Sensor Setups for State and Wind Estimation for Airborne Wind Energy Converters

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Abstract

An unscented Kalman filter with joint state and parameter estimation is proposed for aerodynamics, states and wind conditions for airborne wind energy converters. The proposed estimator relies on different measurement setups. Due to the strict economic constraints of wind energy converters, the sensor setups are chosen with minimal cost and reliability issues in mind. Simulation data with a high fidelity system model and experimental tests using flight data, together with wind measurements obtained using a lidar system for altitude wind measurements, are used for validation. The data was obtained during test flights of the EnerKíte EK30, an airborne wind energy converter currently in research operation in Brandenburg, Germany. Feasible accuracies were achieved even with the simplest of setups and illustrate the gain achievable by airborne sensors. Additionally, the results encourage further research into use of the obtained wind estimates for site assessment.

1 Introduction

Airborne wind energy converters are a promising concept for efficient wind energy conversion. With the ability to reach high altitudes without towers, the interest in these systems is rising. EnerKíte[1] is developing airborne wind energy converters and is currently operating the research platform EK30[8], for which the presented method was developed. The EK30 is a Yo-Yo airborne wind energy systems, an idea described for example in [12]. These systems fly a crosswind motion to generate high traction and reel out a tether connected to a generator. At some point, the tether needs to be reeled in again and the kite is brought into a state that results in a positive net power generation over the full cycle. The company SkySails has been using kites for ship propulsion and is currently developing a prototype for energy generation[2]. Makani power[3] are developing systems with airborne electricity

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1http://www.enerkite.com
2http://www.skysails.info/english/power/power-system
3http://www.makanipower.com
generators. At OPTEC\footnote{http://www.kuleuven.be/optec/} numerous optimization papers with applications to kite power have been published, for example \cite{13,14,15}. A research group\footnote{http://www.kitepower.eu/} at the TU Delft have been researching airborne wind energy since 1999\cite{16} and have been focusing in the aero-elastic modeling of kites\cite{17,18} and control\cite{19}. They also built a prototype system for control applications.

While the material requirements are drastically lower than those of conventional wind turbines, the operational management and control requirements are significantly higher. The airborne system needs to be actively controlled to track a desired trajectory. In case of failures or weather conditions too harsh for the system to withstand, a safe landing needs to be accomplished.

Reliable and accurate state estimates are necessary. For operational management and optimized control, wind condition estimates result in significant advantages. Direct measurement of the wind speeds at kite height using a different measurement system, for example a lighter-than-air based anemometer or a lidar system, is not economically viable. High accuracy measurements on the kite are feasible, but lead to increased cost of operation and, consequently, in increased cost of electricity.

In this article a state estimator is presented, which allows the joint estimation of wind conditions, aerodynamic parameters and system states. An unscented Kalman filter algorithm is employed, with different sensor setups including airborne sensors and ground based measurements.

- Ground-based measurements (low cost),
- Additional acceleration and airspeed pressure measurements (medium cost, additional need of transmission with reliability issues),
- Additional GPS velocity and position measurements (additional high cost and additional reliability issues).

The model is presented and the estimator tested in a more detailed simulation environment. Effects of modeling error on the state and parameter estimation are discussed for the different setups. Using real flight data together with lidar measurements of the wind conditions in altitudes up to 200 m validates the reliability and accuracy in real-world conditions. The focus of the experimental results is the aspect of wind estimation, to compare the estimates with wind measurements.

Wind speed estimation is an important aspect for aviation and wind energy in general. If ground speed vectors and airspeed vectors are available, the wind vector can be calculated by subtracting one vector from the other. The airspeed measurements are actually pressure sensors, which leads to significant errors for low airspeed, even though they are accurate for speed
estimation of high-speed vehicles. For a kite flying with 30 m/s perpendicular to the wind, the total airspeed difference between a wind speed 0 m/s and 10 m/s is just 1.6 m/s. Considering the noise of common airspeed sensors for low airspeed, wind speed estimation from direct airspeed measurements is prone to noise and results in low accuracies.

