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

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Contents

• Introduction SkySails Marine and Power
• Simple Model
• Sensors and Navigation
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• Control System
• Further Challenges of the Real-World System
**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 m²
- autopilot controlled
SkySails Marine – Towing Kite System

Control Systems

Launch and Recovery System

Airborne Control Pod

Kite sizes up to 320m²

Substitute 1-2 MW of main engine power
System Overview

- Telescopic mast
- Guiding line
- Towing kite
- Control pod
- Towing line
Machine Supported Ground Handling
Production and Installation

Michael Erhard, SkySails GmbH, Talk at IMTEK, University of Freiburg, January 20, 2015
Impressions

See http://youtu.be/ckyHeizCAdk
## SKYSAILS POWER Development

### Functional prototype:

- Design load: 20 kN
- Kite size: typ. 30 m²
- Installed generator power: 55 kW
- Maximum winch speed: 5 m/s
- Installed tether length: 450 m

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[http://www.skysails.info/english/power/](http://www.skysails.info/english/power/)
SkySails Power

- Pumping Cycle

M. Erhard, H. Strauch,
*Flight control of tethered kites in autonomous pumping cycles for airborne wind energy,*
SkySails Power

Economic energy generation ➔ Fully automated AWE plants

➔ Reliability of control system crucial
Impressions

(Power Video)
Simple Model
Simple Model

Coordinate System

- Position $\varphi, \theta, l$
- Orientation $\psi$

[Diagram showing coordinate system with axes $e_x$, $e_y$, $e_z$, $e_{\text{roll}}$, $e_{\text{pitch}}$, $e_{\text{yaw}}$, and wind direction]
Simple Model

Model Assumptions

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

2.) Airflow in Roll Direction

3.) Glide Ratio Condition
Aerodynamics of Tethered Kites

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

Tethered Kite:

$$\begin{align*}E &= \frac{v_{\text{hor}}}{v_{\text{vert}}} \\
v_{\text{tot}} &= 1..E \ v_0 \\
F_{\text{tot}} &= 1..E^2 \ F_0 \\
\text{Wind } v_0 = 10\text{m/s with } E=5 \text{ yields } v_{\text{tot}} &= 10..50\text{m/s!} \end{align*}$$
Simple Model

- Equations of motion for $\varphi$, $\dot{\varphi}$, and $l$ (3d kite position)

\[
\begin{align*}
\dot{\varphi} & = \frac{v_a}{l} \left( \cos \psi - \frac{\tan \dot{\varphi}}{E} \right) - \frac{l}{l} \tan \varphi \\
\dot{\varphi} & = -\frac{v_a}{l \sin \varphi} \sin \psi \\
l & = v_{\text{winch}} \\
v_a & = v_w E \cos \varphi - i E
\end{align*}
\]

Parameters

- glide ratio
- wind speed
- orientation $\psi$
- winch speed $v_{\text{winch}}$
Kinematic Equations of Motion

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

\[ \phi = -\frac{v_a}{l \sin \vartheta} \sin \psi \]
Angle $\psi$ is the central control variable:

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

- Keep static zenith position ($\varphi=\text{const}$)

Periodic signal on $\psi$ yields pattern:

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

$$\dot{\varphi} = -\frac{v_a}{l \sin \vartheta} \sin \psi$$
Control of Orientation $\psi$
Steering

Steering by means of canopy (and force vector) rotation

Aerodynamic force vector
Passive section
Actively steered section
Control pod
Towing rope
F_1
F_2

Turn Rate Law

\[ \dot{\psi}_m = g_k \nu_a \delta \]
Sensors and Navigation
Control Pod Sensors

- Line Force Sensor (Strain Gauge)
- Impeller-Anemometer
- Barcode Reader
- Flight Control Computer
- Servo Control
- Energy Buffer
- Cable: Data/Energy
- IMU - 3 Gyro
- 3 Acc.
- Motor

Michael Erhard, SkySails GmbH, Talk at IMTEK, University of Freiburg, January 20, 2015
## Sensor Overview

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertial Measurement Unit (IMU)</td>
<td>$\vec{\omega}_s$</td>
</tr>
<tr>
<td></td>
<td>$\vec{a}_s$</td>
</tr>
<tr>
<td>Impeller Anemometer</td>
<td>$v_a$</td>
</tr>
<tr>
<td>Strain Gauge Pod</td>
<td>$F$</td>
</tr>
<tr>
<td>Barometer</td>
<td>$h$</td>
</tr>
<tr>
<td>Tow Point</td>
<td>$\phi_s, \theta_s$</td>
</tr>
<tr>
<td>Ship Anemometer</td>
<td>$v_w, \phi_w$</td>
</tr>
<tr>
<td>Ship IMU</td>
<td>$L$</td>
</tr>
<tr>
<td>Line length</td>
<td></td>
</tr>
</tbody>
</table>

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Inertial Navigation

- Quaternion integration...

