Motion Estimation for Tethered Airfoils with Tether Sag*

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Abstract—In this contribution a motion estimation approach for the autonomous flight of tethered airfoils is presented. Accurate data measurement is essential for the airborne wind energy sector to optimize the harvested wind energy and for the manufacturer of tethered airfoils to optimize the kite design based on measurement data. We propose an estimation based on tether angle measurements from the ground unit and inertial sensor data from the airfoil. In contrast to existing approaches, we account for the issue of tether sag, which renders tether angle measurements temporarily inaccurate. We formulate a Kalman Filter which adaptively shifts the fusion weight to the measurement with the higher certainty. The proposed estimation method is evaluated in simulations, and a proof of concept is given on experimental data, for which the proposed method yields a three times smaller estimation error than a fixed-weight solution.

I. INTRODUCTION

A. Motivation

Autonomous flying tethered airfoils have two possible areas of application, one of which is the field of Airborne Wind Energy Systems (AWES). The motivation of harvesting high-altitude wind energy has led to a number of start-ups and publications in this field [1],[2],[3],[4]. In the developed concepts, a rigid or flexible airfoil is bound to a ground unit (GU) by tethers. The airfoil is flying in crosswind conditions which generates a force on the tether. This force causes the tether to unwind and drives the generators. For an autonomous flight of the airfoil, an accurate estimation of the airfoil’s motion state and a robust feedback control of these states is essential.

The second application is the systematic testing and further development of sport kites. For this purpose, Hummel et al. developed a test set-up for the characterization of the dynamic properties of tethered airfoils [5]. The applications share the strong demand of a robust, real-time and low-cost solution for the airfoil’s motion state estimation.

B. State of the Art

Information of the state can be obtained by tether angle sensors, Inertial Measurement Units (IMU), cameras, Global Navigation Satellite System (GNSS) receivers, barometers and range sensors using ultra-wideband radios. Contributions that consider AWES like [6],[7],[8] have made use of different sensor fusion approaches for the state estimation problem. Fagiano et al. compared different fusion setups with an IMU, a GNSS receiver, a barometer and tether angle sensors [9]. They concluded that for short tether length a Kalman Filter (KF) state estimator based on IMU data and tether angle measurements is the most effective since the GNSS receiver is restricted by slow update rates. Furthermore, position data from GNSS receivers can suffer dropouts due to rapid changes of the antenna orientation during dynamic flights [10]. Hesse et al. pointed out that the triangulation with the tether angles can only ensure a valid position measurement if the tether force is sufficient [11]. If the tether force is not sufficient, the impact of gravity and wind can lead to sagging of the tether (Fig. 2). This would result in a triangulation error and uncertainty of the tether angle measurements. Therefore, they introduced an expanded setup with range sensors using ultra-wideband radios and a camera system for visual position tracking. The results showed that the tether dynamics is complex and affected by sag and delay, especially for longer tether lengths. They formulate an Extended Kalman Filter (EKF) to fuse the tether angles with gyroscope data. By adding delay-states to the estimation, they take the delayed tether angle measurement into account. This results in a significant reduction of the position estimation delay.

Even though position measurements from cameras are independent from the tether dynamics, new problems arise. A visual detection algorithm has to cope with dynamic backgrounds, change of illumination and backlighting.

Fig. 1. Coordinate system $G$ is based at the GU and coordinate system $S$ is linked to the airfoil. The position of the airfoil is described by the tether angles $\phi$, $\theta$ and the tether length $r$. Because of the constant tether length, the airfoil’s trajectory is bound to the sphere. Based on [5].

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Furthermore, camera-based solutions are limited by line of sight restrictions which prohibits usage during foggy weather and night. This reduces the operating hours to a maximum of twelve hours daily. Especially for AWES, this is a significant downside.

C. Problem description and solution approach

The problem of the motion state estimation for tethered airfoils lies in the reliability and accuracy of the position measurements. Camera-based measurements are limited by the line of sight restriction, dynamic backgrounds and light conditions. The tether angles become inaccurate when sagging occurs, invalidating the straight-tether assumption for the triangulation. During normal test conditions, a sagging of the tether is rare, and if it occurs, it typically occurs for the duration of a few seconds. Despite its rarity, the phenomenon is very important because it leads to false motion state estimates, which may result in a crash of the autonomously steered system and thus represents a great risk for the airfoil. We, therefore, want to propose a solution for the motion state estimation based on tether sag. The idea of adaptively adjusting the covariance matrices is already known in the literature [8],[9],[11], where uncertainties are represented by a fixed duration of a few seconds. Despite its rarity, the phenomenon accounts for tether sag. The idea of adaptively adjusting the covariance matrices is already known in the literature [12],[13],[14]. We transfer this idea to the above mentioned problem and propose a simple and intuitive approach to the adaptive adjustment of the covariance matrices.