Model based estimates can alleviate the problem of accuracy in pressure sensors in part. A kite is unable to fly at 0 m/s wind speed, and in general will fly at maximal crosswind speeds of about glide ratio times wind speed without reeling out. Thus, a model based approach is significantly more sensitive to wind speed and, consequently, allows for more accurate wind speed estimates. Aerodynamic models are needed for a model based approach. In [1] the wind conditions are being estimated using an aerodynamic model in combination with the differential approach described above. The wind fields for efficient soaring are calculated, with very good results in case of high accuracy airspeed vector measurements. In [2] the aerodynamic model of a variable-speed wind turbine is used to maximize the power output and estimate the wind speed without relying on additional anemometers. For kite control, [3] presents a filter model, a control strategy and preliminary numerical results. A simplified aerodynamic model is used for simulation and estimation, but a more detailed tether model is used for simulation. In [9] an unscented Kalman filter using ground-based measurements is employed to estimate state and wind conditions. The simulation and estimation model are identical and the focus lies on the comparison of the unscented Kalman filter with the extended Kalman filter and on the influence of a wind shear model on accuracy.

In this article, joint estimation of aerodynamics, states and wind conditions is applied. Simulation data is obtained using a detailed three tether system of the EK30 with more realistic and complex models for tethers, actuators and aerodynamics. Accuracies during different wind conditions are presented, and experimental data is used to validate the wind estimates.

2 Estimator Model and Filter

In case of the minimal sensor measurement setup, only the angles and forces of the tether lines are available and the states of a full rigid-body model are highly under-determined. Thus, a point-mass model augmented with aerodynamic coefficients for state estimation is employed. The model is similar to the estimator and (optimal-) control models used in [3],[4].

The most important aspect on kite modeling is the aerodynamic forces, which are ultimately quadratic in airspeed. An unscented Kalman filter [6] handles nonlinearities in state update equations better than the extended Kalman filter. The estimator is implemented in square-root formulation [7].
Since the focus of this paper is the aspect of different sensor setups and experimental results, no details are given on the implementation details and theoretical intricacies of the unscented Kalman filter.

2.1 Aerodynamic Forces

The aerodynamic forces are defined as follows. Let $A$ be the aerodynamic area of the kite and $\rho$ the density of the air. Airspeed is given by $v_a = w - v$, with the wind vector $w$ in Cartesian coordinates and the kite velocity $v$ in the same system. The drag force is always parallel to this vector and given by

$$F_D = \frac{1}{2} \rho A c_D |v_a| v_a.$$  \hfill (1)

The lift force is perpendicular to this drag force. The notion of rolling, like an airplane, is used to integrate the effect of steering inputs. Assuming negligible sideslip, the roll axis of the kite aligns with the airspeed. An initial lift vector points perpendicular to the airspeed but parallel to the tether. This can be interpreted as a kite without line length differences with respect to the main tether line. The control input then results in a lift vector $Z$ by a rotation of this vector around the airspeed axis. The force is then given by

$$F_L = c_L \frac{1}{2} \rho A c_L |v_a|^2 Z(c_u u),$$  \hfill (2)

where the coefficient $c_u$ describes the linear relation between the control input $u$ and the roll angle.

The tether drag force acting on the kite is integrated over every point $s$ between the ground station at length 0 and the kite at length $L$, given by

$$F_{Ds} = \frac{1}{2} \rho d c_{Ds} \int_0^L \left| w - \frac{s}{L} L v \right| (w - \frac{s}{L} L v) ds,$$  \hfill (3)

where $d$ is the effective diameter and $c_{Ds}$ is the drag coefficient of the lines.

2.2 Lagrangian and Dynamic Equations

The dynamic equations are derived using the system Lagrangian. The following kinetic energies are considered: the kite, with the kinetic mass of the kite $m_k$ and the encapsulated air, the tether with its density $\mu$ and the winch with rotational velocity $\omega$ and moment of inertia $J$.

$$E_{kin} = \frac{1}{2} (m_k + \rho V) v^2 + \frac{1}{2} \int_0^L \mu \left( \frac{s^2}{L^2} \right)^2 v^2 ds + \frac{1}{2} J \omega^2$$  \hfill (4)

$$= \frac{1}{2} (m_k + \rho V + \frac{1}{3} \mu L) v^2 + \frac{1}{2} J \omega^2$$  \hfill (5)
The work and potential energy is given by the gravitational work of the kite and the tether, the forces acting on the kite and the work done on the tether by the motor with torque $T$.

