Commun Nonlinear Sci Numer Simulat 33 (2016) 57–69

Contents lists available at ScienceDirect

Commun Nonlinear Sci Numer Simulat

journal homepage: www.elsevier.com/locate/cnsns

Nonlinear control of fixed-wing UAVs in presence of stochastic winds

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ARTICLE INFO

Article history:
Received 26 August 2014
Revised 19 August 2015
Accepted 24 August 2015
Available online 15 September 2015

Keywords:
Nonlinear control
State estimation
Extended Kalman filter

ABSTRACT

This paper studies the control of fixed-wing unmanned aerial vehicles (UAVs) in the presence of stochastic winds. A nonlinear controller is designed based on a full nonlinear mathematical model that includes the stochastic wind effects. The air velocity is controlled exclusively using the position of the throttle, and the rest of the dynamics are controlled with the aileron, elevator, and rudder deflections. The nonlinear control design is based on a smooth approximation of a sliding mode controller. An extended Kalman filter (EKF) is proposed for the state estimation and filtering. A case study is presented: landing control of a UAV on a ship deck in the presence of wind based exclusively on LADAR measurements. The effectiveness of the nonlinear control algorithm is illustrated through a simulation example.

1. Introduction

Nonlinear control of fixed-wing UAVs has attracted considerable research efforts during recent years both for civilian and military purposes. The control approaches developed for such systems include gain scheduling, model predictive control, backstepping, sliding modes, nested saturation, fuzzy control, H_∞ control, dynamic inversion based control, model reference adaptive control, and model based fault tolerant control [1,2,4–10]. Most of these works use simplified kinematic and dynamic models ignoring the wind effects.

There are few UAV research papers that consider the wind effects in the literature. In [11], a nonlinear gust attenuation H_1 controller has been proposed to stabilize the velocity, the attitude and the angular rates. Estimation of the wind using a nonlinear disturbance observer can be found in [12]. In [13], an adaptive backstepping approach is employed to achieve directional control in presence of an unknown crosswind. Online wind parameter estimation using adaptive control techniques can be found in [14]. The work in [15] proposes an image-based visual servo control design for fixed-wing UAVs for locally tracking linear infrastructure in the presence of wind. It must be noted that only attitude and airspeed are usually controlled in the aforementioned papers, and limited attention is paid to the accurate tracking of the translational state variables.

Because of the highly nonlinear and uncertain structure of UAVs, many difficulties arise in the design of linear and nonlinear controllers. Sliding mode control is a preferable option, as it guarantees the robustness of the system against changing working conditions. In this paper, a sliding mode control strategy is proposed for the control of fixed-wing UAVs in the presence of wind.

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http://dx.doi.org/10.1016/j.cnsns.2015.08.026
1007-5704/

The equations of motion (EOMs) of the UAV are nonlinear, but partially affine in control input for the chosen aircraft model. It is assumed that the mean wind velocity and its direction are known constants whereas the gust has a stochastic characterization.

The main contributions of this paper are (i) the development of a novel sliding mode controller that is inherently robust to perturbations, (ii) the design of an extended Kalman filter (EKF) for state estimation purposes, and (iii) the application of the theoretical development to the autonomous landing of UAVs on moving vessels based exclusively on laser radar measurements.

This paper is organized as follows: in Section 2, a full nonlinear dynamic model of an aircraft in the presence of wind is presented. In Section 3, the development of a sliding mode controller (SMC) is described. In Section 4, an EKF method is proposed for the state estimation in the presence of noise. Section 5 gives a case study in which the efficacy of the control algorithm is tested. Finally, some conclusions are drawn in Section 6.

2. Aircraft dynamics

As in [16], let F_o, F_b and F_a denote the Earth-fixed frame (considered inertial under the hypothesis of flat and nonrotating Earth), the body frame, and the aerodynamic frame, respectively. The body frame F_b is defined as the aircraft-fixed axes frame (x_b, y_b, z_b), where x_b is the longitudinal axis, y_b is the lateral axis, and z_b is the directional axis. Moreover, it is assumed that x_b–z_b is the symmetry plane. In what follows, a superscript refers to the frame used within the formulations. The abbreviations $\mathrm{s}(\cdot) = \sin(\cdot)$, $\mathrm{c}(\cdot) = \cos(\cdot)$, and $\mathrm{t}(\cdot) = \tan(\cdot)$ are used throughout the paper.

An engine that can deliver a thrust T whose point of application is M, which has coordinates (x_M^b, y_M^b, z_M^b) in the body frame, is considered. It is assumed that symmetry is respected so that $y_M^b = 0$ and that the engine pitch setting is negligible.

Following [16], the translational EOMs for an aircraft having mass of m can be written as follows:

$$\dot{x}^o = V_a \mathrm{c}\gamma_{2_a} \mathrm{c}\gamma_{3_a} + V_{m_w} \mathrm{s}\psi_w + u_{g_w}^o \tag{1}$$

$$\dot{y}^o = V_a \mathrm{c}\gamma_{2_a} \mathrm{s}\gamma_{3_a} + V_{m_w} \mathrm{c}\psi_w + v_{g_w}^o \tag{2}$$

$$\dot{h}^o = V_a \mathrm{s}\gamma_{2_a} - w_{g_w}^o \tag{3}$$

$$m\dot{V}_a = -D + T\mathrm{c}\alpha_a \mathrm{c}\beta_a - mg\mathrm{s}\gamma_{2_a} - mP_1 \tag{4}$$

