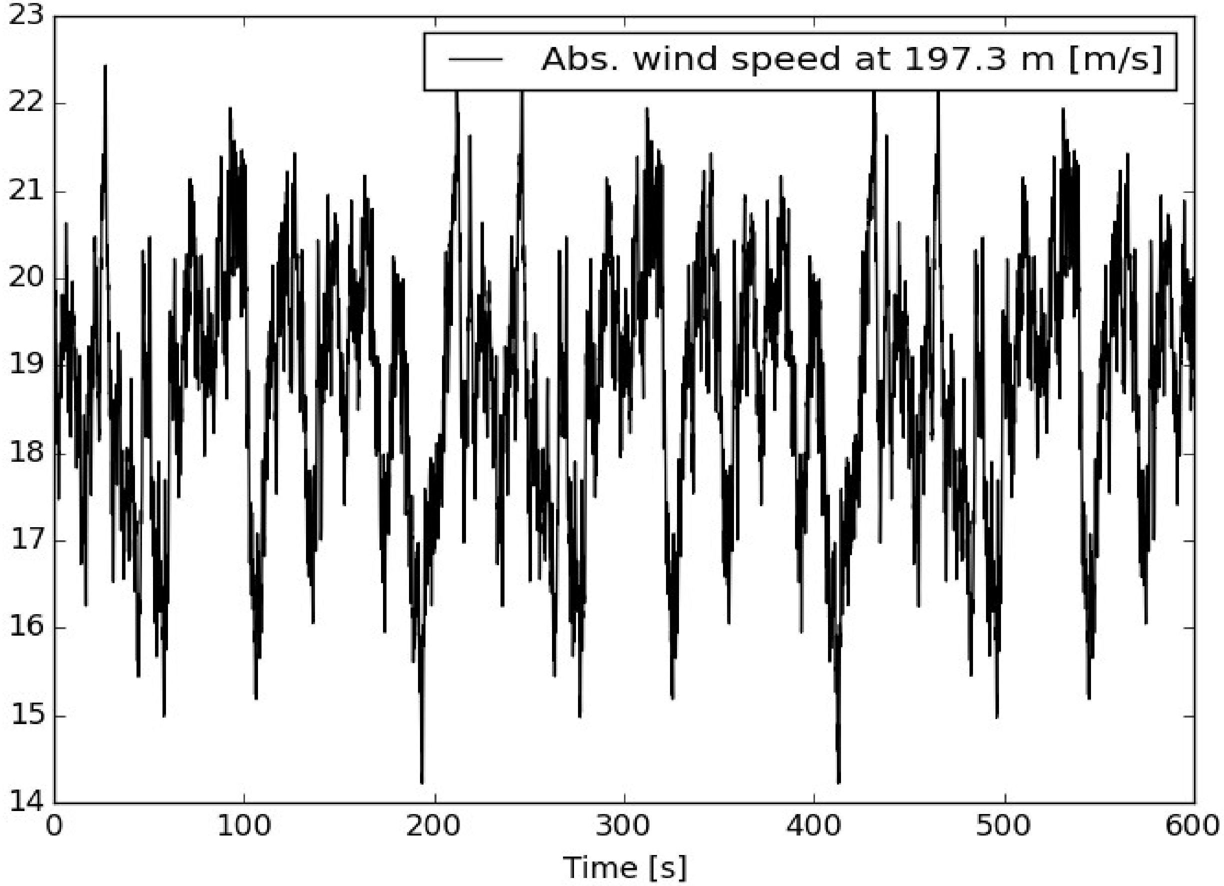
Turbulence intensities

$v_{w,g}$	I_{99}	I_{197}	Description
4.26	8.5 %	6.3 %	Average wind speed
6.00	9.7 %	7.2 %	Nominal wind speed
9.20	9.8 %	7.9 %	High wind speed

Simulation scenarios, based on the wind data from Cabauw 2011. Three average ground wind speeds are used. The average turbulence intensities at 98.7 m and 197.4 m height are shown. The turbulence was modelled as 3D wind field in accordance to *Mann, J. (1994, April)* and *Mann, J. (1998, October)*.

