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Robust attitude control for quadrotors with input time delays

Hao Liu[a,b], Danjun Li[b], Zongyu Zuo[c,*], Yisheng Zhong[b]

[a] School of Astronautics, Beihang University, Beijing 100191, PR China
[b] Department of Automation, TNList, Tsinghua University, Beijing 100084, PR China
[c] Seventh Research Division, Beihang University, Beijing 100191, PR China

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ABSTRACT

Robust attitude controller design problem is investigated for uncertain quadrotors with input delays. The vehicle model can be described as a multiple-input multiple-output nonlinear system subject to parametric uncertainties, external disturbances, and input time delays. A robust controller is proposed consisting of a nominal controller and a robust signal-based compensator. It is shown that the robust stability and the robust tracking property can be achieved. An important feature of the proposed control method is that a systematic way can be given to tune the controller parameters. Experimental results are given to demonstrate the effectiveness of the designed control system.

1. Introduction

In the last decade, researches on various kinds of unmanned multirotors have received much attention in the control and robotic communities as shown in Mahony, Kumar, and Corke (2012), Zuo (2014), Zhao, Xian, Zhang, and Zhang (2015), and Hoffmann, Huang, Waslander, and Tomlin (2011). One kind of typical multi-rotors is the quadrotor, which has a simple mechanical control structure to change the aerodynamic forces and moments. Therefore, the quadrotor platforms have been widely developed in the fields including surveillance, visual acquisition, search, and disaster assistance in urban circumstances. However, two challenges in the flight controller design are often encountered in practical applications: one is that the vehicle dynamics is nonlinear, and prone to being influenced by parametric uncertainties and external disturbances; the other is that the uncertain nonlinear system includes input time delays.

To address the first problem, several controllers based on the dynamic inversion control method, quaternion-based feedback control approach, and singular perturbation theory were proposed to achieve the automatic flight for quadrotors (see, for example, Bertrand, Guenard, Hamel, Piet-Lahanier, & Eck, 2011; Das, Subbarao, & Lewis, 2009; Tayebi & McGilvray, 2006). However, the uncertainty rejection problems in the stability analysis of the closed-loop control system were not fully discussed in these works. In Alexis, Nikolakopoulos, and Tzes (2011), a switching model predictive attitude controller was designed for the quadrotor subject to exteranl atmospheric disturbances. Adaptive tracking control approaches were discussed in Lee (2013) and Dydek, Annaswamy, and Lavretsky (2013), but the transient performances of the designed control system are unpredictable and the dynamical tracking performances cannot be specified by the methods. In Raffo, Ortega, and Rubio (2010), a nonlinear H_∞ controller was proposed for a quadrotor helicopter to stabilize the rotational dynamics. In Derafa, Benalleguel, and Fridman (2012), a discontinuous nonlinear control law was developed based on the sliding model disturbance rejection technique to counteract the effects of bounded external disturbances on the vehicle control system. In Liu, Bai, Lu, and Zhong (2013) and Liu, Lu, and Zhong (2013), robust attitude controllers were designed to restrain the effects of uncertainties on the closed-loop control systems for unmanned helicopters. However, the influences of the input time delays were not further discussed in the stability analysis of these proposed control systems.

The second problem is also intractable for the flight controller design. In Lozano, Castillo, Garcia, and Dzul (2004), a discrete-time state feedback controller based on the predictive control scheme was proposed for linear systems with input time delay and this method was applied to the yaw control of a mini-helicopter. In Ordaz, Salazar, Mondie, Romero, and Lozano (2013), this method was developed to control nonlinear time delayed systems and used to the position control of the unmanned quadrotors. In Iqbal, Roesch, Roth, and Rasool (2005), stabilizing controllers based on the Meta-Heuristics method were designed for nonlinear input delayed systems including a laboratory helicopter system. An experimental study was conducted in Lee et al. (2012) for a tilt rotor unmanned aerial vehicle with time delays on the actuation system. However, the uncertainty rejection problems were not further studied for these nonlinear time delayed

* Corresponding author.
E-mail addresses: liuhao13@buaa.edu.cn (H. Liu), lidj12@mails.tsinghua.edu.cn (D. Li), zzybobby@buaa.edu.cn (Z. Zuo), zys-dau@mail.tsinghua.edu.cn (Y. Zhong).

