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Brief paper

Image-based tracking control of VTOL unmanned aerial vehicles ☆

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ABSTRACT

This paper addresses the image-based control problem of vertical take-off and landing (VTOL) unmanned aerial vehicles (UAVs). Specifically, we propose a control scheme allowing the aircraft to track a moving target captured by an onboard camera where the orientation and angular velocity of the vehicle are assumed available for feedback. The proposed approach relies on appropriate image features, defined based on perspective image moments along with a useful projection, and the design of a bounded adaptive translational controller without linear velocity measurements in the presence of external disturbances. Estimates of the target's acceleration and the disturbances as well as some auxiliary variables are used to simplify the control design and guarantee the stability of the overall closed loop system. Simulation examples are provided to show the effectiveness of the proposed theoretical results.

1. Introduction

Unmanned aerial vehicles (UAVs) capable of vertical take-off and landing (VTOL) have received an increased interest in the recent years due to their potential applications including structures and pipeline inspection, surveillance, fire and traffic monitoring. These vehicles are under-actuated in the sense that the translational motion is controlled by a thrust force along a single body-fixed axis (Hua, Hamel, Morin, & Samson, 2009). Recently, several approaches have been proposed for the control of VTOL UAVs taking into account various problems including position stabilization and tracking, with and without external disturbances (see, for instance, Abdessameud & Tayebi, 2010, 2013; Cabecinhas, Cunha, & Silvestre, 2014; Hua, Hamel, Morin, & Samson, 2013; Naldi, Gentili, Marconi, & Sala, 2010; Roberts & Tayebi, 2011, 2013, and references therein). In addition, a growing interest has been focused on small-scale VTOL UAVs equipped with vision sensors, which provide versatile visual information and constitute a powerful alternative to global positioning systems (GPS) in applications where the latter are unreliable or ineffective.

Visual servoing has been widely investigated, mainly in the area of robotic systems, in the last two decades leading to several interesting control approaches (see, for instance, Chaumette & Hutchinson, 2006, 2007). Among these approaches, image-based methods (IBVS) are more attractive since they rely on simple features extracted from visual measurements, do not require accurate target models, and are robust to camera calibration errors. This last fact is highly desirable when using low-cost and light-weight cameras in VTOL UAVs. However, IBVS methods lead to complex nonlinear control problems and are not generally suitable in applications requiring large displacements (Janabi-Sharifi, Deng, & Wilson, 2011).

In Hamel and Mahony (2002), an IBVS control scheme has been proposed for the stabilization of the translational kinematics of a quadrotor aircraft. Using spherical image moments, centroid image features have been shown to preserve the passivity properties of the system and simplify the control design. This work has been modified in Bourquardez et al. (2009) and Guenard, Hamel, and Mahony (2008) by introducing new image error terms. Bourquardez et al. (2009) have also tested experimentally the control schemes proposed by Guenard et al. (2008) and Hamel and Mahony (2002) as well as a standard IBVS algorithm based on image perspective moments presented by Tahri and Chaumette (2005). It has been demonstrated that spherical moments show undesirable behavior in the vertical axis, due to the conditioning problems of the image Jacobian matrix, whereas perspective moments ensure good stabilization results as long as the aircraft undergoes a smooth and slow motion parallel to the target plane.

A control scheme that exploits the dynamics of the VTOL aircraft and spherical image moments can be found in Mahony, Corke, and Hamel (2008), where a position control law has been proposed

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using centroid image features in addition to measurements of the optical flow to cope for the missing linear velocity of the aircraft. This work has been modified in Le Bras, Mahony, Hamel, and Binetti (2008) by re-scaling the image features and incorporating a nonlinear filter for smooth optical flow measurements. Using only optical flow, a translational control scheme has been proposed in Hérissé, Hamel, Mahony, and Russotto (2012) for the stabilization and the autonomous landing of a quadrotor on a textured target. In Le Bras, Hamel, Mahony, and Treil (2011), an output-feedback IBVS control law has been developed using measurements from a camera and a gyroscope. In Ozawa and Chaumette (2013), a control law based on perspective image moments has been presented with the assumption that the aircraft is always parallel to the planar target lying on the level ground. Based on similar perspective moments, an IBVS control scheme for a quadrotor aircraft has been proposed in Jabbari, Oriolo, and Bolandi (2014) using a different set of sensors. However, all the results cited above consider the stabilization problem of the UAV with respect to a fixed target. The case of a moving target introduces several technical difficulties due to the under-actuation of the system, especially when the full dynamics of the aircraft is considered using partial state measurements.