Wind Environment IV

Wind speed at 197 m height, high wind scenario

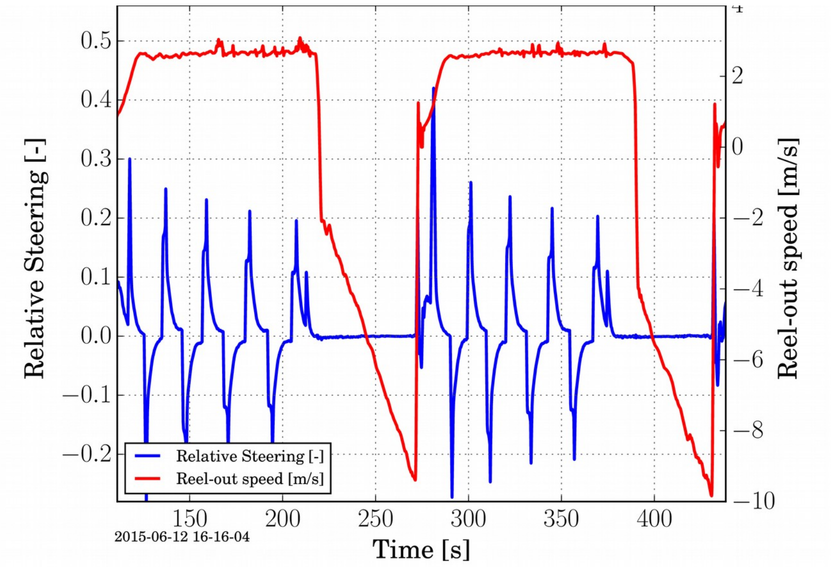


In a 600 s test the wind speed varies between 14.2 and 22.5 m/s.

The changes can be fast, up to 4 m/s².

Flight Path Planner
Design Goals

- *Full description needs at least **4000** parameters;*
- *this algorithm reduces the number of parameters to **13**;*
- *this makes numerical optimization feasible.*



