Modeling and control design for kite power systems
- Airborne Wind Energy at ETH Zurich

AWESCO kick-off week
Freiburg, Germany
03 March, 2016

Eva Ahbe
Tony A. Wood, Henrik Hesse, Aldo U. Zgraggen, and Roy S. Smith

Automatic Control Laboratory, ETH Zurich

Outline

Outline

Introducing myself

Background

- B.Sc. and M.Sc in Physics at Heidelberg University, Germany
- Focus in M.Sc on environmental physics
- Master thesis and predoctoral researcher at Carnegie Institution for Science, Stanford, USA

PhD at ETH Zurich

- Starting date 1. September 2015
- Research in modeling of kite dynamics and control design

Outline

AWE projects at ETH

- CCEM Project: Swiss Kite Power (2010-2013)
  - Foundation for control and modelling work

AWE projects at ETH

- CCEM Project: Swiss Kite Power (2010-2013)
  - Foundation for control and modelling work
- CTI Project: Together with TwingTec (2013-2015, 2016-)
  - Technology transfer between universities and industry in Switzerland

AWE projects at ETH

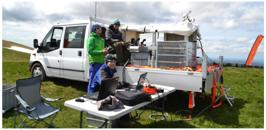
- CCEM Project: Swiss Kite Power (2010-2013)
  - Foundation for control and modelling work
- CTI Project: Together with TwingTec (2013-2015, 2016-)
  - Technology transfer between universities and industry in Switzerland
- SNF Project: A^2WE (2013-2016)
  - Aerodynamic modelling of kites
  - System identification for periodic operation

AWE projects at ETH

- CCEM Project: Swiss Kite Power (2010-2013)
  - Foundation for control and modelling work
- CTI Project: Together with TwingTec (2013-2015, 2016-)
  - Technology transfer between universities and industry in Switzerland
- SNF Project: A^2WE (2013-2016)
  - Aerodynamic modelling of kites
  - System identification for periodic operation
- European Horizon 2020: AWESCO (2015-)
  - Modelling, control and optimisation

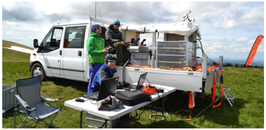
Research focus in AWE

- Two-line kite systems (soft & rigid) for pumping cycles, ground-based steering and power generation



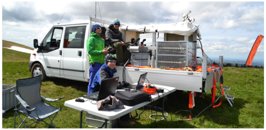
Research focus in AWE

- Two-line kite systems (soft & rigid) for pumping cycles, ground-based steering and power generation
- Development of control algorithms for autonomous flight



Research focus in AWE

- Two-line kite systems (soft & rigid) for pumping cycles, ground-based steering and power generation
- Development of control algorithms for autonomous flight
- Modelling, system identification and estimation of kite systems



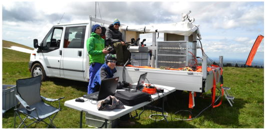
Research focus in AWE

- Two-line kite systems (soft & rigid) for pumping cycles, ground-based steering and power generation

- Development of control algorithms for autonomous flight

- Modelling, system identification and estimation of kite systems

- Real-world test flights



Outline

Introduction

AWE projects at ETH

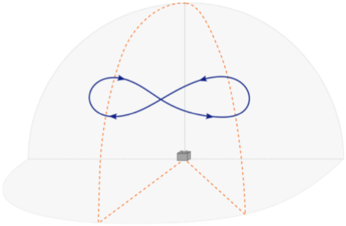
Control approach

Challenges

Research plan

Control aim and strategy

- Goal: Fully autonomous periodic figure eight in power zone

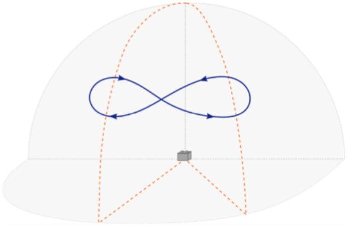


Control aim and strategy

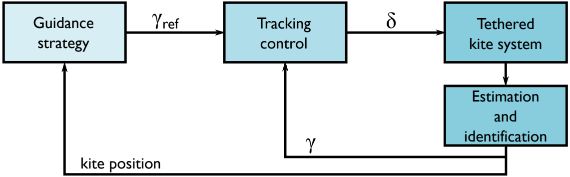
- Goal: Fully autonomous periodic figure eight in power zone

Strategy:

