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Robust adaptive spacecraft attitude tracking control based on similar skew-symmetric structure☆

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ABSTRACT

This paper addresses robust adaptive attitude tracking control for spacecrafts with unknown inertia parameters and bounded external disturbances. The similar skew-symmetric structure is chosen as the desired structure for the closed loop system when there exist no uncertainties. Based on this idea, a backstepping scheme is proposed to design the controller, and adaptive compensation and robust compensation are introduced to deal with the uncertainty of the inertia parameters and the external disturbances respectively. Theoretical analysis shows that fast response and high tracking precision can both be obtained by regulating the related parameters in the proposed controller. Simulation results are provided to demonstrate the effectiveness of the proposed attitude tracking control algorithm.

1. Introduction

With the development of the aerospace science and technology, more and more space missions require that the involved spacecraft or aerial vehicle carry out attitude maneuvers and attitude tracking with large angles. In this case,normally there are strong nonlinearities in the kinematics and the dynamics of the spacecraft; thus it is necessary to design attitude controller by employing nonlinear control theory. In addition, the inertia parameters of the spacecraft often cannot be exactly known, and there often exist uncertain external disturbances in the orbit environment. These uncertainties should be fully considered in the process of attitude controller design such that the control performance can be guaranteed.

Due to the above-mentioned requirements, various nonlinear control theories have been widely applied to the researches on spacecraft attitude control. And the related issue of uncertainty also has been extensively studied. For example, two attitude controllers were presented for large angle maneuvers based on feedback linearization in [1,2]. An optimal controller was proposed for attitude tracking in [3]. Unfortunately, the aforementioned three design procedures do not consider the uncertainties which exist in the spacecraft. In [4–6], slide mode controllers are developed for large angle attitude maneuvers or attitude tracking respectively. However, none of these control laws can remove the undesirable chattering. H_∞ control theory has also been applied to attitude control [7–9], and this method can consider disturbance rejection and control effort based on $\mathcal{L}_2$ gain at the same time. However, conservativeness widely exists in this kind of designs, and conservativeness leads to the requirement for stronger control effort. Furthermore, this method can not evaluate the disturbance rejection

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from the relation between the boundedness of the tracking error and that of the disturbance, and this is another limitation which hinders the application of this method. A robust backstepping controller is proposed for rapid maneuvers with smaller peak control torques in [10]; however, it does not consider the uncertainty in the external disturbances and that in the off-diagonal elements of the inertia matrix. In [11], a robust attitude tracking controller is developed for spacecrafts with uncertain inertia parameters and external disturbances; but there lacks a corresponding method to regulate the parameters in the controller based on the requirements on the performance of the closed loop system. And adaptive methods are used to deal with unknown inertia parameters in [12,13]; however, neither of them deals with the uncertainties of the external disturbances. In [14–17], adaptive methods are extended to dispose of external disturbances. Among them, constant disturbances are considered in [14]. And the two adaptive attitude tracking controllers proposed in [15,16] respectively can both accommodate unknown constant disturbances and sinusoidal disturbances with known frequencies and unknown amplitudes. The adaptive attitude tracking controller proposed in [17] can deal with disturbances without bounded energy, but it is not easy to estimate the size of the bound of the tracking errors. In practical application, the parameters of a certain controller are closely related to the obtained system performance, such us response speed, disturbance rejection, steady-state tracking precision etc. Thus it is important to determine control parameters to achieve satisfactory system response and rend the tracking error to be in a specified bound when the system encounters a bounded disturbance. However, this question has not been addressed for attitude tracking control in the literature as far as we know.

In this paper, we study on robust adaptive attitude tracking for spacecrafts with unknown inertia parameters and bounded external disturbances. Based on the similar skew-symmetric structure [16], a backstepping method is proposed to carry out the controller design. Furthermore the parameter regulation of the proposed controller is addressed according to the requirements on the performance of the closed loop system.

This paper is organized as follows. In Section 2, we introduce some results on the stability of nonlinear systems with a similar skew-symmetric structure. In Section 3, we address the spacecraft model for the attitude tracking. Section 4 is dedicated to robust adaptive controller design for spacecraft attitude tracking. Simulations and analysis are carried out in Section 5. And conclusions follow in Section 6.

2. Stability analysis for nonlinear systems with a similar skew-symmetric structure

We have presented a class of nonlinear system structure named as similar skew-symmetric for controller design in [18], however, only some special forms were given for this system structure therein. More general description was given in [19]. Both papers concerned autonomous case, and only stabilization control is addressed. The aforementioned system structure was extended to non-autonomous case in [16]. Different from an attitude stabilization system, an attitude tracking system generally is a non-autonomous system. Thus to facilitate the subsequent attitude tracking controller design, we introduce some results on the stability of nonlinear systems with a non-autonomous similar skew-symmetric from [16] in this section.