II. SYSTEM DESCRIPTION

The testing equipment shown in Fig. 2 consists of a GU that is linked to a flexible airfoil by three tethers. The length of the two steering tethers can be controlled via actuators by manual commands or by a feedback control algorithm. The third tether has a fixed tether length \( r = 26 \text{m} \) and transmits the force generated by the airfoil to the GU. A load cell is placed in the third tether to measure the tether force \( F_t(k) \) at the discrete time instance \( k \). Rotary encoders in the pivot joint at the GU provide the tether angles \( \tilde{\phi}(k) \) and \( \tilde{\theta}(k) \). Here, the notation \( ' \cdot ' \) stands for the measurement of the tether angles defined in Fig. 1. A MEMS-IMU (Micro-Electro-Mechanical System) attached to the airfoil’s middle strut measures the magnetic field \( \mathbf{m}(k) \), angular velocity \( \mathbf{w}(k) \) and acceleration \( \mathbf{a}(k) \). Another MEMS-IMU is placed at the GU. Furthermore, we make the assumption that the angle measurements are not delayed since the tether length is relatively short.

A. Coordinate Systems

Due to the fixed tether length, the airfoil’s trajectory is bound to a quarter sphere with the GU in the center. We further assume that when sagging occurs the movement of the airfoil in radial direction towards the GU is negligible. To describe the position of the airfoil, we introduce a right-handed coordinate system \( \mathcal{G} \) in Fig. 1. The origin of the coordinate system is fixed to the GU. The \( x \)-axis is parallel to the ground and points into the aforementioned quarter sphere. The \( z \)-axis points upwards, and the \( y \)-axis completes a right-handed coordinate system. The airfoil’s Cartesian position \( \mathbf{G}\mathbf{p}(k) \) in the coordinate system \( \mathcal{G} \) can be calculated from the elevation angle \( \tilde{\theta}(k) \in [0; \frac{\pi}{2}] \) and the azimuth angle \( \tilde{\phi}(k) \in [-\frac{\pi}{2}; \frac{\pi}{2}] \) as follows:

\[
\mathbf{G}\mathbf{p}(k) = \begin{bmatrix}
\mathbf{G}\mathbf{x}(k) \\
\mathbf{G}\mathbf{y}(k) \\
\mathbf{G}\mathbf{z}(k)
\end{bmatrix} = r \begin{bmatrix}
\cos(\tilde{\theta}(k)) \\
\sin(\tilde{\phi}(k)) \sin(\tilde{\theta}(k)) \\
\cos(\tilde{\phi}(k)) \sin(\tilde{\theta}(k))
\end{bmatrix}.
\]
The inverse operation is defined by
\[ \vartheta(k) = \arccos \left( \frac{x(k)}{r} \right) \]  
(2) and
\[ \phi(k) = \arccos \left( \frac{z(k)}{r_1 \sin(\vartheta(k))} \right). \]  
(3)

The local coordinate system \( S \), which moves with the airfoil, is depicted in Fig. 1. The local \( z \)-axis points in the flight direction, the local \( x \)-axis points radially away from the GU and the local \( y \)-axis completes a right-handed coordinate system. When the airfoil is at the position \( (\varphi = 0^\circ, \vartheta = 0^\circ) \), the orientations of the coordinate systems \( G \) and \( S \) are equal.

The measurements of the IMU in the local coordinate system \( S \) are denoted by \( ^S\omega(k), ^S\mathbf{m}(k) \) and \( ^S\mathbf{a}(k) \). The third coordinate system \( E \) shown in Fig. 3 is an earth-fixed South-East-Up (SEU) system. By means of sensor fusion of \( ^S\omega(k), ^S\mathbf{m}(k) \) and \( ^S\mathbf{a}(k) \), the IMU attached to the airfoil can determine its orientation \( ^E\mathbf{q}(k) \) with respect to the inertial coordinate system \( E \). The IMU on the GU provides the orientation \( ^G\mathbf{q}(k) \). For this purpose, we use the quaternion-based algorithm proposed in [15], which is known to yield estimation errors in the range of a few degrees [16], [17]. The following quaternion-based vector transformation allows to express the acceleration \( ^S\mathbf{a}(k) \) from system \( S \) in system \( G \).