Cascaded Control

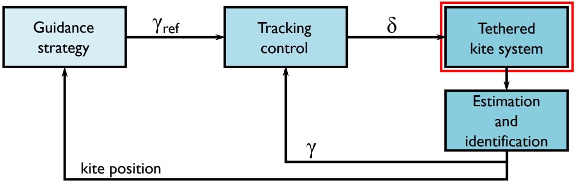


Cascaded Control



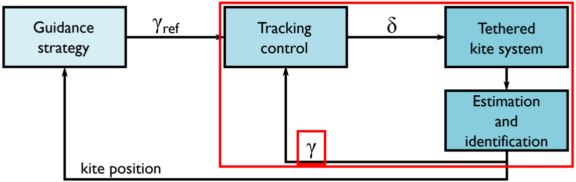
Cascaded Control

Kite system



Cascaded Control

Heading angle estimation

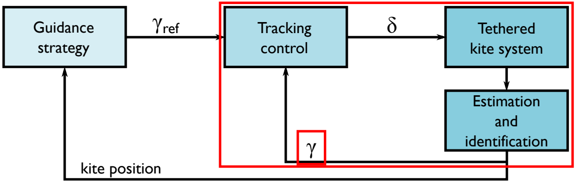


Control variable:

Heading angle

Cascaded Control

Heading angle estimation

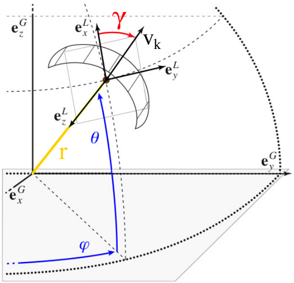


Control variable:

Heading angle

- wing flight direction as a scalar in tangent plane

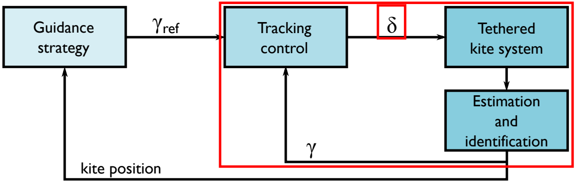
$$\gamma := \arctan\left\{\frac{\cos(\theta)\dot{\phi}}{\dot{\theta}}\right\}$$



[Fagiano et al., TCST, 2014]

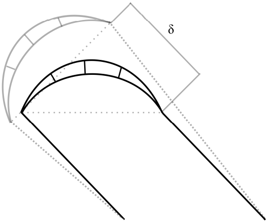
Cascaded Control

Low-level controller



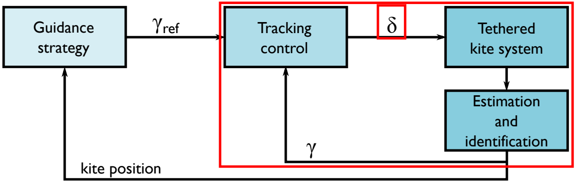
Control input:

Line length difference δ



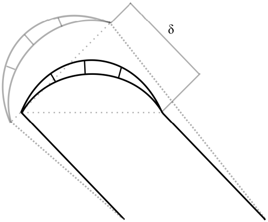
Cascaded Control

Low-level controller



Control input:

Line length difference δ



- Simple steering law

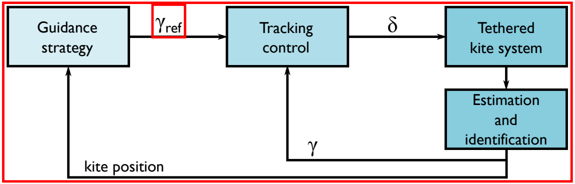
$$\dot{\gamma}(t) \simeq K\delta(t)$$

- Linear in δ, approx. constant K.

[Fagiano et al., TCST, 2014]

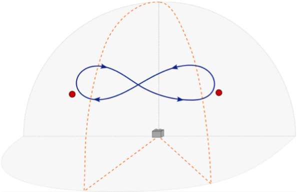
Cascaded Control

High-level controller



Guidance strategy:

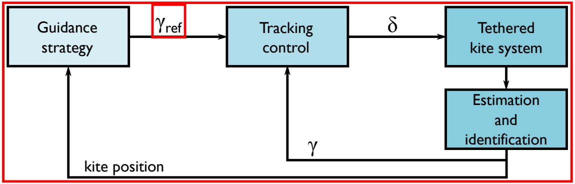
Switching points for reference heading angle



[Fagiano et al., TCST, 2014]

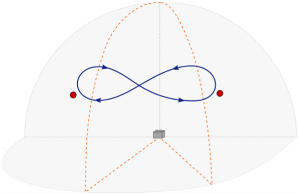
Cascaded Control

High-level controller



Guidance strategy:

Switching points for reference heading angle



- New approach: model based path following (LQR)

[Fagiano et al., TCST, 2014], [Wood et al., CDC, 2015]

