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Research article

Attitude output feedback control for rigid spacecraft with finite-time convergence

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ABSTRACT

The main problem addressed is the quaternion-based attitude stabilization control of rigid spacecraft without angular velocity measurements in the presence of external disturbances and reaction wheel friction as well. As a stepping stone, an angular velocity observer is proposed for the attitude control of a rigid body in the absence of angular velocity measurements. The observer design ensures finite-time convergence of angular velocity state estimation errors irrespective of the control torque or the initial attitude state of the spacecraft. Then, a novel finite-time control law is employed as the controller in which the estimate of the angular velocity is used directly. It is then shown that the observer and the controlled system form a cascaded structure, which allows the application of the finite-time stability theory of cascaded systems to prove the finite-time stability of the closed-loop system. A rigorous analysis of the proposed formulation is provided and numerical simulation studies are presented to help illustrate the effectiveness of the angular-velocity observer for rigid spacecraft attitude control.

1. Introduction

Accurate and reliable attitude control is one of the most important problems and widely studied application in current spacecraft attitude control system design, meanwhile, there are many valuable researches in this area. Many studies related to attitude control scheme have been published based on several inspiring approaches, such as proportional-derivative (PD) control algorithm which has been widely applied in practical projects [1], optimal control [2], adaptive control [3], but there are few works that have explicitly dealt with the running characteristics of reaction wheel. In practical spacecraft attitude control implementation, reaction wheel is often used as actuator to provide effective and continuous control torque. However, reaction wheel always suffers the friction torque inevitably, which will influence the control performance to some extent [4]. One method to deal with the influence caused by reaction wheel friction torque is adding a prior friction torque versus speed of reaction wheel to control torque command in a feed-forward way. But it is difficult to measure friction torque accurately due to measurement error of wheel speed and friction uncertainties. Furthermore, the friction torque increases due to aging of reaction wheel. Thus, this method could hardly achieve accurate attitude control in some sense. However, except for literature [5], there are few research works found for this related area, which was acknowledged by the author.

Note that most of the existing attitude control laws are asymptotically stable, which means state errors converge to the equilibriums as time goes to infinity [6]. Obviously, such stability performance requiring infinite settling time is not an optimal option during critical mission phases of some high-value real-time missions. Finite-time control theory provides fast convergence rate and high-precision performance. Thus, the research on finite-time stabilization is an interesting and challenging problem. Existing finite time control methods can be broadly classified into two categories: the Lyapunov-based approach [7–9] and the homogeneous domination approach [10,11]. Some significant recent researches have been done using finite time control-based strategies to guarantee finite time stability for spacecraft attitude. In Ref. [12], a robust sliding mode controller was developed to guarantee the spacecraft attitude system states can be forced to be attained in the small set of a sliding surface in finite time. The terminal sliding mode controller was developed in [13] and consisted of the estimation of inertia uncertainty and disturbance by adaptive method. Lu and Xia [14] proposed a finite-time nonsingular terminal sliding mode control law associated with adaptation which provides finite-time convergence and higher precision. By employing terminal sliding mode and some properties of dual quaternion in [15], the practical finite-time stability of the closed-loop system for spacecraft formation flying is guaranteed through the designed control law. In Ref. [16], a sliding mode based finite-time control scheme is presented to address the

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problem of attitude stabilization for rigid spacecraft in the presence of actuator faults and external disturbances.

A typical feature in all the above-mentioned attitude control schemes is in dependence on angular velocity measurements. Unfortunately, this requirement is not always satisfied in reality since the cost limitations and the implementation constraints. Thus, a common practice is to approximate the angular velocity signal through an ad hoc numerical differentiation of the attitude angles. Aiming at the condition that completely independent of angular velocity measurement, a nonlinear output feedback attitude control is designed by involving a linear passivity filter, which is derived without explicit differentiation of attitude to synthesize angular velocity-like signals [17]. Furthermore, an angular velocity observer was developed in Ref. [18] to achieve global convergence of angular velocity estimation error. In [19–21], the quaternion-based output feedback control scheme was designed for velocity-free attitude control of spacecraft. However, the convergence rate of angular velocity estimation error couldn't be guaranteed by above techniques. With this in mind, Sun [22] established a switched saturated feedback controller developed based on a state observer, which could ensure the closed-loop system is semi-global finite-time stable in the presence of constraints on control input magnitude, but the external disturbances was not considered. Zou [23] proposed the finite-time observer, and designed an attitude stabilizing control law to guarantee that the attitude states of the spacecraft converge to the equilibriums in finite time. While the above two corresponding finite-time controllers are designed via non-smooth controller construct. Hu [24] et al. investigated the finite-time relative position coordinated tracking problem by output feedback for spacecraft formation flying in the absence of velocity measurement. Ref. [25] introduced the power integrator method and homogeneous system to demonstrate the finite time stabilization of velocity-free attitude control system. To obtain a more realistic control performance, the finite-time observer combined with output feedback controller is studied in the presence of saturation and external disturbances [26].

