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Nonlinear control of a tethered UAV: The taut cable case[☆]

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ABSTRACT

This paper focuses on the design of a stabilizing control law for an aerial vehicle physically connected to a ground station by means of a tether cable. By taking advantage of the tensile force acting along the taut cable, it is shown that the tethered UAV can maintain a non-zero attitude while hovering in a constant position. The control objective is to stabilize the desired configuration while simultaneously ensuring that the cable remains taut at all times. This leads to a nonlinear control problem subject to constraints. This paper provides a two-step solution. First, the system is stabilized using a cascade control scheme based on thrust vectoring. Then, constraint satisfaction is guaranteed using a novel Reference Governor scheme.

1. Introduction

Recent advancements in the field of Unmanned Aerial Vehicles (UAVs) have lead to the availability of inexpensive aerial robots with a growing range of applications ranging from surveillance (Beard, McLain, Nelson, Kingston, & Johanson, 2006) to advanced robotic operations including environment interaction (Marconi & Naldi, 2012), grasping (Mellinger, Shomin, Michael, & Kumar, 2013; Pounds, Bersak, & Dollar, 2011) and manipulation (Willmann et al., 2012). The full potential of these systems, however, is still limited by key factors such as flight time, computing capabilities and airspace safety regulations (Feron, Johnson, & robotics, 2008). A possible solution to these limitations is to connect the UAV to a ground station by means of a tether cable able to supply energy, transmit data and/or apply forces.

Since the dynamic properties of the UAV are deeply influenced by the cable, the safe deployment of tethered UAVs requires the development of specific control strategies. Early works on the subject (Rye, 1985; Schmidt & Swik, 1974) studied the stabilization of tethered UAVs using linearized models. Although the primary interest in tethered UAVs is their virtually unlimited flight-time (Muttin, 2011), recent results have shown the advantage of using the taut cable as an additional control input. Possible examples include: guiding the landing of a helicopter on a ship (Oh, Pathak, Agrawal, Pota, & Garratt, 2006), improving fight stability in the presence of wind (Eeckhout, Nicotra, Naldi, & Garone, 2014; Sandino, Bejar, Kondak, & Ollero, 2013), and using multiple cables to achieve full actuation (Naldi, Gasparri, & Garone, 2012). Moreover, it has been shown in Lupashin and D'Andrea (2013) and Tognon and Franchi (2015) that the taut cable configuration can also be used to measure the position of the UAV. A common feature of these papers is that the cable tension is controlled by an actuated winch, whereas the UAV position is controlled by the UAV itself.

This paper investigates an alternative approach where the actuated winch imposes only the cable length whereas the UAV controls its elevation angle while ensuring a minimal cable tension. Interestingly enough, the proposed control law does not specifically require an actuated winch and can also be applied to the case of fixed-length cables. To the author's best knowledge, this approach to the control of a tethered UAV has not been addressed previously.

The first contribution of the paper is to show that the tethered UAV is able to achieve a set of equilibrium configurations that is different from the untethered case. This set is characterized both analytically and geometrically.

Another major contribution is the development of a specialized control strategy for ensuring constraint satisfaction at all times. The proposed solution consists in two separate design steps: first, the nonlinear system is stabilized using a cascade approach (Hua, Hamel, Morin, & Samson, 2013). Second, the closed loop system is

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augmented with a Reference Governor (RG) to provide constraint handling capabilities. Reference Governors are *add-on* control units that ensure constraint enforcement by suitably manipulating the reference of the pre-stabilized system (see Garone, Cairano, & Kolmanovsky, 2017, Kolmanovsky, Garone, & Cairano, 2014 and references therein). Nonlinear RG schemes have been proposed in Bemporad (1998) and Garone and Nicotra (2016). This paper presents a novel backtracking RG strategy that is specifically tailored to the system.

A preliminary conference version of this paper appeared in Nicotra, Naldi, and Garone (2014). The main novelty with respect to this earlier work is the introduction of the backtracking RG algorithm, which greatly reduces the online computational effort. Other improvements include the analytical characterization of the set of attainable steady-state attitudes, more rigorous stability proofs and the determination of a more stringent inner loop gain using the ℓ_1 norm.

2. Preliminaries

This section provides a brief description of the notation that will be used throughout the paper. In particular, let $\mathbb{R}_{>0}$ denote the set $\{x \in \mathbb{R} : x > 0\}$, let $\mathbb{R}_{\geq 0}$ denote the set $\{x \in \mathbb{R} : x \geq 0\}$, let $\|\cdot\|$ denote the Euclidean norm, and let $\|\cdot\|_\infty$ denote the infinity norm as in Isidori (1995). Moreover, define the saturation function $\sigma_\lambda(x)$ as

$$\sigma_\lambda(x) = \text{sign}(x)\min(|x|, \lambda)$$

and the atan2 (y, x) function

$$\text{atan2}(y, x) = \begin{cases} \arctan\dfrac{y}{x} & x > 0 \\ \arctan\dfrac{y}{x} + \pi & y \geq 0,\ x > 0 \\ \arctan\dfrac{y}{x} - \pi & y < 0,\ x > 0 \\ \dfrac{\pi}{2} & y > 0,\ x = 0 \\ -\dfrac{\pi}{2} & y < 0,\ x = 0 \\ \text{undefined} & y = 0,\ x = 0. \end{cases}$$

The following definition of Input-to-State Stability (ISS) given in Sontag and Wang (1995) is reported for the sake of completeness.