$$E_{pot} = m_k z + \int_{0}^{L} \mu \frac{s}{L} z ds$$

$$= (m_k + \frac{1}{2} \mu L) z$$

$$dW = (F_L + F_D + F_{Ds}) dx + T d\phi$$

Since the movement of the kite is constrained by the tether, the constraint equation is given by

$$g(x, L) = \frac{1}{2} (|x|^2 - L^2)$$

with the gradients $\nabla_x g = x^T$ and $\nabla_L = L$. The equations are given such that the Lagrange multiplier $\lambda$ results in a tether traction force in Newton, using the radius of the drum $R$ and the normalized position $\hat{r}$. The twice differentiated constraint equation is given by

$$x^T \ddot{x} = L \ddot{L}$$

$$\lambda = \frac{F_L + F_D + F_{Ds}}{R}$$

The structure of the mass matrix on the left hand side permits a convenient inversion. With $\tau = J + mR^2$, $J = \frac{1}{m}$ and $\hat{r} = (x, y, z)$ the inverse is given by

$$\left( \begin{array}{c} y^2 + z^2 \\ -xy \\ -xz \end{array} \right) \left( \begin{array}{c} x \\ y \\ z \end{array} \right) = R \left( \begin{array}{c} x \\ y \\ z \end{array} \right)$$

Note that for $J \to \infty$ the constraint force is given by $F_S = \hat{r} \cdot \sum F$, which is the force resulting from a fixed rod. For $J \to 0$ the tension is given by $F_S = -T/R$, that is the force depends completely on the applied torque.
| Measurement              | Standard Deviation | Model Parameter     | Value  |
|--------------------------|--------------------|---------------------|--------|
| Length                   | 0.5 m              | Kite mass $m_k$     | 6 kg   |
| Angles                   | 0.5°               | Aerodynamic area $A$| 12.8 m²|
| Force                    | 100N               | Tether mass $\mu$   | 1.3 kg/100m |
| Acceleration             | 1 m/s²             | Drum inertia $J$    | 27 kg m²|
| Airspeed ($v_a^2$)       | 50 m²/s²           | Tether drag $c_{D_s}$| 1.2    |
| GPS position             | 3 m                | Tether diameter $d$ | 9 mm   |
| GPS velocity             | 1 m/s              |                     |        |

Table 1: Filter parameters used in the simulation runs.

2.3 Implementation

Joint estimation of the parameters is employed, using the following states with additional parameters $w, c_L, c_D, c_u$. The wind $w$ is a two-dimensional vector, neglecting vertical wind speeds.

$$ q = (x, \dot{x}, \ddot{x}, w, c_L, c_D, c_u) $$

(14)

The state update equations are given by (11). The differential equations for the parameters are $\dot{w} = \dot{c}_l = 0$. The measurement equations are dependent on the sensors available.

Tether angles are measured on the ground using angle measurement sensors and given by $\phi = \text{atan2}(y, x)$, $\theta = \arcsin \frac{z}{r}$. The measured forces on each of the three lines are being added to be comparable to the model tether force. The velocity and position is obtained using the GPS information. An airspeed sensor is able to obtain absolute airspeed pressure estimates.

The sigma points (see [6]) are chosen using the parameters $\alpha = 0.01, \beta = 2$ and $\kappa = 0$.

3 Simulation Model

To validate the estimator in a simulation environment, the system model describing the research platform EK30 with the currently used wings [8] is employed. The model has been used for control development. Since the detailed system model is not within the scope of this article, it will only be described briefly.

