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A Nonlinear Model-Based Wind Velocity Observer for Unmanned Aerial Vehicles

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Abstract: This paper presents an exponentially stable nonlinear wind velocity observer for fixed-wing unmanned aerial vehicles (UAVs). The observer uses a model of the aircraft combined with a GNSS-aided inertial navigation system (INS). The INS uses an attitude observer together with a pitot static probe measuring dynamic pressure in the longitudinal direction as well as the airspeed. The observer is able to estimate the wind velocity and from this compute the relative velocity, which directly contains information about the angle of attack (AOA) and sideslip angle (SSA). The nonlinear observer is also able to estimate the scaling factor of the pitot static probe measurement and there are no requirements on persistence of excitation (PE) of the UAV maneuvers. The computational footprint is smaller than the conventional Kalman filter, which makes the algorithm well suited for embedded systems. The designed observer is proven exponentially stable under stable flight and through simulations it is verified that the estimates converge to the true values of a realistic wind velocity when there are no model errors.

Keywords: Nonlinear Observers, Wind Velocity, Unmanned Aerial Vehicles, Inertial Navigation Systems

1. INTRODUCTION

The ability to correctly estimate the wind and relative velocity for a fixed-wing UAV is very important. Knowledge of the wind velocity can be exploited in the control system where the wind can be treated as a disturbance and from the relative velocity both the AOA and SSA are directly computable. The AOA and SSA contain useful information related to the performance and safety of the aircraft, e.g. the value of the AOA is directly related to whether the wing is under stall conditions which leads to turbulent air flow and a considerable drop in the wing-produced lift force (Beard and Mclain [2012]). Autonomous landing operations also require information about the wind.

Larger fixed-wing aircraft are often equipped with sensors, such as vanes and multi-hole pitot probes, that provide measurements of the wind velocity along with the AOA and SSA. For a small UAV, this solution is expensive and impractical due to space limitations, weight constraints and increased power consumption. Yet having the information about the wind would be useful for the relatively inexpensive aircraft to perform autonomous missions such as a payload deployment or pickup, or a precise landing in a small net aboard a ship. It is therefore highly desirable to have a wind and relative velocity observer only utilizing measurements obtained by the standard sensor suite equipped on a UAV, an inertial measurement unit (IMU), a Global Navigation Satellite System (GNSS) receiver (Beard and Mclain [2012], Farrell [2008]), and a pitot static probe in conjunction with a differential pressure sensor supplying an air speed measurement (Beard and Mclain [2012]).

When designing an observer for a nonlinear system a common approach is to use the Extended Kalman Filter (EKF) (Brown [1972]). This approach has been used for developing wind velocity observers based on the kinematic equations in combination with an aerodynamic model of the aircraft, e.g. Kumon et al. [2005], Long and Song [2009], Langelaan et al. [2011], Ramprasadh and Arya [2012], and Cho et al. [2013]. Rodriguez et al. [2007] present a method for estimating wind velocity for a miniature aerial vehicle (MAV) by using optical flow. Paces et al. [2010] proposes a twin differential sensor setup for estimating the AOA and SSA. An EKF structure with a pitot static probe is also used by Hansen and Blanke [2014] for detecting sensor failure and Lie and Gebre-Egziabher [2013] propose an EKF for estimating the wind velocity without the pitot static probe air speed measurement. A model-free wind velocity observer has been proposed by Cho et al. [2011] and Rhudy et al. [2013] avoiding the aircraft model. Johansen et al. [2015] have also developed a model-free observer, which is able to estimate the pitot static probe correction factor and thus provide online calibration and fault detection of the airspeed sensor. The model-free observer requires that the yaw and pitch motions are persistently excited (PE) in order to ensure convergent estimates. An extension that also uses IMU measurements and lift coefficient estimation is given in Wenz et al. [2016]. The observer in this paper removes the PE condition for the price of using a relatively simple aircraft model to obtain convergent estimates.

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1.1 Contributions of this paper

The main contribution of the paper is a nonlinear observer that provides exponential stability and convergent estimates of wind velocity from which estimates of AOA and SSA can be derived. The observer utilizes a standard UAV sensor suite combined with a relatively simple aerodynamic model of the aircraft, which is updated using propeller revolutions and pitot static probe measurements. An advantage of the observer is that no maneuvers or requirements for PE are needed. A potential disadvantage is that model errors may give errors in the estimates. Another contribution of the paper is the compact representation of the small aircraft model of Beard and Mclain [2012] using the matrix-vector representation of Fossen [2011]. For the proof, the aerodynamic forces were divided into a stabilizing linear term and a vector of the remaining nonlinear aerodynamic forces with physical properties such as energy dissipation, which can be exploited when constructing the Lyapunov function for observer error dynamics. Finally, the nonlinear observer is validated through simulation using a small fixed-wing UAV exposed to wind.