Definition 1. A system $\dot{x} = f(x, u)$ with $x \in \mathbb{R}^n$ and $u \in \mathbb{R}$ is Input-to-State Stable (ISS) with restriction $\mathcal{X} \subset \mathbb{R}^n$ on the initial state $x(0)$ and restriction $\mathcal{U} \subset \mathbb{R}$ on the input u if there exist a class-$\mathcal{K}$ function[1] $\gamma : \mathbb{R} \to \mathbb{R}$ and a class-$\mathcal{KL}$ function[2] $\beta : \mathbb{R}^2 \to \mathbb{R}$ such that

$$\|x(t)\| \leq \beta(\|x(0)\|, t) + \gamma\left(\sup_{\tau \leq t}\|u(\tau)\|\right), \qquad (1)$$

for all $x(0) \in \mathcal{X}$ and $u(t) \in \mathcal{U}$.

3. Problem statement

3.1. System modelling

Consider the planar model of a tethered UAV depicted in Fig. 1. The vehicle has mass $m \in \mathbb{R}_{>0}$, moment of inertia $\mathcal{J} \in \mathbb{R}_{>0}$ and is

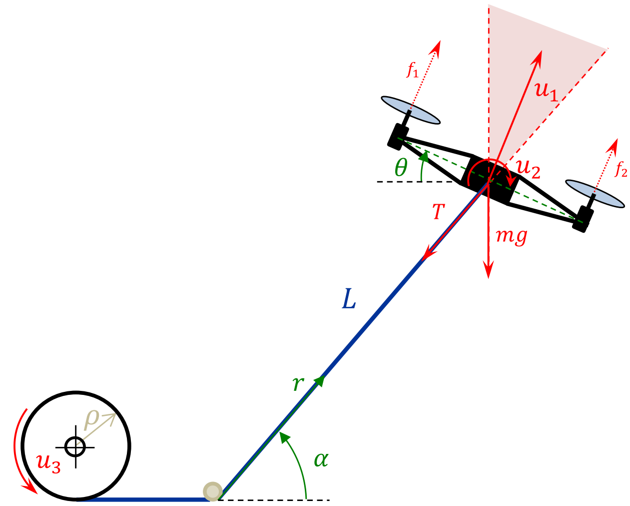

Fig. 1. Planar model of a tethered UAV with a taut cable.

physically connected to the ground by means of a tether cable of length $L \in \mathbb{R}_{>0}$. Let the *radial position* $r \in \mathbb{R}_{>0}$ and the *elevation angle* $\alpha \in [0, \pi]$ be the polar coordinates of the UAV, and let the *pitch angle* $\theta \in (-\pi, \pi]$ be the attitude of the UAV with respect to the horizon.

The vehicle is subject to the gravity acceleration g, the cable tension $T \in \mathbb{R}_{\geq 0}$, and is actuated by two propellers that generate a total thrust $u_1 \in \mathbb{R}_{\geq 0}$ and a resultant torque $u_2 \in \mathbb{R}$. The UAV actuator dynamics are assumed to be negligible. The cable is governed by a control torque $u_3 \in \mathbb{R}$ that acts on a winch of radius $\rho \in \mathbb{R}_{\geq 0}$ and moment of inertia $\mathcal{I} \in \mathbb{R}_{\geq 0}$. The following approximations are made.

Assumption 2. The cable is inextensible, massless and has zero shear stiffness. Moreover, it is attached to the centre of mass of the UAV.

Assumption 3. Air viscosity is negligible.

Under Assumption 2, the total kinetic energy $\mathcal{K}$ and potential energy $\mathcal{P}$ of the UAV are

$$\mathcal{K} = \frac{1}{2}\frac{\mathcal{I}}{\rho^2}\dot{L}^2 + \frac{1}{2}m\dot{r}^2 + \frac{1}{2}mr^2\dot{\alpha}^2 + \frac{1}{2}\mathcal{J}\dot{\theta}^2$$
$$\mathcal{P} = mgr\sin\alpha.$$

Following from Assumption 3, it is possible to define the Lagrangian function $\mathcal{L} = \mathcal{K} - \mathcal{P}$. The dynamic model of the system can then be obtained via the Euler–Lagrange theorem

$$\frac{d}{dt}\frac{\partial\mathcal{L}}{\partial\dot{q}_i} - \frac{\partial\mathcal{L}}{\partial q_i} = F_i \quad i = L, r, \alpha, \theta$$

where

$$F_L = u_3 + \rho T, \qquad F_r = u_1\sin(\alpha + \theta) - T,$$
$$F_\alpha = ru_1\cos(\alpha + \theta), \quad F_\theta = u_2.$$

This leads to the dynamic model

$$\begin{cases} \dfrac{\mathcal{I}}{\rho}\ddot{L} = u_3 + \rho T \\ m\ddot{r} = mr\dot{\alpha}^2 - mg\sin\alpha + u_1\sin(\alpha + \theta) - T \\ mr^2\ddot{\alpha} = -2mr\dot{r}\dot{\alpha} - mgr\cos\alpha + ru_1\cos(\alpha + \theta) \\ \mathcal{J}\ddot{\theta} = u_2, \end{cases} \qquad (2)$$

which is the generic model for a tethered UAV. To specialize it to the taut cable configuration, the following definition is given

[1] A continuous function $\gamma(x)$ is said to be of class-$\mathcal{K}$ if it is strictly increasing and satisfies $\gamma(0) = 0$.

[2] A continuous function $\beta(x, s)$ is said to be of class-$\mathcal{KL}$ if, for each fixed s, $\beta(x, s)$ is a class-$\mathcal{K}$ function and, for each fixed x, $\beta(x, s)$ is decreasing and satisfies $\beta(x, s) \to 0$ for $s \to \infty$.