3.1 Actuator Model

The actuator model simulates the ground station in detail. The EK30 has three coupled drums, a main drum, to which the main line is attached, and two control drums, to which the control lines are attached. Each drum and motor has coulomb and viscous friction, and external torques due to tether forces and motors are applied.
3.2 Kite Model and Aerodynamics

The kite is modeled using rigid-body kinematics. The moments of inertia and the masses are defined by the used sensor unit, encapsulated air and textile material. For orientation integration the quaternion form of the rigid-body equations is used. With the quaternion \( q \) (with vector parts in the last three components), the velocity in body-fixed coordinates \( v_k \), the rotational rates \( \omega_k \), the earth-fixed position \( x_g \), the kite mass (regarding acceleration) \( m \), the inertia tensor \( J \), the transformation matrix from kite-fixed coordinates to earth-fixed coordinates \( T_{gk}(q) \) and the external kite-fixed forces and torques \( F_k, M_k \), the equations are given by

\[
E(q) = \begin{pmatrix}
- q_1 & - q_2 & - q_3 \\
 q_0 & - q_3 & q_2 \\
 q_3 & q_0 & - q_1 \\
- q_2 & q_1 & q_0
\end{pmatrix},
\]

(15)

\[
\dot{v}_k = \frac{F}{m} + v_k \times \omega_k \\
\dot{x}_g = T_{gk}(q)v_k \\
\dot{q} = \frac{1}{2}E(q)\omega_k \\
J\dot{\omega}_k = M_k + J\omega_k \times \omega_k.
\]

(16)

(17)

The aerodynamics are modeled using a table look-up in both airspeed angles and quadratic functions in the controls for all forces and torques in a body-fixed coordinate system. Forces and torques due to rotational rates are modeled using linear functions in \( \omega_k \). Additional forces and torques result from the three tethers and gravitational force. The aerodynamic functions are derived from CFD simulations and have been adjusted due to flight experience.

3.3 Coupling and Tether Model

The effect of control line differences is modeled more realistically than with a prescribed roll angle. Additionally, the measured tether angles used in the filter algorithm result in errors due to sagging and lag, an effect that is captured by the more detailed model. The three tethers are described using point masses inflexibly chained together and thus constrained in their tether-directional movement due to line acceleration. At each end of the tether, a spring-damper system is used to connect the actuator and the kite model. Assuming nearly constant tension along the tether, the spring and damper constants of the material are used, but scaled according to the relation of tether length and one tether piece. Using these assumptions, the constraint on the tether-wise direction is used to calculate the tether force on every element and consequently integrate the equations of motion for all points. This approach is similar to the method described in [9].
4 Simulation Results

The results of this sections are obtained using the model described in the previous section. Model parameters for estimation are shown in Tab. 1. The kite is controlled to fly figure-eight trajectories during reel-out, and to fly windward to reel-in. A trajectory of a flight path is shown in Fig. 1. During all simulations a turbulence of 5% was added to the wind. The turbulence has only minor effects on the estimation quality within bounds of sensible operation but affects control accuracy, which is not discussed here.

A simplified point-mass model is used to explain the results of a complex aerodynamic and mechanical system. Thus, the identified aerodynamic properties cannot be compared directly to simulation parameters. The states of position and velocity are necessary for control applications, and wind vector and airspeed are useful for advanced control strategies.

4.1 Wind Step Response

In this subsection, a step change on the wind conditions is applied. After 5 minutes, the direction changes about 20° and the speed increases from 7 m/s to 10 m/s. The errors in wind speed and direction are shown in Fig. 2a and Fig. 2b respectively. Wind speed errors below 0.5 m/s are achieved after 2 minutes for airborne sensors and 5 minutes for ground based estimation. The new wind direction is found faster. For errors below 5° ground based estimates take 3 minutes and additional acceleration and airspeed pressure setups take 2 minutes. Additional GPS data results in accurate direction estimates in 1.5 minutes. In contrast to wind speed, a gain in wind direction
(a) Wind speed error.

(b) Wind direction error.

(c) Kite velocity error $\|\hat{v} - v\|$.

Figure 2: Simulation results during a step change in wind direction and speed.

Accuracy can be seen with GPS data.

Velocity errors are shown in Fig. 2. During the controller adaptation time, the error graphs differ from the periodically repeated curves past 9 minutes and before the step change. With additional accelerometer and pressure sensors, the velocity error is reduced significantly. Since GPS allows direct measurement of the velocity, the error can be reduced even further.