Flight Path Planner

Design Goals

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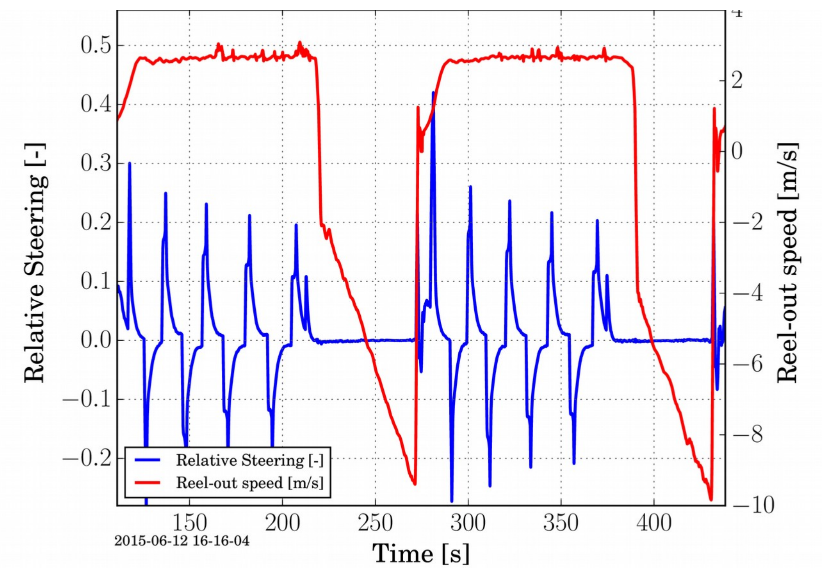
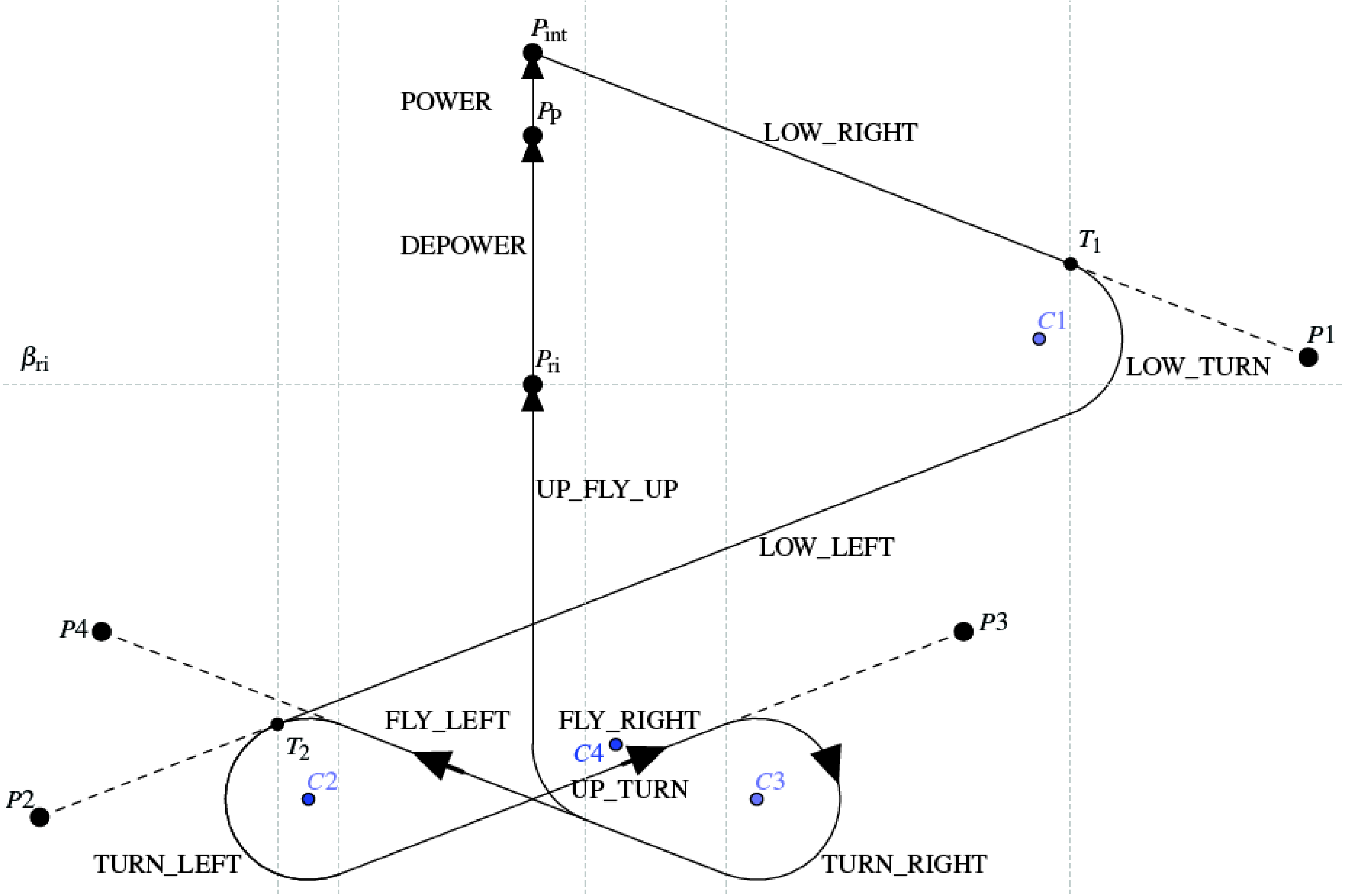


Flight Path Planner

Flight path at low and medium wind speeds



The flight path is constructed of lines and turns.

Straight lines are always flown towards an attractor point.

Eleven states are used.

Flight Path Planner

Only 13 parameters need to be optimized

β_{min}: minimal elevation angle
β_{max}: maximal elevation angle
β_{ri}: elevation angle for switching to reel-in
l_{up}: upper tether length
l_{max}: maximal tether length
l_{low}: lower tether length
w_{fig}: width of the figure-of-eight
r_{min}: minimal turn radius
r_{max}: maximal turn radius

F_h: set value for the maximal (high) tether force
F_l: set value for the mini (low) tether force
F_{ri}: set value for the reel-in tether force
k_v: quotient of the optimal reel-out speed and
the sqare root of the tether force

