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Robust control of transition maneuvers for a class of V/STOL aircraft ☆

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ABSTRACT

This work focuses on the control law design for a class of aerial systems able to perform transition maneuvers from hover to level flight configurations. An analysis of the aircraft dynamics and of the flight envelope of the vehicle, encompassing both the hover and the level flight conditions, is proposed in presence of wind disturbances. This analysis is used to derive a control strategy able to enforce the desired transition while maintaining the flight envelope within prescribed sets despite the influence of wind disturbances. To this end, a path following approach is adopted in which the time law is synthesized by a flight envelope protection controller. The paper complements our earlier work (Naldi & Marconi, 2011) in which optimal transition trajectories are computed. Simulation results, obtained with the parameters of a miniature tail-sitter prototype, show the effectiveness of the proposed approach.

1. Introduction

For many years Unmanned Aerial Vehicles (UAVs) have been successfully employed to address a large variety of applications. To mention a few, it is worth recalling applications in the area of surveillance (Beard, McLain, Nelson, Kingston, & Johanson, 2006), environmental awareness (Merino & Ollero, 2002), search and rescue operations (Doherty & Rudol, 2007), aerial robotics and many others (Feron & Johnson, 2008). Among the different configurations of aerial vehicles, tail-sitter aircraft (McCormick, 1998) have recently received attention for their capability of combining in a single vehicle both the flight efficiency of an airplane and the maneuverability of a helicopter (Stone & Clarke, 2001). With respect to other similar V/STOL (Vertical and/or Short Take-Off and Landing) vehicles, such as tilt-rotors or tilt-wings, tail-sitter vehicles are characterized by a reduced number of actuators hence by a lower mechanical complexity and a lower weight. These features, in turn, make it possible to design miniature vehicles suitable to operate also indoor. The distinguishing feature of such a class of systems, however, is the ability of operating both in the stable *hover* flight and in the fast and efficient *level* flight. During level flight, the aircraft configuration appears similar to the one of a fixed-wing aerial vehicle, in which the force of gravity is compensated through the lift obtained by means of suitable aerodynamic surfaces installed on the vehicle, such as wings or canards. On the other side, at hover, the aircraft configuration is more similar to the one of a helicopter, in which the gravity force is compensated only by the force produced by the propeller. In this case the additional maneuverability typical of helicopters is paid back with a larger amount of energy consumed to sustain the flight. In this setting, the transition maneuver is a particular trajectory of the system in which the flight configuration of the vehicle is changed from hover to level flight or vice versa. A crucial requirement to successfully obtain a transition between the two operative modes is to maintain the *flight envelope* – see (Stengel, 2004; Stevens & Lewis, 2003) – of the aircraft within specified sets, avoiding potentially dangerous configurations that may cause aerodynamic stall of the wings and of the control surfaces employed to govern the attitude of the vehicle (Yavrucuk, Unnikrishnan, & Prasad, 2003). This requirement, in turn, is particularly challenging in presence of wind disturbances as these latter directly influence the actual flight envelope.

The problem of performing transition maneuvers has been recently under investigation in the control systems literature by focusing, for example, on large scale V/STOL aircraft – see among others (Benosman & Lum, 2007; Oishi & Tomlin, 1999) – on miniature acrobatic airplanes – (Casau, Cabecinhas, & Silvestre, 2011; Frank, McGrew, Valenti, Levine, & How, 2007; Green & Oh, 2005) – and on ducted-fan aerial vehicles – (Guerrero, Londenberg,

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Gelhausen, & Myklebust, 2003; Jadbabaie, Yu, & Hauser, 1999; Johnson & Turbe, 2005) – and other tail-sitter configurations (Kubo, 2006). Optimal trajectories to achieve the transition have been computed numerically in Stone and Clarke (2001), by considering a miniature T-wing aircraft, and in Naldi and Marconi (2011) for a prototype of tail-sitter vehicle. In Randall, Hoffmann, and Shkarayev (2010) the aerodynamic characterization of an aerobatic airplane during a transition maneuver has been proposed.