4.2 Limit Accuracies

In the previous section different sensor setups during a step change in wind conditions were compared. During constant conditions the estimation errors converge to periodic phases with the period time $T$. The influence of different wind conditions on the accuracy can be compared using the mean error value
over one period, defined in the following equations.

\[
e_{\text{vel}}^\infty = \frac{1}{T} \int_{T} \|\hat{v} - v\| \, dt \tag{18}
\]

\[
e_{\text{pos}}^\infty = \frac{1}{T} \int_{T} \|\hat{x} - x\| \, dt \tag{19}
\]

\[
e_{w}^\infty = \frac{1}{T} \int_{T} \|\hat{w} - w_{xy}\| \, dt . \tag{20}
\]

The error in velocity is shown in Fig.\[3a\]. Additional accelerometer and airspeed pressure measurements significantly reduce the velocity error. Without these measurements, the velocity estimates are solely corrected due to the angular measurements that are not only lagging behind on the true movement, but misrepresent the true velocity due to the discrepancy of tether length and distance. An effect that increases with wind speed. There is a flat optimum at about 7.5 m/s in velocity accuracy with additional accelerometer measurements. The negative effect of increased reel-in time and the positive effect of increased airspeed pressure result here in the most accurate estimation. Using GPS velocity data, the error decreases further to under 1 m/s. Due to the discrepancy between ground based measurements and GPS data, the residual could probably be decreased further by neglecting angular measurements, or increasing their uncertainty, during GPS availability. Position errors shown in Fig.\[3b\] are increasing with wind speed, and additional airborne sensors improve the accuracy.

The limit accuracy in wind estimation is shown in Fig.\[3c\]. The errors are similar across the different measurement setups. For ground based measurement only, the errors are increasing with wind speed, but not significantly faster than the standard deviation of the turbulence rises. Additional airborne measurements seem to rise slower than the turbulence. However, the accuracy fluctuates more with the periodic trajectory which results at the wind speed, than with the wind speed itself. The steady-state trajectories are not smooth functions of the wind speed. There are only discrete numbers of figure eight paths to fly before the backtracking phase starts. For example, at a wind speed of 7.5 m/s to 8 m/s the kite may fly 4 figure eight trajectories before the reel in. At 9 m/s the kite may only fly 3 figure eight trajectories. Due to the long adaption rates of wind speed estimates, these control decisions have a significant effect on wind speed accuracy. This stands in contrast to the other errors, where the adaption rates are short in comparison to the trajectory pattern. Although, the effect is hinted in the position errors in Fig.\[3b\], in which a step in the error values between 8 m/s and 8.5 m/s can be seen.
Figure 3: Limit accuracies (see equations (18), (19) and (20)) over different wind speeds with quadratic regression fits. The higher the wind speed, the faster the movement and the shorter the periods in backtracking.
(a) Ten minute mean values of the wind speeds during the flight day.

(b) Operational altitudes (Min/Max/Mean over 10 minutes). The kite was landed twice past 4pm.

(c) Ten minute mean values of the wind direction during the most interesting segment of the day, where the wind shear becomes apparent and the speeds rise.

Figure 4: Experimental wind speed and direction.
5 Experimental Results

In this section results obtained during a joint flight program with the IWES Institute on the 19th of June 2013 are presented. Wind speed measurements at kite height were obtained using a pulsed lidar system. Since no additional measurements on the state of the kite or more information about the aerodynamic assumptions are available, the wind measurements are the benchmark to validate the filter estimates.

5.1 Setup

No airborne measurements besides inertial accelerations were available during the course of the tests. The results of the estimates and measurements between noon and 22:30 are presented. During warm and sunny summer days, the wind conditions at the site have a remarkable pattern. With sunshine, the wind speeds during the day are low, usually under 5 m/s, with heavy turbulence especially in the z-direction. There are no significant differences between ground conditions and conditions at 200m altitude. Operation during these conditions is difficult, because the tether tension needs to be very low. When the temperature drops during dusk, the wind speed increases over all altitudes with reduced turbulence. Additionally, an altitude dependent profile becomes apparent, with higher wind speeds and consequently significantly higher energy densities at higher altitudes.

Pulsed lidar measurement systems allow measurements of wind speeds in variable altitudes [11]. In [10] lidar and anemometer measurements of wind turbines at altitudes of 100m are compared and show excellent correlation. A Leosphere WINDCUBEv2 was used to obtain the measurements.