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systems and the tracking performances of the closed-loop delayed control systems cannot be guaranteed.

Only a few studies considered the robust control problem of the uncertain quadrotor systems with input time delays. In Song, Han, and Liu (2013), an active model-based predictive control approach was developed to compensate the effects of model errors and input time delays on the linear control systems for unmanned helicopters. In Wang, Wang, Yu, and Sun (2014), a robust controller design method based on the linear matrix inequality was developed for the obtained linear uncertain quadrotor model with input delays. In Chen, Jiang, Wen, and Su (2015), the adaptive global sliding mode control approach was combined with the quantum logic to deal with a class of linear helicopter systems with actuator time delays. However, in these works, the quadrotor models were simplified as linear models with uncertain parameters, while further studies on the robust control problems of the input time delayed quadrotor systems subject to nonlinear dynamics, parametric uncertainties, and external disturbances remain challenging.

In this paper, the robust attitude controller design problems for the nonlinear uncertain quadrotor systems with unknown time-varying delays in the inputs are investigated. A time-invariant dynamic feedback controller is proposed by considering the real vehicle system as a nominal system with nonlinear time-varying uncertainties and time-varying delays. The controller is designed in two steps: a nominal nonlinear controller is firstly designed to achieve desired tracking for the nominal system introduced artificially; then, a robust signal-based compensator is added to achieve the robust stability of the whole system against uncertainties and nonlinear dynamics. This design results in a robust controller with a two-loop form. It is shown that the robust stability and the robust tracking property can be achieved for the closed-loop control system under uniform finite norm bounded disturbances. In practical applications, an important feature of the presented control scheme is that the robust controller parameters can be tuned online unidirectionally.

This paper is constructed as follows: Section 2 briefly gives the nonlinear model description for the quadrotor dynamics; Section 3 shows the robust controller design method; the robust stability of the closed-loop control system is analyzed in Section 4; Section 5 gives the experimental results and conclusions are stated in Section 6.

Notations: Throughout this paper, the norms are denoted as $\|x\| = \sqrt{x_1^2+\cdots+x_n^2}$, for $x \in \mathbb{R}^{n\times 1}$ and $\|y\|_\infty = \sup_{t\ge t_0}\|y(t)\|$, for $y(t) \in \mathbb{R}^{n\times 1}$. $0_{n\times m}$ represents an $n \times m$ matrix with zero elements, $I_{n\times n}$ an $n \times n$ unit matrix, and $c_{vn,j}$ an $n \times 1$ vector with 1 on the jth element and zeros elsewhere. For the square matrices $A = [a_{ij}]_{n\times n} \in \mathbb{R}^{n\times n}$ and $B = [b_{ij}]_{n\times n} \in \mathbb{R}^{n\times n}$, define the Kronecker sum as follows:

$$A \oplus B = A \otimes I_{n\times n} + I_{n\times n} \otimes B,$$

where $\otimes$ denotes the Kronecker product satisfying that

$$A \otimes B = \begin{bmatrix} a_{11}B & \cdots & a_{1n}B \\ \vdots & \ddots & \vdots \\ a_{n1}B & \cdots & a_{nn}B \end{bmatrix}.$$

2. Attitude model description

The basic flight mechanism of the rotational motion of a quadrotor can be depicted as follows: the differential spinning velocities of the front and back rotors can lead to the pitch motion; the roll motion is resulted from the differential spinning speeds of the lateral rotors similarly; the yaw motion can be realized by the different reaction torques between the front–back rotor set and the left–right rotor set (Fig. 1).