Flight Path Planner

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Simulation model

Dynamic, 4-point kite, segmented tether and winch model

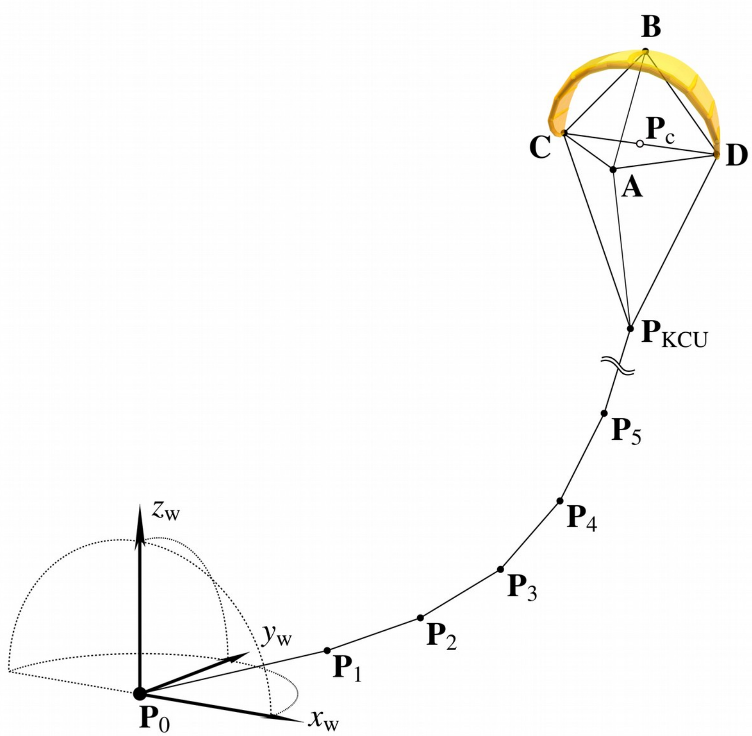


Figure 1: Four point model of the kite defined by points **A**, **B**, **C** and **D**. Points $\mathbf{P}_0$ to $\mathbf{P}_{KCU}$ discretize the tether.

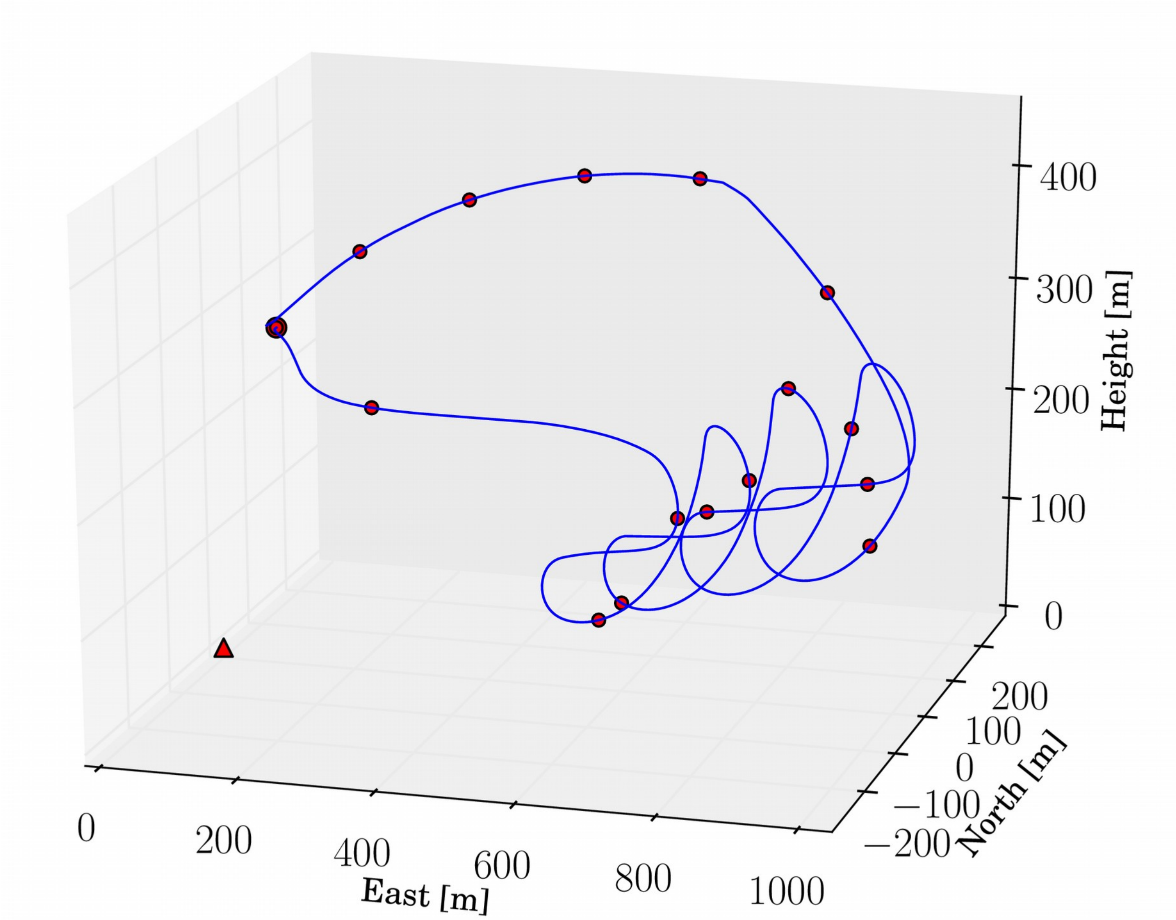
For simulating the flight path, the 4-point kite model with a segmented tether and a dynamic winch model was used, as presented in