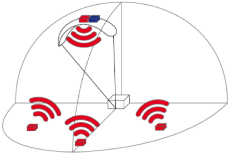
Outline

Estimation of kite dynamics

- Better estimates of kite position, velocity, heading angle

Sensor fusion:

- Range-inertial estimation using UWB sensors and IMUs [Millane et al., CDC, 2015]

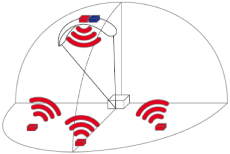


Estimation of kite dynamics

- Better estimates of kite position, velocity, heading angle

Sensor fusion:

- Range-inertial estimation using UWB sensors and IMUs [Millane et al., CDC, 2015]



Visual motion tracking (VMT):

- Novel VMT algorithm to reliably locate the position of the wing
- Make it applicable in real-time (100Hz) [Polzin et al., Poster AWEC, 2015]

Including time delay in control design

- Delay t_d between steering input at ground-station and estimated heading angle caused by kite dynamics and estimation.

$$\text{Observed steering law:} \qquad \dot{\gamma}(t) = K\delta(t - t_d)$$

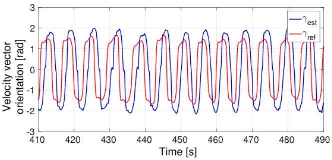
- Smith predictor design to compensate input delay
- Delay limits the signal that can be tracked

Including time delay in control design

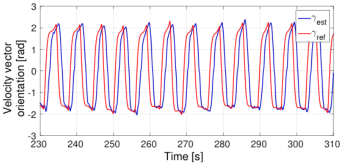
- Delay t_d between steering input at ground-station and estimated heading angle caused by kite dynamics and estimation.

Observed steering law: $$\dot{\gamma}(t) = K\delta(t - t_d)$$

- Smith predictor design to compensate input delay
- Delay limits the signal that can be tracked



Without delay compensation



With delay compensation

Flight experiments with delay compensation

(Flight experiment with delay compensation)

Outline

Research projects

- **Modeling of kite dynamics:** find improved model formulations, more accurate but still feasible in real-time control (e.g. account for varying kite velocity)
- **Control design:** employing nMPC for model-based path planning and flight control, use in cascaded control strategy

Research projects

- **Modeling of kite dynamics:** find improved model formulations, more accurate but still feasible in real-time control (e.g. account for varying kite velocity)
- **Control design:** employing nMPC for model-based path planning and flight control, use in cascaded control strategy

- Explore new state estimation approach with a dynamically moving camera tracking system
  - Real-time detection of key features of the kite (heading angle, shape deformation, line angles)

Research projects

- **Modeling of kite dynamics:** find improved model formulations, more accurate but still feasible in real-time control (e.g. account for varying kite velocity)
- **Control design:** employing nMPC for model-based path planning and flight control, use in cascaded control strategy

- Explore new state estimation approach with a dynamically moving camera tracking system
  - Real-time detection of key features of the kite (heading angle, shape deformation, line angles)

- Modeling of tether dynamics for improved state estimation

Research plan and secondments

First year:

- Literature review, background on kite modeling, control design
- Improve existing models, sketch new control design idea
- Secondment at EPFL (1m): Estimation of periodic orbits

Research plan and secondments

First year:

- Literature review, background on kite modeling, control design
- Improve existing models, sketch new control design idea
- Secondment at EPFL (1m): Estimation of periodic orbits

Second year:

- Test, validate model of kite dynamics and control design approach
- Finish first projects, new modeling approach, improve control design
- Secondment at FlySurfer (2m): Periodic orbits of different kite design

Research plan and secondments

First year:

- Literature review, background on kite modeling, control design
- Improve existing models, sketch new control design idea
- Secondment at EPFL (1m): Estimation of periodic orbits

Second year:

- Test, validate model of kite dynamics and control design approach
- Finish first projects, new modeling approach, improve control design
- Secondment at FlySurfer (2m): Periodic orbits of different kite design

Third year:

- Continue second year research
- Secondment at Skysails (1m): Gather data for uncertain periodic orbits

Research plan and secondments

First year:

- Literature review, background on kite modeling, control design
- Improve existing models, sketch new control design idea
- Secondment at EPFL (1m): Estimation of periodic orbits

Second year:

- Test, validate model of kite dynamics and control design approach
- Finish first projects, new modeling approach, improve control design
- Secondment at FlySurfer (2m): Periodic orbits of different kite design

Third year:

- Continue second year research
- Secondment at Skysails (1m): Gather data for uncertain periodic orbits

Fourth year:

- Wrap up research, final tests
- Write thesis

Thank you! Questions?