1.2 Notation and preliminaries

For a vector or matrix $\boldsymbol{X}$, $\boldsymbol{X}^\top$ denotes its transpose. The operator $\|\cdot\|$ denotes the Euclidean norm for vectors and the Frobenius norm for matrices. For a vector $\boldsymbol{x} \in \mathbb{R}^3$, $\boldsymbol{S}(\boldsymbol{x})$ denotes the skew-symmetric matrix:

$$\boldsymbol{S}(\boldsymbol{x}) = \begin{bmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{bmatrix}$$

The $n\times n$ identity matrix is denoted by $\boldsymbol{I}_{n\times n}$ and the $m\times n$ zero element matrix by $\boldsymbol{0}_{m\times n}$. Vectors in the body-fixed (BODY) and North-East-Down (NED) coordinate frames are denoted by the superscripts b and n, respectively. Consequently, the linear velocity vector satisfies $\boldsymbol{v}^n = \boldsymbol{R}\boldsymbol{v}^b$ where $\boldsymbol{R} \in \mathrm{SO}(3)$ is the rotation matrix from BODY to NED.

1.3 Problem formulation

The UAV's velocity over ground can be expressed as the sum of the relative velocity and the wind velocity according to:

$$\boldsymbol{v}^b = \boldsymbol{v}_r^b + \boldsymbol{v}_w^b \tag{1}$$

where $\boldsymbol{v}^b = [u, v, w]^\top$ is the UAV's linear velocity vector, $\boldsymbol{v}_r^b = [u_r, v_r, w_r]^\top$ is the relative velocity vector and $\boldsymbol{v}_w^b = [u_w, v_w, w_w]^\top$ is the wind velocity vector. The goal is to estimate $\boldsymbol{v}_w^b$ and $\boldsymbol{v}_r^b$, since the airspeed V_a, AOA and SSA are recognized as:

$$V_a = \sqrt{u_r^2 + v_r^2 + w_r^2} > 0 \tag{2}$$

$$\alpha = \tan^{-1}\left(\frac{w_r}{u_r}\right) \tag{3}$$

$$\beta = \sin^{-1}\left(\frac{v_r}{V_a}\right) \tag{4}$$

2. UAV RIGID-BODY KINETICS

By application of *Euler's first and second axioms* the rigid-body kinetics for the translational and rotational dynamics of a rigid body is (Fossen [2011])

$$m(\dot{\boldsymbol{v}}^b + \boldsymbol{S}(\boldsymbol{\omega}^b)\boldsymbol{v}^b) = \boldsymbol{f}^b \tag{5}$$

$$\boldsymbol{J}\dot{\boldsymbol{\omega}}^b - \boldsymbol{S}(\boldsymbol{J}\boldsymbol{\omega}^b)\boldsymbol{\omega}^b = \boldsymbol{m}^b \tag{6}$$

where m is the mass of the vehicle, $\boldsymbol{\omega}^b = [p, q, r]^\top$ is the body-fixed angular velocities, $\boldsymbol{J} \in \mathbb{R}^{3\times 3}$ is the symmetric inertia tensor and $\boldsymbol{f}^b$ and $\boldsymbol{m}^b$ are the forces and moments on the vehicle. In Beard and Mclain [2012] it is shown that a small aircraft can be modeled by (5) and (6) where

$$\boldsymbol{J} = \begin{bmatrix} J_x & 0 & -J_{xz} \\ 0 & J_y & 0 \\ -J_{xz} & 0 & J_z \end{bmatrix} \tag{7}$$

is a matrix of products and moments of inertia. The aircraft forces and moments can be approximated by the following formula (Beard and Mclain [2012]):