Fechner, U., Vlugt, R. V. D., Schreuder, E. & Schmehl, R. (2015).

This allows an accurate simulation of the tether force including possible, fast oscillations. The time resolution was 20 ms.

Simulation results I

Nominal wind speed



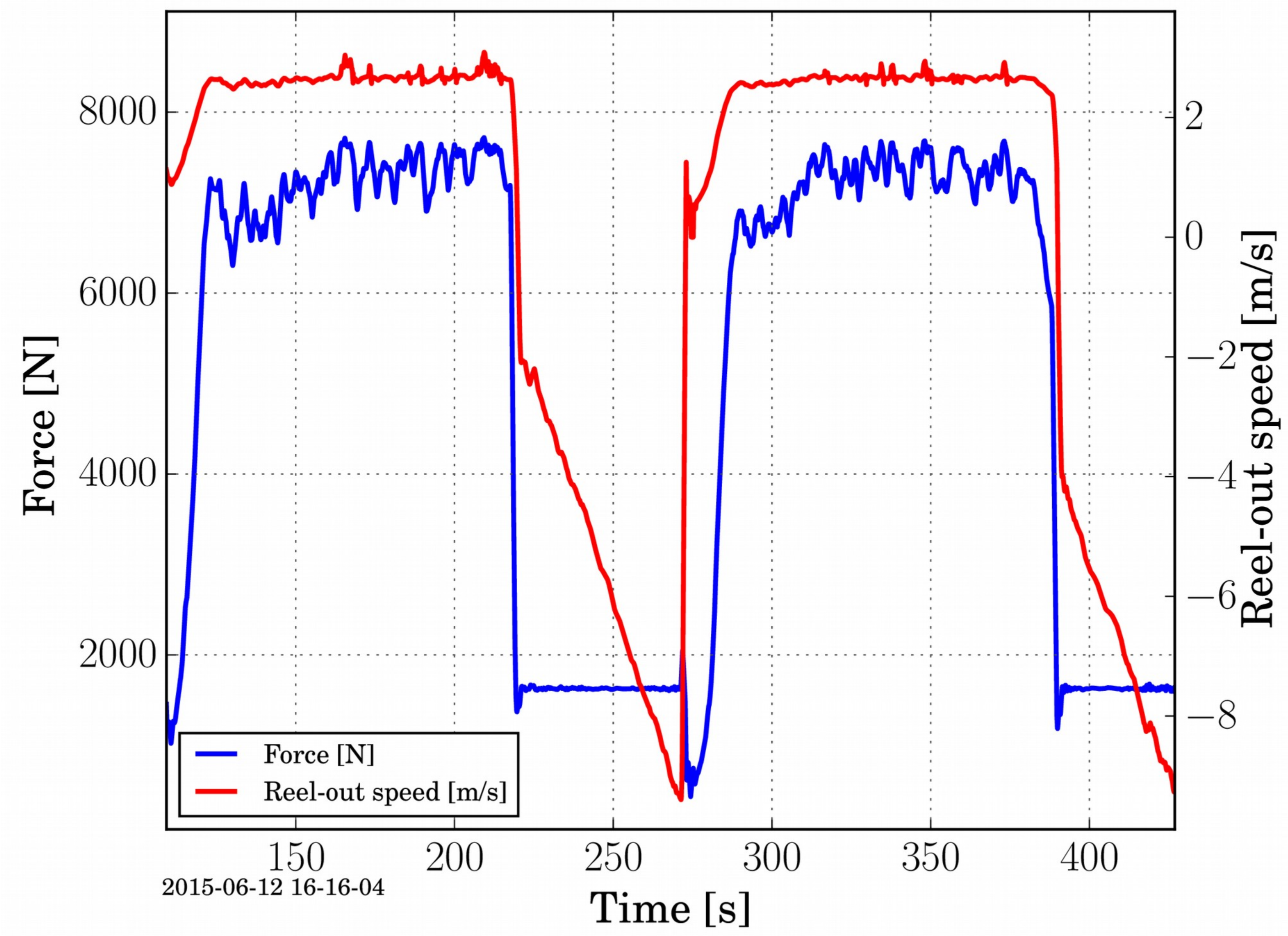
The kite is reeled out at about 22 ° elevation angle.