In this paper, we present an image-based control scheme that drives a VTOL aircraft to track a planar object moving in the level ground. The aircraft is equipped with a camera and an inertial measurement unit (IMU) providing estimates of the orientation of the vehicle and its angular velocity. To solve this problem, we define new image features using perspective image moments along with the projection of the image points onto a non-rotating virtual plane always parallel to the target. As a result, suitable dynamics of the image features are derived and are shown to significantly simplify the control design. To account for the under-actuation of the vehicle, we adopt a control design methodology presented in Abdessameud and Tayebi (2010, 2013). First, an intermediary translational input is derived by taking into account the lack of measurements of the linear velocity of the aircraft and the target's acceleration as well as the presence of external disturbances. Then, an appropriate torque input is designed such that tracking of the target is achieved, while maintaining the aircraft at a desired height and a specified orientation about its vertical axis. As it will become clear later, the intermediary translational input is subject to several constraints that prevent the application of standard control techniques using the measured image features. To cope for this situation and simplify the input torque design, useful auxiliary dynamic systems are introduced. A preliminary version of the results in this paper has been published in Abdessameud and Sharifi (2013). Simulation results are provided to illustrate the effectiveness of our proposed approach.

Notation: Throughout the paper, we use $|x|$ to denote the Euclidean norm of a vector x, and $\|M\|$ to denote the induced norm of a matrix M. The matrix $\boldsymbol{I}_q$ denotes the identity matrix of dimension q, and $SO(3) := \{\boldsymbol{R} \in \mathbb{R}^{3\times 3} \mid \det(\boldsymbol{R}) = 1, \boldsymbol{R}^\top \boldsymbol{R} = \boldsymbol{I}_3\}$ denotes the Special Orthogonal group of order 3. We also use $\mathcal{I}$ to denote the inertial frame that is rigidly attached to a position on the Earth (assumed flat) in North-East-Down coordinates. The orthonormal (right-handed) basis associated to $\mathcal{I}$ is denoted by $\{\hat{x}, \hat{y}, \hat{z}\}$. Also, $\mathcal{B}$ denotes the body-fixed frame attached to the center of gravity (CoG) of the aircraft. The orthonormal basis of $\mathcal{B}$ is denoted by $\{\hat{x}_b, \hat{y}_b, \hat{z}_b\}$, where $\hat{x}_b$ is directed towards the front of the aircraft, $\hat{y}_b$ is taken towards the right side, and $\hat{z}_b$ is directed downwards.

2. Background

2.1. System model

Consider a VTOL UAV modeled as

$$\dot{\boldsymbol{p}} = \boldsymbol{v}, \qquad \dot{\boldsymbol{v}} = g\hat{z} - \frac{\mathcal{T}}{m}\boldsymbol{R}^\top \hat{z} + \boldsymbol{F}_d, \tag{1}$$

$$\dot{\boldsymbol{Q}} = \frac{1}{2}\boldsymbol{T}(\boldsymbol{Q})\boldsymbol{\omega}, \qquad \boldsymbol{J}\dot{\boldsymbol{\omega}} = \boldsymbol{\Gamma} - \mathbf{S}(\boldsymbol{\omega})\boldsymbol{J}\boldsymbol{\omega}, \tag{2}$$

where $\boldsymbol{p}$ and $\boldsymbol{v}$ denote, respectively, the position and linear velocity of the aircraft in $\mathcal{I}$, the system's mass and the gravitational acceleration are denoted by m and g, respectively, $\hat{z} := (0, 0, 1)^\top$, $\boldsymbol{J} \in \mathbb{R}^{3\times 3}$ is the symmetric positive definite constant inertia matrix of the aircraft with respect to $\mathcal{B}$. The scalar $\mathcal{T}$ and the vectors $\boldsymbol{F}_d$, $\boldsymbol{\Gamma}$, represent, respectively, the magnitude of the thrust applied to the vehicle in the opposite direction of $\hat{z}_b$, the vector of unknown external disturbances expressed in $\mathcal{I}$, and the input torque applied to the system expressed in $\mathcal{B}$. The vector $\boldsymbol{\omega}$ denotes the angular velocity of the vehicle with respect to $\mathcal{I}$ expressed in $\mathcal{B}$. The orientation of the vehicle is represented by the unit quaternion $\boldsymbol{Q} := (\boldsymbol{q}^\top, \eta)^\top \in \mathbb{R}^4$, with $\boldsymbol{q} \in \mathbb{R}^3$, $\eta \in \mathbb{R}$, $|\boldsymbol{Q}| = 1$, and

$$\boldsymbol{T}(\boldsymbol{Q}) = \begin{pmatrix} \eta \boldsymbol{I}_3 + \mathbf{S}(\boldsymbol{q}) \\ -\boldsymbol{q}^\top \end{pmatrix}, \tag{3}$$