\[
\begin{bmatrix}
0 \\
^E\mathbf{a}(k)
\end{bmatrix} = ^S\mathbf{q}(k) \otimes \begin{bmatrix}
0 \\
^S\mathbf{a}(k)
\end{bmatrix} \otimes ^G\mathbf{q}^*(k) \]  
(4)

\[
\begin{bmatrix}
0 \\
^G\mathbf{a}(k)
\end{bmatrix} = ^E\mathbf{q}(k) \otimes \begin{bmatrix}
0 \\
^E\mathbf{a}(k)
\end{bmatrix} \otimes ^G\mathbf{q}^*(k) \]  
(5)

Here the operator \( \otimes \) stands for a quaternion multiplication and \( ^G\mathbf{q}^*(k) = ^G\mathbf{q}^{-1}(k) \) for the conjugated quaternion. The coordinate transformation defined by (4) and (5) can also be described by the rotation matrix \( ^G\mathbf{M}(k) \).

Both IMUs are connected to a micro-controller where the orientation estimation algorithm, proposed in [15], is installed. The aforementioned measurements of the tether angles, the tether force, the acceleration and the orientations are updated in time intervals of \( t_s = 20 \text{ms} \) and merged on an embedded controller at the GU. The measurements are then used to calculate a valid and robust estimation of the airfoil’s position on the sphere.

III. METHOD

As a state estimator we introduce a discrete KF. Here, we follow the notation of [9] where ‘\( \cdot \)’ describing a measurement and ‘\( \cdot \)’ an estimate. The position and velocity dynamics of the system are modeled by

\[
\begin{bmatrix}
^G\mathbf{p}(k+1) \\
^G\mathbf{\dot{p}}(k+1) \\
^S\mathbf{a}_{\text{bias}}(k+1)
\end{bmatrix} =
\begin{bmatrix}
\mathbf{I}_3 & t_s \mathbf{I}_3 & 0_3 \\
0_3 & t_s \mathbf{I}_3 & -t_s \mathbf{G}(k) \mathbf{M}(k)_3 \\
0_3 & 0_3 & \mathbf{I}_3
\end{bmatrix}
\begin{bmatrix}
^G\mathbf{p}(k) \\
^G\mathbf{\dot{p}}(k) \\
^S\mathbf{a}_{\text{bias}}(k)
\end{bmatrix} +
\begin{bmatrix}
0_3 \\
t_s \mathbf{I}_3 \\
0_3
\end{bmatrix}^G\mathbf{a}(k) + \mathbf{w}(k) \]  
(6)

In contrast to the state-of-the-art KF, were the ratio between \( Q \) and \( R \) is fixed, we propose an adaptive adjustment depending on the tether force. Therefore, we introduce a dimensionless weighting factor \( W(k) \) that increases when the tether force \( F_t(k) \) decreases. This yields a statement about the uncertainty of the tether angles and adjusts the weighting adaptively. \( W(k) \) is then calculated as follows:

\[
W(k) = \begin{cases}
\frac{1}{10^r} \left( \frac{1}{F_t(k)} \right)^r, & \text{for } F_t(k) > 0 \\
10^{-10}, & \text{for } F_t(k) = 0
\end{cases} \]  
(10a)

(10b)

Based on data analysis and experience it was concluded that tether sag becomes significant when the tether force drops below 50 N and is negligible above 100 N. In Fig. 4 the function is plotted for different \( r \) and \( c \) values to give an intuition on the functions behavior. The exponent \( r \) can be used to set the bending of the function and the value \( c \) for scaling it. For \( r = 5 \) and \( c = 10.5 \) the weight \( W \) quickly increases when the tether force is below 50 N and goes to zero when the tether force is above 100 N. The parameters \( r \) and \( c \) can be understood as tuning parameters for the adaptive weighting and may change depending on the set-up including kite, tether and pivot joint. A scheme of the fusion model is illustrated in Fig. 5.
Fig. 5. Scheme of the fusion model. The tether angles $\tilde{\theta}$, $\tilde{\phi}$, provided by the rotary encoders, are used to calculate the position $G\tilde{p}$. The position $G\tilde{p}$ is then fused with the acceleration measurement $G\tilde{a}$ from the IMU to estimate the position $G\hat{p}$. The load cell provides the tether force $F_t$ to adjust the weighting through $W$. The position $\hat{G}\tilde{p}$ is then expressed via $\hat{\theta}$ and $\hat{\phi}$.