If the tether length is more than 500 m it is steered upwards.

At 580 m tether length it is depowered on the reel in phase begins.

Simulation results II

Force and speed at nominal wind speed



The tether force just reaches the upper limit of 7600 N.

When the force limit because active, the reel out speed increases, otherwise it is pretty constant.

Simulation results III

Power, force and efficiencies at nominal wind speed

```
Average mechanical power  [W]:    9529.6
Duty cycle:               [%]:      73.5
Pumping efficiency:       [%]:      76.3
Cycle efficiency:         [%]:      56.1
Max. rel. force overshoot [%]:       1.1
Crest factor reel-out power:        1.26
Max. reel-out power [W]:        22577.86
Crest factor reel-out force:        1.13
Max. reel-out force [N]:         7683.39
```

Good results:

About 9.5 kW average mechanical power.

The crest factor is 1.26 for the reel-out power and 1.13 for the reel-out force.

Simulation results III

Power, force and efficiencies at nominal wind speed

```
Average mechanical power  [W]:    9529.6
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Max. reel-out force [N]:         7683.39
```

Crest factor:
Quotient of peak value and average value of a physical quantity.

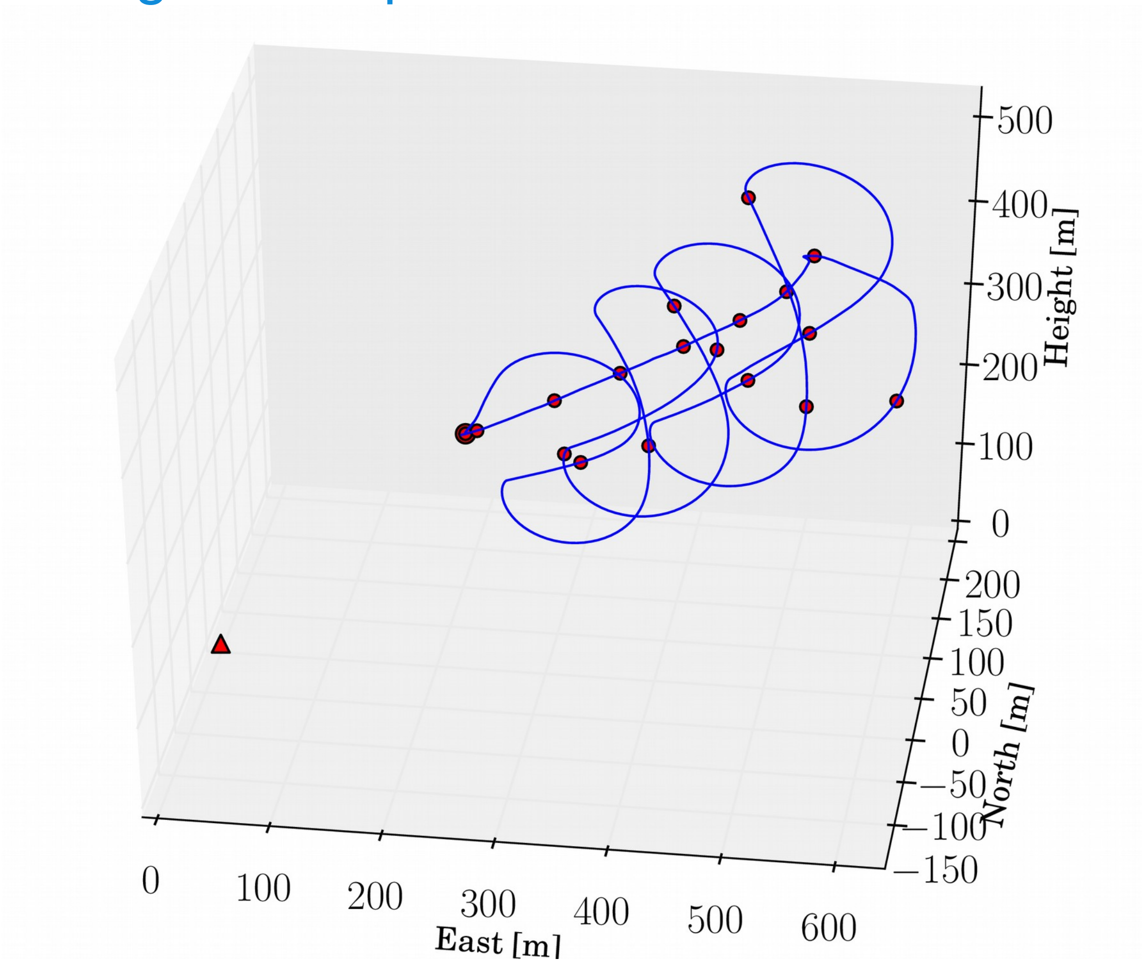
Good results:

About 9.5 kW average mechanical power.

The crest factor is 1.26 for the reel-out power and 1.13 for the reel-out force.

Simulation results IV

High wind speed

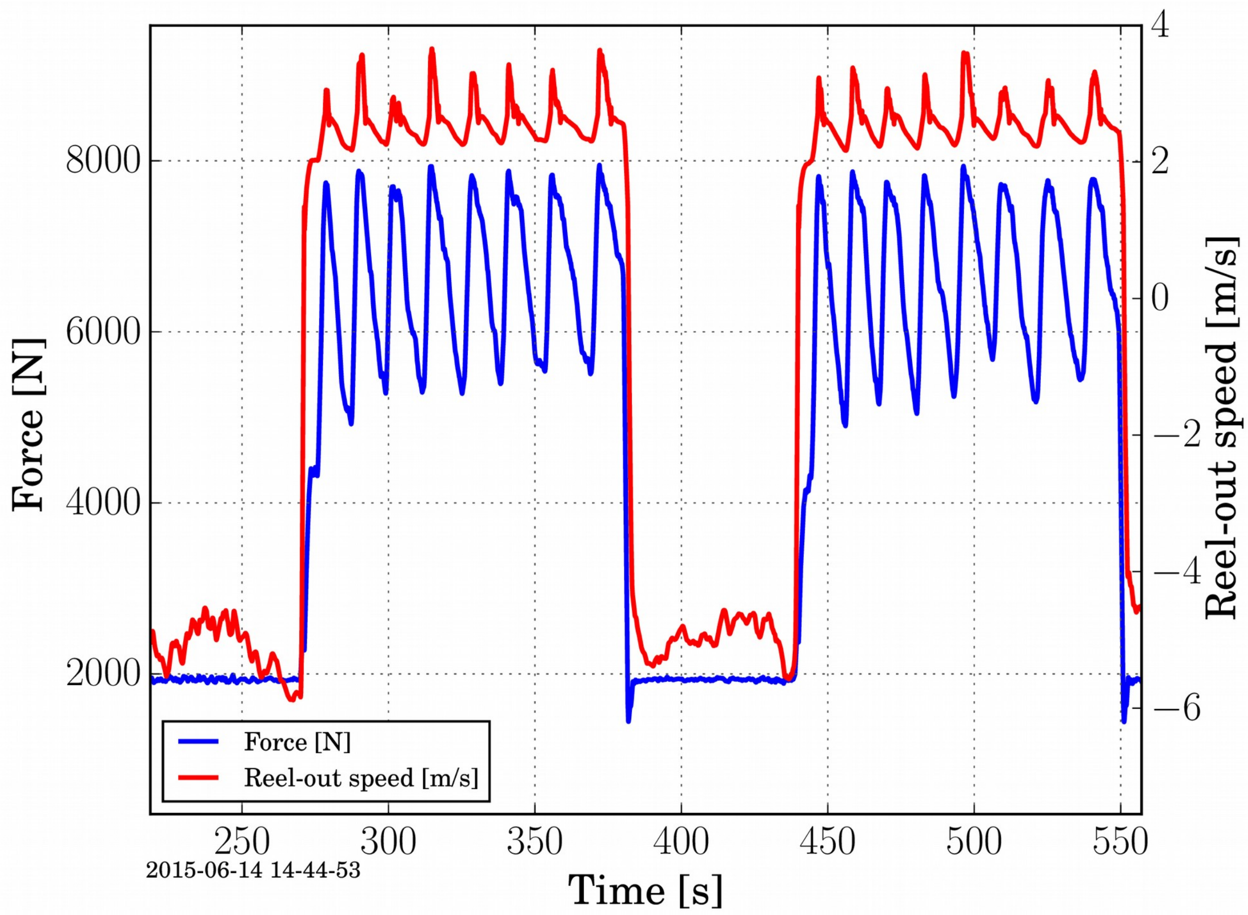


The kite is reeled out at about 60 ° elevation angle.

Reeling in happens at about the same elevation angle.

Simulation results V

Force and speed at high wind speed



The tether force nearly reaches the maximal limit of 8000 N.

The force varies much more than at lower elevation angles.

Simulation results VI

Power, force and efficiencies at nominal wind speed

```
Average mechanical power   [W]:    8039.7
Duty cycle:                [%]:      69.0
Pumping efficiency:        [%]:      70.3
Cycle efficiency:          [%]:      48.6
Max. rel. force overshoot  [%]:       4.5
Crest factor reel-out power:         1.69
Max. reel-out power [W]:         28960.79
Crest factor reel-out force:         1.22
Max. reel-out force [N]:          7942.19
```

Crest factor:
Quotient of peak value and average value of a physical quantity.

Reasonable results:

About 8 kW average mechanical power: This is 16% less than at nominal wind speed.

The crest factor is 1.69 for the reel-out power and 1.22 for the reel-out force.

Summary and Conclusion

A flight-path planner, that can be configured and optimized with only 13 parameters was presented. It was operated in three different wind conditions, typical for the location Cabauw, The Netherlands.

The (partially) validated kite power system model as presented in *Fechner, U., Vlugt, R. V. D., Schreuder, E. & Schmehl, R. (2015)* was used for simulating the performance of the flight path planner.

It was shown, that the proposed algorithm can operate the kite at 20 to 60 degree elevation angle and thus compensate wind speed changes of a factor of 1.54.