$$\begin{aligned}\begin{bmatrix} \boldsymbol{f}^b \\ \boldsymbol{m}^b \end{bmatrix} &= \frac{1}{2}\rho V_a^2 S \begin{bmatrix} -C_D(\alpha)\cos(\alpha) + C_L(\alpha)\sin(\alpha) \\ C_{Y_0} + C_{Y_\beta}\beta \\ -C_D(\alpha)\sin(\alpha) - C_L(\alpha)\cos(\alpha) \\ b\left(C_{l_0} + C_{l_\beta}\beta + C_{l_{\delta a}}\delta_a + C_{l_{\delta r}}\delta_r\right) \\ c\left(C_{m_0} + C_{m_\alpha}\alpha + C_{m_{\delta e}}\delta_e\right) \\ b\left(C_{n_0} + C_{n_\beta}\beta + C_{n_{\delta a}}\delta_a + C_{n_{\delta r}}\delta_r\right) \end{bmatrix} \\ &+ \frac{1}{2}\rho V_a^2 S \begin{bmatrix} C_{X_q}(\alpha)\frac{c}{2V_a}q + C_{X_{\delta_e}}(\alpha)\delta_e \\ C_{Y_p}\frac{b}{2V_a}p + C_{Y_r}\frac{b}{2V_a}r + C_{Y_{\delta_a}}\delta_a + C_{Y_{\delta_r}}\delta_r \\ C_{Z_q}(\alpha)\frac{c}{2V_a}q + C_{Z_{\delta_e}}(\alpha)\delta_e \\ b\left(C_{l_p}p + C_{l_r}r\right)\frac{b}{2V_a} \\ c\left(C_{m_q}q\right)\frac{b}{2V_a} \\ b\left(C_{n_p}p + C_{n_r}r\right)\frac{b}{2V_a} \end{bmatrix} \\ &+ \begin{bmatrix} -mg\sin\theta \\ mg\cos\theta\sin\phi \\ mg\cos\theta\cos\phi \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} \frac{1}{2}\rho S_{\mathrm{prop}}C_{\mathrm{prop}}\left((k_{\mathrm{motor}}\delta_t)^2 - V_a^2\right) \\ 0 \\ 0 \\ -k_{T_p}(k_\Omega\delta_t)^2 \\ 0 \\ 0 \end{bmatrix}\end{aligned} \tag{8}$$

where ρ is the density of air, and θ and ϕ are pitch and roll angles. The aerodynamic lift and drag coefficients, $C_L(\alpha)$ and $C_D(\alpha)$, and the aerodynamic force coefficients are nonlinear functions of AOA:

$$C_{X_q}(\alpha) \triangleq -C_{D_q}\cos(\alpha) + C_{L_q}\sin(\alpha)$$

$$C_{X_{\delta_e}}(\alpha) \triangleq -C_{D_{\delta_e}}\cos(\alpha) + C_{L_{\delta_e}}\sin(\alpha)$$

$$C_{Z_q}(\alpha) \triangleq -C_{D_q}\sin(\alpha) - C_{L_q}\cos(\alpha)$$

$$C_{Z_{\delta_e}}(\alpha) \triangleq -C_{D_{\delta_e}}\sin(\alpha) - C_{L_{\delta_e}}\cos(\alpha)$$

while C_{Y_0}, C_{Y_β}, C_{l_0}, C_{l_β}, $C_{l_{\delta a}}$, C_{n_0}, C_{n_β}, $C_{n_{\delta a}}$, $C_{n_{\delta r}}$, C_{Y_p}, C_{Y_r}, $C_{Y_{\delta_a}}$, C_{l_p}, C_{l_r}, C_{m_q}, C_{n_p}, C_{n_r}, and C_{prop} are constant aerodynamic coefficients. $\boldsymbol{\delta} = [\delta_a, \delta_e, \delta_r, \delta_t]$ are the control signals of the aileron deflection, elevator deflection, rudder deflection and throttle deflection. The area of the wing is given by S, the propeller area is S_{prop}, b is the wing span, and c is the mean aerodynamic chord of the wing. k_{motor} is the efficiency of the motor and k_{T_p} and k_Ω are constants that relate the throttle deflection δ_t to the moment opposite the propeller rotation.

3. MATRIX-VECTOR FORM AIRCRAFT MODEL

The aircraft model of Beard and Mclain [2012] can be expressed in matrix-vector form according to (Fossen [2011])

$$\boldsymbol{M}_{RB}\dot{\boldsymbol{\nu}} + \boldsymbol{C}_{RB}(\boldsymbol{\nu})\boldsymbol{\nu} = \boldsymbol{\tau}_{RB} \tag{9}$$