By complementing our previous work in Naldi and Marconi (2011), in this work we address the design of a nonlinear robust control strategy able to accomplish the transition maneuver in presence of wind disturbances. The problem is divided into four different steps. In the first one, the design of the reference maneuvers is addressed. To take into account for the presence of possible wind, the idea is to rely upon a path following approach (Aguiar, Hespanha, & Kokotovic, 2005) in which the geometric path is designed a priori whereas the time law has to be selected in real-time according to the current flight envelope of the vehicle. With the references at hand, the second step amounts in computing the low-level control laws synthesized for the hover and the level flight configurations, respectively. As a third step, the design of a flight envelope protection unit is proposed. The idea is to generate the time law for the reference maneuvers using a feedback control strategy able to guarantee the invariance of the current desired flight envelope of the vehicle despite the presence of wind. Finally a control policy able to switch between the hover and the level flight controllers is designed. For sake of compactness the paper focuses only on the hover to level flight transition maneuver. Simple adaptations of the proposed theory can be used to address also the converse maneuver from level flight to hover.

Notation: $\mathbb{R}$, $\mathbb{R}_{\geq 0}$ and $\mathbb{R}_{>0}$ denote respectively the set of real, nonnegative real, and positive real numbers. For a vector $\mathbf{v} \in \mathbb{R}^n$, $\|\mathbf{v}\|$ denotes the Euclidean norm. A vector $\mathbf{x} := [x_1\ x_2]^T \in \mathbb{R}^2$ in polar coordinates will be represented as $\mathbf{x} = x[\cos(\arg(\mathbf{x}))\quad \sin(\arg(\mathbf{x}))]^T$ where the function $\arg : \mathbb{R}^2 \setminus \{0\} \mapsto (-\pi, \pi)$ is defined as $\arg(\mathbf{x}) := \arctan(x_2/x_1)$ and $x = \|\mathbf{x}\|$. For $\mathcal{A}$ a closed subset of $\mathbb{R}^n$, $|x|_{\mathcal{A}} = \min_{y\in\mathcal{A}} \|x - y\|$ denotes the distance of x from $\mathcal{A}$, while $\partial\mathcal{A}$ represents the boundary of $\mathcal{A}$. For a bounded function $f : \mathcal{D} \to \mathbb{R}^n$, $\mathcal{D} \subset \mathbb{R}$, $\|f\|_\infty$ denotes the infinity norm defined as $\sup_{t\in\mathcal{D}} \|f(t)\|$. For a set $\mathcal{A} \subset \mathbb{R} \times \mathbb{R}$ and two positive reals $(\bar{x}, \bar{y})$, with the notation $\mathcal{A} + \mathcal{B}_{(\bar{x},\bar{y})}$ we denote the set $\{(x', y') \in \mathbb{R} \times \mathbb{R} : |x' - x| \leq \bar{x}$ and $|y' - y| \leq \bar{y}$ for some $(x, y) \in \mathcal{A}\}$. For a function $x : \mathbb{R}^m \to \mathbb{R}^n$ and a set $\Sigma \subset \mathbb{R}^m$ we let $\mathrm{gr}\, x|_\Sigma := \{x' \in \mathbb{R}^n : x(\rho) = x'$ for some $\rho \in \Sigma\}$.

2. Dynamical model

The tail-sitter aircraft considered in this paper (see Fig. 1) is composed of three main subsystems. The first one is given by a fixed-pitch propeller driven by an electric motor. This subsystem generates the main thrust $T \in \mathbb{R}_{\geq 0}$ that is required to counteract the gravity force at hover and the aerodynamic resistance during level flight. The second subsystem consists of a set of actuated aerodynamic control surfaces designed in order to govern the attitude of the vehicle, by generating a control torque $\tau \in \mathbb{R}^3$, both during hover and level flight. To achieve this goal, the control surfaces are positioned below the propeller so that they are immersed into the propeller airflow. The third subsystem is given by a main wing. The aerodynamic lift force that can be produced through this airfoil allows the vehicle to achieve level flight similarly to a fixed-wing aircraft configuration. We refer the reader to Castillo, Lozano, and Dzul (2003); McCormick (1998) for additional details about the principles and the mathematical models.