Furthermore, a turbulent wind field was modeled in three dimensions, using the approach, suggested by *Mann, J. (1994, April)*.

Summary and Conclusion II

The results show, that the effect of a turbulence intensity of 6.3-7.9% on the flight path and the power output is small (< 5% power loss at high wind speeds, none otherwise).

At higher turbulence intensities (up to 20%) the flight path is significantly effected (up to 4° elevation error), which means that at high wind speeds the average output power must be reduced significantly (up to 30%), as long as the peak power is only controlled by changing the elevation angle.

Nevertheless the control system stays stable. It should be investigated, if the power drop in these situations can be reduced by changing the angle of attack, too and not only the elevation angle.

Future work

- *Integrate a rigid kite model into the framework;*
- *investigate the performance of flying up-loops;*
- *determine optimal parameters for a full set of wind speed, wind profile and turbulence intensity values;*
- *add the option to reel in at the side of the wind window;*
- *implement an estimator for the wind speed, wind profile and turbulence intensity;*
- *extend the environmental model with wind gusts;*
- *model validation.*

Literature

Phd research Uwe Fechner

Mann, J. (1994, April). The spatial structure of neutral atmospheric surface-layer turbulence. Journal of Fluid Mechanics, 273, 141. doi:10.1017/S0022112094001886

Mann, J. (1998, October). Wind field simulation. Probabilistic Engineering Mechanics, 13(4), 269–282. doi:10.1016/S0266-8920(97)00036-2

Fechner, U., Vlugt, R. V. D., Schreuder, E. & Schmehl, R. (2015). Dynamic Model of a Pumping Kite Power System. Renewable Energy, 83, 705–716. doi:10.1016/j.renene.2015.04.028

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