satisfying $\boldsymbol{T}(\boldsymbol{Q})^\top \boldsymbol{T}(\boldsymbol{Q}) = \boldsymbol{I}_3$. The rotation matrix $\boldsymbol{R} \in SO(3)$ that brings $\mathcal{I}$ into $\mathcal{B}$ can be obtained from the unit quaternion $\boldsymbol{Q}$ as

$$\boldsymbol{R} = (\eta^2 - \boldsymbol{q}^\top \boldsymbol{q})\boldsymbol{I}_3 + 2\boldsymbol{q}\boldsymbol{q}^\top - 2\eta \mathbf{S}(\boldsymbol{q}), \tag{4}$$

where $\mathbf{S}(\cdot)$ is the skew-symmetric matrix such that $\mathbf{S}(\boldsymbol{x}_1)\boldsymbol{x}_2 := \boldsymbol{x}_1 \times \boldsymbol{x}_2$, where $\boldsymbol{x}_1, \boldsymbol{x}_2 \in \mathbb{R}^3$, and '$\times$' denotes the vector cross product.

2.2. Mathematical preliminaries

We consider a class of saturation functions σ_i, used in Gayaka, Lu, and Yao (2012), satisfying the following properties for all $x_i \in \mathbb{R}$

(i) $x_i\sigma_i(x_i) \geq 0$, for $x_i \neq 0$, and $\sigma_i(0) = 0$
(ii) $\sigma_i(x_i) = k_i x_i$, $\forall |x_i| \leq l_i$
(iii) $\sigma_i(x_i) = M_i \text{sign}(x_i)$, $\forall |x_i| \geq L_i$
(iv) $0 \leq \frac{d\sigma_i}{dx_i} \leq k_i$, $\forall x_i$.

where l_i, L_i, k_i and M_i are strictly positive design parameters satisfying: $l_i = \beta_i L_i$, with $\beta_i \leq 1$, and $M_i = k_i l_i(1 + \gamma_i)$ with $\gamma_i > 0$. Note that σ_i can be designed to be differentiable up to a desired order and the interval of x_i is divided into three regions: a linear unsaturated region $\Omega_{i1} = \{x_i : |x_i| \leq l_i\}$, a possibly nonlinear intermediate region $\Omega_{i2} = \{x_i : l_i < |x_i| \leq L_i\}$, and a saturated region $\Omega_{i3} = \{x_i : |x_i| > L_i\}$. For a vector $X \in \mathbb{R}^q$, we use for simplicity the notation $\sigma_i(X)$ to denote the application of σ_i element-wise. Consider the following lemma, which is a special case of Gayaka et al. (2012, Theorem 1).

Lemma 1. *Consider the second order system:*

$$\ddot{\boldsymbol{\xi}} = \kappa(\boldsymbol{\xi}, \dot{\boldsymbol{\xi}}) + d(t), \quad \kappa(\boldsymbol{\xi}, \dot{\boldsymbol{\xi}}) := -\sigma_2(\dot{\boldsymbol{\xi}}(t) + \sigma_1(\boldsymbol{\xi}(t))) \tag{5}$$

where $\boldsymbol{\xi} \in \mathbb{R}^3$ and $d(t)$ is a uniformly bounded perturbation term. Suppose that there exists a time $t_1 \geq 0$ such that $|d(t)| \leq d_M$ for all $t \geq t_1$. Suppose also that the design parameters of the saturation functions satisfy:

$$k_1 l_1 > l_2, \qquad k_2 l_2 > k_1(L_2 + M_1) + d_M. \tag{6}$$

Then, for any initial conditions, there exists a finite time $t_2 > t_1$ such that the states $\boldsymbol{\xi}$ and $\dot{\boldsymbol{\xi}}$ reach the linear unsaturated region $\Omega_{11} \cup \Omega_{21}$; one can formally consider that $\kappa(\boldsymbol{\xi}, \dot{\boldsymbol{\xi}}) = -k_2(\dot{\boldsymbol{\xi}}(t) + k_1\boldsymbol{\xi}(t))$ for all $t \geq t_2$.

Proof. In Gayaka et al. (2012, Theorem 1), the result of the lemma has been shown for any perturbation term satisfying $|d(t)| \leq d_M$ for all $t \geq 0$. In our case, $d(t)$ satisfies this condition for $t \geq t_1 \geq 0$. Then, the result of the lemma can be shown by noticing that, if $|d(t)| > d_M$ for $t < t_1$ and $d(t)$ is uniformly bounded, the states of the system (5) cannot escape in finite time.