- Problem: drift of turn rate sensors
Inertial Navigation

Reference to 'Down'-Direction

Average Accelerations \( \langle \tilde{a}_s \rangle \approx -|g| \, \tilde{e}_z \)
Yaw Angle Estimator

Experimental Results

IMU Angles

Tow Point Angles

Tether

\( \theta_g \)
\( \phi_g \)

- \( e_{\text{yaw}} \)

\( \theta_s \)
\( \phi_r \)

Graph showing IMU angles over time:

- \( \theta_g \)
- \( \theta_s \)
- \( \phi_g \)
- \( \phi_r \)

Angle [rad]

Time [s]

5800 5850 5900 5950 6000
Wind Referencing

Pod IMU

$\bar{\omega}_g$

$\bar{d}_s$

Yaw Angle Estimator

$\psi_g$

$\phi_g$

$\theta_g$

Calc. $\psi$

$\psi_m$

Controller

Reference Block

$\phi_{gr}$

Ship Sensors

$\phi_r = \phi_s + (\pi - \phi_w)$

IMU

$\phi_g$

Highpass

Lowpass

$\phi_{gr}$

Wind-direction

$\theta_g$, $\theta_s$, $\phi_g$, $\phi_{gr}$, $\phi_r$

Angle [rad]

5800 5850 5900 5950 6000

Time [s]
Merging of Algorithms

Complementary Filter

Validation of kinematics
Validation of Kinematics

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

\[ \dot{\phi} = -\frac{v_a}{l \sin \dot{\psi} \sin \psi} \]
Validation of Kinematics

Flight Direction

\[ \gamma = \arctan(-\dot{\phi} \sin \vartheta, \dot{\vartheta}) = \arctan \left( \sin \psi, \cos \psi - \frac{\tan \vartheta}{E} \right) \]
Validation of Turn Rate Law
Turn Rate Law

\[ \psi_m = g_k v_a \delta \]

- Turn rate
- Parameter
- 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

\[ +\delta_0 \]
\[ -\delta_0 \]

\[ \psi_m = g_k v_a \delta \]
Extended Turn Rate Law

\[ \psi_m = g_k \nu_a \delta + M \frac{\cos \theta_k \sin \psi_k}{\nu_a} \]

2 Fit Parameter

Gravitation

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Online Parameter Estimation

Weighted least-square

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

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

\[ \overline{R}(t) = \sum_{k=1}^{t} \beta(t, k) \varphi(k) \varphi^T(k) \]

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

Example: turn rate law

\[ \dot{\psi}_m = g_{\psi} v_a \delta \]

See e.g.: Ljung, System identification

\[
\begin{align*}
\dot{\psi}_m = g_{\psi} v_a \delta \\
y(k) & \quad \hat{\theta}_t & \quad \varphi(k) \\
\text{result}
\end{align*}
\]
Online Parameter Estimation

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

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Control System
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
Control System

- Cascaded control setup

![Diagram of control system with labeled components: TPi, Trigger event, TP1, TP2, Flight control, Switching of target points, Position, Cycle and winch control, Flight direction, Control orientation, Stabilize yaw axis, Kinematics, Turn rate law, \( \delta \), \( \varphi_m, \dot{\varphi}_m, \dot{\varphi}_m \), \( \psi_m \), \( \psi'_m \), \( \nu_{\text{winch}} \).]
Controller Performance

Turn rate control loop

\[ FF_\dot{\psi} \rightarrow \dot{\psi}_m \rightarrow C_\dot{\psi} \rightarrow \delta \rightarrow \dot{\psi} \]

\[ \delta_{ff} \]

\[ \dot{\psi}_{s} \] to \[ \dot{\psi}_{m} \]

\[ \text{(FBK \ll FF)} \rightarrow \text{'Indirect' system identification} \]

\[ \text{Data file 140722_170704} \]
Limits and challenges
Challenges and limits

Wind is challenging: Profile

How to model the wind field?
→ Profile?
→ Boundary layer?
→ ...
Challenges and limits

Soft Materials

- Modelling Accuracy is limited
- Limited Sensor ‘Accuracy’

Free Flight

Tether Slack

Line Angle Sensors
Free flight

Due to gusts or wave induced motion: temporarily untethered system

Angle w.r.t. Horizon ‘undefined’

Line Angle Sensor

\[ \psi_k \]
Thank you for your Attention!

Questions?