The main contribution of this paper is designing a class of finite-time control algorithm respect to the rigid spacecraft attitude stabilization that explicitly takes account of velocity-free and external disturbances as well as reaction wheel friction, and assures a fast response. More specifically, by exploiting structural properties of the spacecraft model, a nonlinear finite time observer is proposed to estimate the angular velocity in finite time, in which both the external disturbances and friction torque of reaction wheel are explicitly accounted for. Then, based on the results obtained from the finite time observer, a finite time attitude-control law from the use of a velocity estimator is developed. The proposed control strategy is analytically verified and also validated via a simulation study.

The rest of this paper is organized as follows: Section 2 provides the rigid spacecraft kinematics and dynamics models in attitude control system along with some lemmas which could be applied to this research. In Section 3, a finite time observer design scheme is proposed and we provide the associated stability analysis for the estimation error dynamics. In Section 4, based on the finite-time observer, an output feedback control law is given by introducing a power integrator technique, meanwhile, Lyapunov theorem provides a rigorous proof of finite-time stabilization on closed-loop system. Section 5 illustrates the performance of the presented control scheme which is analyzed combined with the results of digital simulation.

2. Background and preliminaries

2.1. Definitions and lemmas

Consider a general system as followings:

$$\dot{x} = f(x, t), f(0, t) = 0, x \in U \subset R^n \quad (1)$$

where f is continuous function on an open neighborhood U of the origin.

Lemma 1 *([27]): Suppose a Lyaponov function $V(x, t)$ is defined as:*

$$\dot{V}(x, t) \le -lV^{\alpha}(x, t), \forall x \in U_1 \backslash \{0\} \quad (2)$$

where U_1 is a neighborhood of the origin, and $l > 0,\ 0 < \alpha < 1$. Then, the origin of system is locally finite-time stable. The settling time satisfies

$$T \le \frac{V^{1-\alpha}(x(t_0, t_0))}{l(1-a)}, x(t_0) \in U_1 \quad (3)$$

Then, suppose there exists a Lyapunov function $V(x, t)$ on U_1, and

$$\dot{V}(x, t) \le -lV^{\alpha}(x, t) + kV(x, t), \forall x \in U_1 \backslash \{0\} \quad (4)$$

where $l, k > 0$,and $0 < \alpha < 1$. For an initial condition $x(t_0)$, the origin of system is locally finite-time stable if $x(t_0) \in \{U_1 \cap U_2\}$, where $U_2 = \left\{x | V^{1-\alpha}(x, t) < \frac{l}{k}\right\}$ is a neighborhood of the origin and satisfies that $U_1 \subseteq U_2$ or $U_2 \subseteq U_1$. The settling time satisfies

$$T \le \frac{V^{1-\alpha}(x(t_0), t_0)}{\left(l - kV(x(t_0), t_0)\right)(1-\alpha)} \quad (5)$$

Lemma 2 *([28]): If $0 < \kappa = \kappa_1/\kappa_2 \le 1$, where κ_1 and κ_2 are positive odd integers, then $|x^{\kappa} - y^{\kappa}| \le 2^{1-\kappa}|x - y|^{\kappa}, \forall x, y \in R$.*

Lemma 3 *([29]): For any $x \in R, y \in R, c > 0, d > 0$ and $\gamma > 0$, there is an inequality which satisfies $|x|^c|y|^d \le c\gamma|x|^{c+d}/(c+d) + d|y|^{c+d}/\left(\gamma^{c/d}(c+d)\right)$.*

Lemma 4 *([30]): For any $x_i \in R$, $i = 1, 2, \cdots, n$, and a real number $\kappa \in (0, 1]$,*

$$\left(\sum_{i=1}^{n} |x_i|\right)^{\kappa} \le \sum_{i=1}^{n} |x_i|^{\kappa} \le n^{1-\kappa}\left(\sum_{i=1}^{n} |x_i|\right)^{\kappa}.$$

Given a vector $x \in R^n$ and a scalar $\alpha \ge 0$, define $sig^{\alpha}(x)= \left[sig^{\alpha}(x_1), sig^{\alpha}(x_2), \ldots, sig^{\alpha}(x_n)\right]^T$, where $sig^{\alpha}(x_i) = \mathrm{sgn}(x_i)|x_i|^{\alpha}$ $(i = 1, 2, \ldots, n)$, and $\mathrm{sgn}(\cdot)$ denotes the signum function.

2.2. Rigid spacecraft model

The rigid spacecraft attitude control system with disturbances and reaction wheel friction can be described as following kinematics and dynamics models [4]:

$$\mathbf{J}\dot{\boldsymbol{\omega}} = -S(\boldsymbol{\omega})\left(\mathbf{J}\boldsymbol{\omega} + \mathbf{J}_{rw}\Omega\right) + \mathbf{u} + \mathbf{d} + \mathbf{d}_f \quad (6)$$

$$\dot{\mathbf{q}} = \frac{1}{2}E(\mathbf{q})\boldsymbol{\omega} \quad (7)$$

where $\boldsymbol{\omega} = [\omega_1, \omega_2, \omega_3]^T$ denotes the angular velocity vector of spacecraft body-fixed reference frame, and $\mathbf{q} = \left[q_0, \mathbf{q}_v\right]^T=$

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