Nonlinear systems with a similar skew-symmetric structure can be described as

$$\dot{\boldsymbol{x}} = \boldsymbol{A}(\boldsymbol{x}, t)\boldsymbol{x} \tag{1}$$

where $\boldsymbol{x} = [\boldsymbol{x}_1^T \ \boldsymbol{x}_2^T \ \ldots \ \boldsymbol{x}_m^T]^T$ with $\boldsymbol{x}_i \in \mathbb{R}^{n_i} (i = 1, 2, \ldots, m)$ represents the states; t denotes the time; $\boldsymbol{A} = [\boldsymbol{A}_{ij}(\boldsymbol{x}, t)](i, j = 1 \ldots m)$ with $\boldsymbol{A}_{ij}(\boldsymbol{x}, t) : \mathbb{R}^n \times \mathbb{R} \to \mathbb{R}^{n_i \times n_j} (n = \sum_{i=1}^m n_i)$ is a functional matrix which satisfies $\boldsymbol{A}_{ij} = -\boldsymbol{L}_i \boldsymbol{A}_{ji}^T \boldsymbol{L}_j^{-1} (\forall i = 1, 2 \ldots, m; i > j)$, $\boldsymbol{A}_{ii} = \boldsymbol{L}_i \boldsymbol{A}_i$ and $\boldsymbol{L}_i (\boldsymbol{i} = 1, 2, \ldots m)$ is a symmetric positive definite constant matrix. As pointed in [16,18], after a linear state state transformation $\boldsymbol{x} = \boldsymbol{C}\boldsymbol{z}$, then the off-diagonal blocks of the new state matrix are block skew-symmetric. And the state transformation matrix has the form of $\boldsymbol{C} = diag(\boldsymbol{C}_1, \boldsymbol{C}_2, \ldots, \boldsymbol{C}_m)$, where $\boldsymbol{C}_i$ is a symmetric positive definite constant matrix which satisfies $\boldsymbol{C}_i^2 = \boldsymbol{L}_i$.

Theorem 1. *If all* $\boldsymbol{A}_i \le 0$, *then* $V = \frac{1}{2} \sum_{k=1}^m \boldsymbol{x}_i^T \boldsymbol{L}_i^{-1} \boldsymbol{x}$ *is a Lyapunov function of system (1) and* $\dot{V} = \sum_{k=1}^m \boldsymbol{x}_i^T \boldsymbol{A}_i \boldsymbol{x}_i \le 0$.

Concerning the autonomous case, Theorem 1 has been proved in [18] by choosing $V = \frac{1}{2} \sum_{k=1}^m \boldsymbol{x}_i^T \boldsymbol{L}_i^{-1} \boldsymbol{x}$ as Lyapunov function candidate; the proof for the non-autonomous case is given in [16] using the same Lyapunov function candidate.

3. Modeling of spacecraft attitude tracking

The relative kinematics of a rigid spacecraft can be expressed as

$$\dot{\boldsymbol{q}}_\varepsilon = \frac{1}{2} \boldsymbol{E}(\boldsymbol{q}_\varepsilon) \boldsymbol{\omega}_e \tag{2}$$

where $\boldsymbol{\omega}_e$ is the relative angular velocity vector of the body-fixed frame $\boldsymbol{B}_b$ with respect to the reference frame $\boldsymbol{B}_d$ and expressed in $\boldsymbol{B}_b$; $\boldsymbol{q}_\varepsilon = [q_{\varepsilon 0} \ \ q_{\varepsilon 1} \ \ q_{\varepsilon 2} \ \ q_{\varepsilon 3}]^T \triangleq [q_{\varepsilon 0} \ \ \boldsymbol{q}_{\varepsilon v}^T]^T \in \mathbb{R}^4$ is the relative attitude quaternion representing the orientation of $\boldsymbol{B}_b$ with respect to $\boldsymbol{B}_d$; and $\boldsymbol{E}(\boldsymbol{q}_\varepsilon)$ can be expressed as

$$\boldsymbol{E}(\boldsymbol{q}_\varepsilon) = \begin{bmatrix} -\boldsymbol{q}_{\varepsilon v}^T \\ \boldsymbol{q}_{\varepsilon v}^\times + q_{\varepsilon 0} \boldsymbol{I}_3 \end{bmatrix} \triangleq \begin{bmatrix} -\boldsymbol{q}_{\varepsilon v}^T \\ \boldsymbol{E}_1(\boldsymbol{q}_\varepsilon) \end{bmatrix} \tag{3}$$