Let I = $\{e_{Io}, e_{Ix}, e_{Iy}, e_{Iz}\}$ denote an earth-fixed inertial frame and B = $\{e_{Bo}, e_{Bx}, e_{By}, e_{Bz}\}$ a body-fixed frame with the origin e_{Bo} locating at the mass center of the vehicle. $R \in SO(3)$ represents the rotation matrix

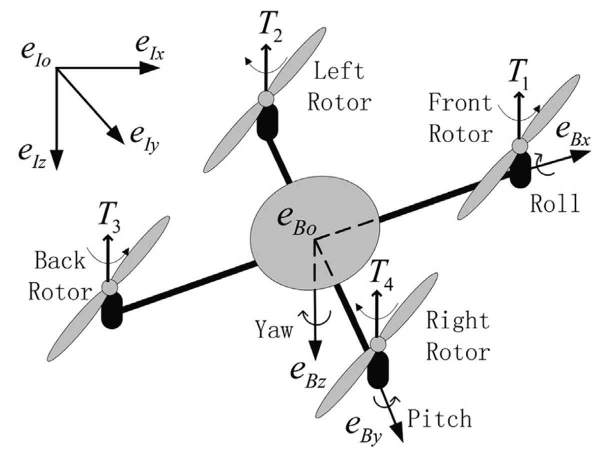

Fig. 1. The schematic of the quadrotor system.

mapping vectors expressed in B into vectors expressed in I, and $\omega_b = [\omega_{bi}]_{3\times 1} \in \mathbb{R}^{3\times 1}$ indicates the angular velocity expressed in B, and satisfies that

$$\dot{R} = RS(\omega_b), \tag{1}$$

where

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

Moreover, the relationship between the derivatives of the angular velocities and the external moment $\tau_b = [\tau_{bi}]_{3\times 1} \in \mathbb{R}^{3\times 1}$ expressed in B can be described by the following expression:

$$J\dot{\omega}_b = -S(\omega_b)J\omega_b + \tau_b, \tag{2}$$

where J indicates the inertia tensor of the vehicle body and is a symmetric and positive definite constant matrix. As shown in Isidori, Marconi, and Serrani (2003), the group of rotation matrices can be parametrized by means of unit quaternions $q = [q_0\ \bar{q}]^T \in \mathbb{R}^{4\times 1}$, where q_0 and $\bar{q} = [q_i]_{3\times 1}$ represent the scalar and the vector parts of the quaternion, respectively, and satisfy that $q_0^2 + \|\bar{q}\|^2 = 1$. Accordingly, the rotation matrix R can be given by the unit quaternions as:

$$R = \begin{bmatrix} 1-2q_2^2-2q_3^2 & 2q_1q_2-2q_0q_3 & 2q_1q_3+2q_0q_2 \\ 2q_1q_2+2q_0q_3 & 1-2q_1^2-2q_3^2 & 2q_2q_3-2q_0q_1 \\ 2q_1q_3-2q_0q_2 & 2q_2q_3+2q_0q_1 & 1-2q_1^2-2q_2^2 \end{bmatrix}.$$

Then, Eq. (1) can be rewritten by the quaternion propagation equations as:

$$\dot{q}_0 = -\tfrac{1}{2}\bar{q}^T\omega_b,\ \dot{\bar{q}} = \tfrac{1}{2}[q_0I_{3\times 3} + S(\bar{q})]\omega_b.$$

For the special case of quadrotors, the torque τ_b is generated by the four rotors. Following Zuo (2014), the thrusts produced by the four propellers are denoted by T_i $(i = 1, 2, 3, 4)$, respectively. The total thrust T_T and the torque τ_b can be determined by

$$\begin{bmatrix} T_T \\ \tau_{b1} \\ \tau_{b2} \\ \tau_{b3} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & l_T & 0 & -l_T \\ l_T & 0 & -l_T & 0 \\ k_{\tau T} & -k_{\tau T} & k_{\tau T} & -k_{\tau T} \end{bmatrix}\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix},$$

where l_T indicates the distance from the rotors to the center of mass and $k_{\tau T}$ is the force-to-moment scaling factor, which is a positive proportionality constant relative to the geometrical features of the blades. For the attitude control problem discussed here, the total thrust T_T is selected as a positive constant in order to counteract the gravity in hovering approximately. The four thrusts T_i $(i = 1, 2, 3, 4)$ produced by the propellers can be obtained by