IV. SIMULATION

After describing the fusion method, we want to analyze its performance by comparing it to a state-of-the-art KF with fixed variances as used in [9]. We approach the problem by simulating a sagging tether. This allows us to compare the fusion method to the true reference which can be difficult to obtain in experiments. With the simulation, we want to investigate if the described method with adaptive weights is favorable over the state-of-the-art filter. Therefore, we compare the position $G\tilde{p}_{\text{true}}$ that is unaffected by sagging with the position $G\tilde{p}_{\text{false}}$ that is affected. A reduction of the tether force occurs when the tether sags. This results in a difference between the true angles and the measured angles. For the angle $\tilde{\phi}$, this is illustrated in Fig. 6. The tether force not only depends on the wind condition but also on the position of the airfoil. When the airfoil is at the zenith position the generated lift is minimal and gradually increases when the airfoil moves into the sphere.

The simulation is divided into the following steps:

1) We consider $G\tilde{p}_{\text{true}}$ to be the true position of the airfoil.
2) To simulate a sagging tether, we add and scale a sinusoidal error to the position $G\tilde{p}_{\text{true}}$ and the tether force $F_t$. This results in the error periods depicted in Fig. 7 and Fig. 8. The dashed lines are representing the defective position $G\tilde{p}_{\text{false}}$ and the defective tether force $F_{t,\text{false}}$.

3) To generate acceleration data, we twice differentiate the true position $G\tilde{p}_{\text{true}}$ to obtain the true acceleration $G\tilde{p}_{\text{true}}$. For the moment, zero bias and noise is assumed.
4) We then use the KF with the defective position $G\tilde{p}_{\text{false}}$ and the true acceleration $G\tilde{p}_{\text{true}}$ to estimate the true position $G\hat{p}_{\text{true}}$.

$$
\begin{bmatrix}
G\tilde{p}(k+1) \\
G\tilde{p}_{\text{false}}(k) \\
G\tilde{a}_{\text{bias}}(k+1)
\end{bmatrix} =
\begin{bmatrix}
I_3 & t_k & I_3 \\
0_3 & I_3 & -t_k & S(M)_k & 0_3 \\
0_3 & I_3 & I_3 & 0_3
\end{bmatrix}
\begin{bmatrix}
G\hat{p}(k) \\
G\tilde{p}(k) \\
G\tilde{a}(k)
\end{bmatrix} +
\begin{bmatrix}
0_3 \\
0_3 \\
0_3
\end{bmatrix}
G\tilde{p}_{\text{true}}(k) + w(k) \quad (11)
$$

$$
G\tilde{p}_{\text{false}}(k) = [I_3 & 0_3 & 0_3] \begin{bmatrix} G\tilde{p}(k) \\ G\tilde{p}_{\text{false}}(k) \\ G\tilde{a}_{\text{bias}}(k) \end{bmatrix} + v(k). \quad (12)
$$

5) Fig. 7 shows the results of the position estimation with the fixed-weight covariance matrix

$$
R(k) = \begin{bmatrix}
W_{\text{fix}} & 0 & 0 \\
0 & W_{\text{fix}} & 0 \\
0 & 0 & W_{\text{fix}}
\end{bmatrix} \quad (13)
$$

with

$$
W_{\text{fix}} \in \{10^4, 10^5, 10^6\}.
$$

6) Fig. 8 shows the results of the position estimation with the adaptive-weight covariance matrix

$$
R(k) = \begin{bmatrix}
W(k) & 0 & 0 \\
0 & W(k) & 0 \\
0 & 0 & W(k)
\end{bmatrix} \quad (14)
$$

with $W(k)$, defined in (10), and with

$$
r \in \{3.5, 4, 4.5, 5\},
$$

$F_{t,\text{false}}$ and $c = 15$.

Since the acceleration data $G\tilde{p}_{\text{true}}$ were calculated from the true position, a double integration of the data would lead back to the unaffected true position. After the described method in (11) and (12), a fusion with the defective position data $G\tilde{p}_{\text{false}}$ and the unaffected acceleration $G\tilde{p}_{\text{true}}$ is expected to approach the true position $G\hat{p}_{\text{true}}$ with increasing uncertainty on $G\tilde{p}_{\text{false}}$.