$$mV_a\dot{\gamma}_{3_a}\mathrm{c}\gamma_{2_a} = Y\mathrm{c}\gamma_{1_a} + L\mathrm{s}\gamma_{1_a} - T(\mathrm{c}\alpha_a\mathrm{s}\beta_a\mathrm{c}\gamma_{1_a} - \mathrm{s}\alpha_a\mathrm{s}\gamma_{1_a}) - m(P_2\mathrm{c}\gamma_{1_a} - P_3\mathrm{s}\gamma_{1_a}) \tag{5}$$

$$mV_a\dot{\gamma}_{2_a} = -Y\mathrm{s}\gamma_{1_a} + L\mathrm{c}\gamma_{1_a} + T(\mathrm{c}\alpha_a\mathrm{s}\beta_a\mathrm{s}\gamma_{1_a} + \mathrm{s}\alpha_a\mathrm{c}\gamma_{1_a}) - W\mathrm{c}\gamma_{2_a} + m(P_2\mathrm{s}\gamma_{1_a} + P_3\mathrm{c}\gamma_{1_a}) \tag{6}$$

where

$$\begin{aligned}
P_1 &= \left(q_w^b w_w^b - r_w^b v_w^b\right)\mathrm{c}\alpha_a\mathrm{c}\beta_a + \left(r_w^b u_w^b - p_w^b w_w^b\right)\mathrm{s}\beta_a + \left(p_w^b v_w^b - q_w^b u_w^b\right)\mathrm{s}\alpha_a\mathrm{c}\beta_a \\
P_2 &= V_a\left(r_w^b\mathrm{c}\alpha_a - p_w^b\mathrm{s}\alpha_a\right) - \left(q_w^b w_w^b - r_w^b v_w^b\right)\mathrm{c}\alpha_a\mathrm{s}\beta_a + \left(r_w^b u_w^b - p_w^b w_w^b\right)\mathrm{c}\beta_a - \left(p_w^b v_w^b - q_w^b u_w^b\right)\mathrm{s}\alpha_a\mathrm{s}\beta_a \\
P_3 &= V_a\left(p_w^b\mathrm{c}\alpha_a\mathrm{s}\beta_a - q_w^b\mathrm{c}\beta_a + r_w^b\mathrm{s}\alpha_a\mathrm{s}\beta_a\right) - \left(q_w^b w_w^b - r_w^b v_w^b\right)\mathrm{s}\alpha_a + \left(p_w^b v_w^b - q_w^b u_w^b\right)\mathrm{c}\alpha_a
\end{aligned}$$

Here V_a is the air speed, V_{m_w} is the mean wind speed (assumed to act in a horizontal plane at a heading angle ψ_w); (x^o, y^o, h^o) denote the inertial coordinates (range, lateral displacement and altitude) of the aircraft's center of mass; (D, L, Y) are the drag, lift, and side forces (see the expressions in Appendix) which contain the aileron, elevator and rudder deflections $(\delta_a, \delta_e, \delta_r)$; g is the gravitational acceleration; $(\gamma_{1_a}, \gamma_{2_a}, \gamma_{3_a})$ are the aerodynamic bank angle, the aerodynamic climb angle (constrained as $\gamma_{2_a} < \pi/2$), and the aerodynamic azimuth or track angle; $(u_{g_w}^o, v_{g_w}^o, w_{g_w}^o)$ are the inertial gust velocity components; (u_w^b, v_w^b, w_w^b) are the wind velocity components, and (p_w^b, q_w^b, r_w^b) are the angular velocity components of the local wind in the body frame, respectively. The aerodynamic angle of attack and sideslip angle are denoted by α_a and β_a, respectively.

Again following [16], the rotational EOMs can be written as follows:

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix}1 & \mathrm{s}\phi\mathrm{t}\theta & \mathrm{c}\phi\mathrm{t}\theta\\ 0 & \mathrm{c}\phi & -\mathrm{s}\phi\\ 0 & \dfrac{\mathrm{s}\phi}{\mathrm{c}\theta} & \dfrac{\mathrm{c}\phi}{\mathrm{c}\theta}\end{bmatrix}\begin{bmatrix}p_a^b\\ q_a^b\\ r_a^b\end{bmatrix} + \begin{bmatrix}p_w^o\dfrac{\mathrm{c}\psi}{\mathrm{c}\theta} + q_w^o\dfrac{\mathrm{s}\psi}{\mathrm{c}\theta}\\ -p_w^o\mathrm{s}\psi + q_w^o\mathrm{c}\phi\\ p_w^o\mathrm{c}\psi\mathrm{t}\theta + q_w^o\mathrm{s}\psi\mathrm{t}\theta + r_w^o\end{bmatrix} \tag{7}$$

$$\begin{bmatrix}\dot{p}_a^b\\ \dot{q}_a^b\\ \dot{r}_a^b\end{bmatrix} = \mathbf{I}^{-1}\begin{bmatrix}\mathcal{L} - (I_z - I_y)q_a^b r_a^b + I_{xz}p_a^b q_a^b - q_a^b h_z' + r_a^b h_y' - P_4\\ \mathcal{M} + Tz_M^b + (I_z - I_x)p_a^b r_a^b - I_{xz}\left(p_a^{b^2} - r_a^{b^2}\right) - r_a^b h_x' + p_a^b h_z' - P_5\\ \mathcal{N} - (I_y - I_x)p_a^b q_a^b - I_{xz}q_a^b r_a^b - p_a^b h_y' + q_a^b h_x' - P_6\end{bmatrix} \tag{8}$$