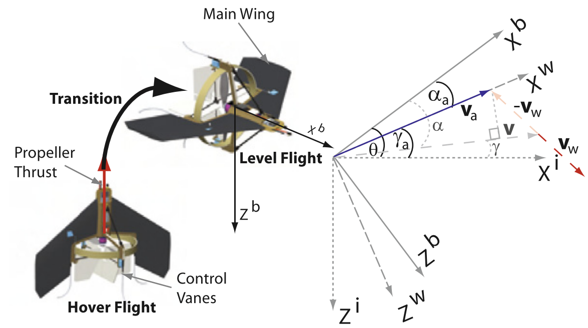

Fig. 1. A prototype of tail-sitter V/STOL aerial vehicle performing a transition maneuver and the reference frames, the vectors and the angles used in the paper.

For sake of simplicity the analysis of the paper focuses on the reduced order planar dynamical model of the system describing the longitudinal, the vertical and pitch dynamics of the vehicle. These are the degrees of freedom that play a role in the control problem at hand, as the neglected yaw and lateral dynamics of the vehicle can be stabilized to a constant value during the maneuver. The equations of motion can be derived by defining two Euclidean reference frames: the inertial earth-fixed reference frame, denoted as F_i, with the x-axis oriented with the horizon, and the body-fixed reference frame, denoted as F_b, having the x-axis aligned with the longitudinal direction of the aircraft, i.e. the propeller axis of rotation. The two reference frames are related by the 2×2 rotation matrix $R_{ib}(\theta)$ whose first and second row is respectively $[\cos\theta\quad \sin\theta]$ and $[-\sin\theta\quad \cos\theta]$, where θ is the *pitch angle* of the vehicle. A crucial role in the equations of motion is given by the *airspeed vector* $\mathbf{v_a}$, that is the speed of the aircraft relative to the surrounding air, the *ground speed vector* $\mathbf{v}$, that is the speed of the aircraft relative to the ground, and the *wind speed vector* $\mathbf{v_w}$, that is the motion of the airmass over the ground. The three vectors $\mathbf{v_a}$, $\mathbf{v}$ and $\mathbf{v_w}$, which are expressed in the inertial frame, fulfill the relation (see Stengel, 2004)

$$\mathbf{v_a} := \mathbf{v} - \mathbf{v_w}. \tag{1}$$

In polar coordinates the airspeed and ground speed vectors are represented as

$$\mathbf{v_a} = v_a \left[\cos\gamma_a \quad -\sin\gamma_a\right]^T, \qquad \mathbf{v} = v\left[\cos\gamma \quad -\sin\gamma\right]^T$$

where the scalar v_a and v are the so-called *airspeed* and *ground speed* of the vehicle, while the angles γ_a and γ are known as airmass-referenced and inertial-referenced *flight path angles*, respectively. Fig. 1 graphically sketches the vectors and the angles just introduced. With the pitch and the flight path angles in hand, it is finally possible to introduce the so-called angles of attack. Similarly to the flight path angles, both an airmass-referenced and inertial-referenced angle of attack can be introduced respectively as $\alpha_a := \theta - \gamma_a$, $\alpha := \theta - \gamma$ or alternatively (see Fig. 1),

$$\alpha_a := \arg\left(R_{ib}(\theta)^T \mathbf{v_a}\right), \qquad \alpha := \arg\left(R_{ib}(\theta)^T \mathbf{v}\right). \tag{2}$$

It is worth noting that, in the special case in which the magnitude of the wind speed vector $\|\mathbf{v_w}\|$ is negligible compared to the ground speed v, $\mathbf{v_a} \approx \mathbf{v}$, and thus $\alpha_a \approx \alpha$.

Following Stengel (2004), the main lift and drag aerodynamic forces acting on the vehicle are expressed as a function of the airmass-referenced angle of attack and of the airspeed of the vehicle. In this work the aerodynamic forces have been modeled by considering the presence of a main wing as the most important airfoil on the vehicle. The main wing is characterized by a symmetric aerodynamic profile and it has the chord line aligned along the x-axis of the vehicle. In this respect, the lift, $L(\cdot)$, and the drag, $D(\cdot)$, are given by the following expressions

$$L(\alpha_a, v_a) := SC_L(\alpha_a)q(v_a), \qquad D(\alpha_a, v_a) := SC_D(\alpha_a)q(v_a) \tag{3}$$