5.2 Results

The measurements and the wind speed estimates are shown in Fig. 4. Operational altitude is shown in Fig. 4b to allow the comparison between filter estimate at operational height and lidar measurement. During the day until 4:30pm, high turbulence and similar wind speeds across all altitudes can be seen in Fig. 4a. The wind speed estimates are similar to the measurements, but occasionally 0.5 m/s to 1 m/s lower. When the turbulence decreases and the wind profile separates after 5:30 pm, a close following of the estimates and the measurements at operational altitudes can be seen, including the peaks and dips. There are, however, additional dips. The dip at 7:30 pm corresponds to a decrease in operational altitude. This illustrates the difficulties that arise. Not only the trajectories greatly affect the estimation quality. A change in aerodynamic parameters, for example because

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[6] http://www.iwes.fraunhofer.de

[7] http://www.leosphere.com/
the pilot decides that a change in the difference between the control lines and the main line are in order to improve flight stability, will have an impact on the wind speed estimation. The system takes time to adapt to the changed aerodynamics, and in between additional dips or peaks may occur. In Fig. 4c the wind directions are shown during the segment of the flight, where the low wind speed turbulent conditions change to the separated conditions. The direction estimate follows the measured values at the different altitudes, and most closely the measurement at 140m which corresponds to the mean operational altitude.

6 Summary and Outlook

A simple nonlinear point-mass model with aerodynamic parameter and wind velocity states for an airborne wind energy converter system was presented. The model was used with an unscented Kalman filter to estimate the kinematic states, the aerodynamics and the current wind conditions with three different sensor setups with different cost and reliability requirements in mind. Using a significantly more detailed simulation model including a rigid-body model of the kite, sophisticated aerodynamics, detailed actuator dynamics and a discretized elastic tether the approach was evaluated for more elaborate system models. The limit accuracies of mean errors over steady-state periodic trajectory for constant wind speeds were used to evaluate the filter accuracy over a range of different wind speeds. The simulations show good results with respect to wind estimation even for low-cost ground-based-only sensors. Decreased reaction times can be achieved with more advanced airborne sensors. Acceleration and airspeed pressure data result in significant improvements for velocity estimation, while GPS measurements unsurprisingly lead to higher position accuracy.

The simulations show that the results depend strongly on the flown trajectory. Long backtracking times reduce the accuracy due to strong sagging and slow movement, as well as significant aerodynamic changes due to strong sideslip. Using different wings, a different backtracking trajectory is possible by reducing the glide-ratio significantly and directly flying directly towards the ground station. The results will need to be reevaluated with these trajectories, at least with respect to the influence of wind speed on accuracies.

It will be possible to use full airspeed vector measurements with the EK30 in the near future. It may allow for considerable shorter adaption times with regards to the wind speed, and thus could allow turbulence assessment. A point mass model may not be the most efficient use of data, with a setup including inertial measurements, GPS data and airspeed vectors.

In June 2013 flights with the EnerKíte EK30 research platform were conducted, with additional lidar wind speed measurements in a range of altitudes with detailed results up to 200 m. The comparison of filter estimates
and lidar measurements show a close correlation. Although it is difficult to quantify the error due to a range of altitudes of operation with significantly different local wind speeds, the estimation seems to be very close to the measured values at the mean altitude. However, turbulence levels remain difficult to estimate from kite dynamics. The response time of the wind estimates is between half a minute for airborne sensors to two minutes without airborne sensors, and thus short time wind variance cannot be picked up. While airborne measurements are able to decrease this response time considerably, for reliable turbulence estimates the response time is still too slow. The wind speed estimation is sensitive to aerodynamic changes and thus great care must be taken with the estimated wind speed values.

The good correlation with the wind speed measurements is encouraging, but the ability to fly in a range of altitudes is not efficiently used. A common model for the local wind shear is a logarithmic profile, see for example [20]. However, these models are only valid up to a certain altitude. The model-based approach may allow us to estimate the wind conditions within the bounds of the operational altitudes, as long as the wind shear model is suitable at the site. With additional comparisons and sufficiently close correlation, these estimates may be a viable option for reliable wind site evaluation.

**Acknowledgments**

This research was made possible by funds from the ILH\(^8\). The author would like to express his gratitude to the EnerKíte Team, especially Alexander Bormann for discussion and proofreading and Stefan Skutnik for insight into sensors.

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