Fig. 7 and Fig. 8 are showing the estimated position in respect of different weights $W$. It is visible that during the error period, a higher covariance on the position data leads to a better approximation of the true position. Fig. 8 shows that by linking the tether force to the weight of the position $G\tilde{p}_{\text{false}}$, the estimate converges faster to the true position $G\hat{p}_{\text{true}}$ after the error period ended. Whereas, an induced error in Fig. 7 leads to a longer lasting difference between the estimate and the true position. The observation in Fig. 8 leads to the question why not to increase the weight $W$ until the estimate fits the true position. Since real life measured acceleration data are corrupted by noise and bias, an integration over time will lead to a sustained difference for the position.
In Fig. 9 Gaussian white noise with a standard deviation of 0.1 m s\(^{-2}\) and a bias of 0.3 m s\(^{-2}\) are modeled in the sensor frame \(S\), transformed in the frame \(G\) and added to the acceleration data \(\ddot{\mathbf{p}}_{\text{true}}\). It can be seen that by a further reduction of the \(r\) value to \(r = 3\) and therefore increasing the weight \(W\), the estimate worsens compared to \(r = 3.5\). The performance of the estimates is quantified in Fig. 10, showing the average absolute difference between the true position and the estimates over the depicted time interval. Regarding the overall accuracy, the exponent \(r = 3.5\) has the lowest difference to the true position. This illustrates that the estimation problem requires balancing between accurate long-term stability and sensitivity to tether sag errors.

V. EXPERIMENT

The working mechanism of the proposed method has been investigated by simulation. We now want to provide a proof of concept for the proposed method using experimental data. Therefore, we apply the method to measurement data which were acquired with the aforementioned testing equipment.

Fig. 8. Simulation: The plots show the true position \(\mathbf{p}_{\text{true}}\), the simulated position \(\mathbf{p}_{\text{false}}\) and the estimated position \(\hat{\mathbf{p}}\) (colored) for different exponents \(r\) of the adaptive weight \(W\) with \(c = 15\). With a decreasing exponent \(r\) and therefore higher uncertainty on the position \(\mathbf{p}_{\text{false}}\), the estimated position fits better to the true position \(\mathbf{p}_{\text{true}}\). In comparison to the fixed weight estimation, the adaptive weight estimation converges faster when the error period ends.

Fig. 9. Simulation: The plots show the true position \(\mathbf{p}_{\text{true}}\), the simulated position \(\mathbf{p}_{\text{false}}\) and the estimated position \(\hat{\mathbf{p}}\) (colored) for different exponents \(r\) of the adaptive weight \(W\) with \(c = 15\). To the acceleration data used for the fusion, bias and noise were added, leading to a greater off-set for the estimation.
and a wind speed of 5 m s$^{-1}$. The data were recorded during a flight maneuver where the kite is held in the zenith position ($\varphi = 0^\circ$, $\theta = 90^\circ$). In Fig. 11 the measurements and estimations of the angles $\varphi$ and $\theta$, the tether force $F_t$ and the weight $W$ are shown. Between $t = [85\, s, 86\, s]$ the tether force decreases to $F_t = 20\, N$ and as a result the tether starts sagging. This becomes clearer when comparing the tether angles with the camera data (delay and offset compensated) which shows no such event and can be understood as the true course of the airfoil and is treated as ground-truth. A comparison between the fixed-weight and the adaptive-weight estimation shows that latter converges faster and approximates the camera data better. Furthermore, overshooting can be seen for the fixed-weight estimation. For the adaptive-weight $W$, $r = 5$ and $c = 10.5$, and for the fixed-weight $W_{fix} = 10^3$ showed the best results.

VI. CONCLUSION

We have considered the problem of estimating the position of tethered airfoils from tether angle measurements and IMU data, whereby we focused on the effect of tether sag on the position. We proposed a novel method that adaptively weights between the tether angles and the IMU data according to the tether force. In comparison to a state-of-the-art KF, the developed fusion method has demonstrated to converge significantly faster on simulated and experimental data and has led to an improved accuracy. The method assures that the tether angles are trusted whenever they are known to be reliable. Furthermore, the method uses the IMU data to overcome the periods when sagging occurs and the tether angles are unreliable. However, the experimental data only provides a proof of concept and a detailed validation study with an accepted ground-truth measurement will be subject of future research.

We conclude that the developed method allows the user to increase the position estimation performance for tethered airfoils regarding the accuracy. Moreover, we provide a solution that is independent from camera data and is not restricted by weather or light conditions. The proposed method uses low-cost IMUs and can be applied for the systematic testing of sport kites as well as for AWESs.

APPENDIX

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