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Event-triggered attitude control of spacecraft

Baolin Wu [a,*], Qiang Shen [b], Xibin Cao [a]

[a] Harbin Institute of Technology, 150080 Harbin, People's Republic of China
[b] National University of Singapore, Singapore 117582, Singapore

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Abstract

The problem of spacecraft attitude stabilization control system with limited communication and external disturbances is investigated based on an event-triggered control scheme. In the proposed scheme, information of attitude and control torque only need to be transmitted at some discrete triggered times when a defined measurement error exceeds a state-dependent threshold. The proposed control scheme not only guarantees that spacecraft attitude control errors converge toward a small invariant set containing the origin, but also ensures that there is no accumulation of triggering instants. The performance of the proposed control scheme is demonstrated through numerical simulation.

Keywords: Spacecraft control; Attitude stabilization; Event-triggered control; Limited communication

1. Introduction

The objective of spacecraft attitude control system is to make the spacecraft achieve fine pointing, rapid maneuvering, accurate tracking and other desired performances. Since a spacecraft involves nonlinear and highly coupled dynamics, and may subject to unexpected factors, such as external disturbances, inertia matrix uncertainties and actuators failures/faults, numerous control schemes have been investigated for solving the spacecraft attitude control problem. These include sliding mode control (Boskovic et al., 2001; Liang et al., 2007; Du and Li, 2012; Hu et al., 2013; Zou, 2014; Eshghi and Varatharajoo, 2017), optimal control (Luo et al., 2005; Boyarko et al., 2011; Shen et al., 2015; Jikuya et al., 2016), adaptive control (Ahmed et al., 1998; Cai et al., 2008; Xia et al., 2011), and iterative learning control (Wu et al., 2015), etc.

Plug-and-play spacecraft (Lyke, 2012) have received a significant research attention over the past few years. The functional components of plug-and-play spacecraft are independent modules. These functional modules interact through wireless links. The plug-and-play spacecraft offers more flexibility and robustness than conventional monolithic spacecraft. Data transmission among independent modules is performed by low-cost wireless network in this kind of spacecraft. Data communication rate of low-cost wireless network is limited. As a result, a key problem encountered for plug-and-play spacecraft is how to decrease the signal transmission burden among independent modules. Thus, novel attitude control method with limited communication should be investigated. Although there are plenty of results on spacecraft attitude control in the literature, there is few result available which investigates attitude control with limited communication.

One possible solution to the problem of attitude control with limited communication is to utilize signal quantization with recently proposed quantizer. Based on this idea, Wu (2016) proposes a control scheme for spacecraft attitude

* Corresponding author at: Research Center of Satellite Technology, Harbin Institute of Technology, Room 507, Block B3, No. 2 Yikuang Street, Nangang District, Harbin 150080, People's Republic of China.
E-mail address: wuba0001@e.ntu.edu.sg (B. Wu).

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stabilization with control torque quantized by a logarithmic quantizer, and a guideline to choose the quantizer parameters. Besides signal quantization, event-triggered control is another effective method to reduce the waste of communication and computation resources for network control systems (Tabuada, 2007). The main difference between the classical sample-data control and event-triggered control lies in how the controller is implemented to the system. For the classical control, the control signal is sampled and applied to the system periodically no matter the system needs it or not. While under the event-triggered control strategy, the controller is activated only when a defined measurement error exceeds a given threshold, and only triggered data at some discrete triggered times need to be transmitted. Therefore, the event-triggered method can be expected to have an efficient effect on reducing the communication pressure for spacecraft attitude control system.

Note that the results of event-triggered control for nonlinear systems are still very limited. Event-triggered control algorithms are investigated in Tabuada (2007) and Tallapragada and Chopra (2013) for stabilization of nonlinear systems, and in Postoyan et al. (2015) for trajectory tracking in nonlinear systems. The above event-triggered control algorithms in Tabuada (2007), Tallapragada and Chopra (2013), Postoyan et al. (2015) are based on the input to-state stability (ISS) assumption which implies the existence of a feedback control law ensuring an ISS property with respect to measurement errors. The design of both the controller and the event-triggering condition simultaneously for nonlinear systems has been proposed in Sahoo et al. (2016), Xing et al. (2016), Li et al. (in press). Adaptive neural network-based event-triggered control law is studied in Sahoo et al. (2016) for single-input single-output uncertain nonlinear discrete-time systems. Adaptive backstepping control-based event-triggered control method is presented in Xing et al. (2016) for a class of uncertain nonlinear systems. Furthermore, observer-based fuzzy adaptive event-triggered control law is proposed in Li et al. (in press) for uncertain nonlinear systems. Though some results have been established for event-triggered control for nonlinear systems, to our best of knowledge, there is still no consideration of spacecraft attitude control with an event-triggered mechanism. Since attitude dynamics is nonlinear and highly coupled, it is not straightforward to apply the above event-triggered control laws to attitude control of spacecraft.

This paper aims to provide a solution to the problem of spacecraft attitude stabilization control with limited communication. An event-triggered control method is investigated to reduce the communication pressure. Under the event-triggered strategy, the information of attitude and control torque only need to be transmitted at some discrete triggered times when a defined measurement error exceeds a state-dependent threshold. Through Lyapunov analysis, it is shown the proposed control law ensures that attitude control errors converge toward a small invariant set containing the origin in spite of external disturbances. A positive lower bound on inter-update time is also guaranteed to avoid accumulation of triggering instants. Simulation results demonstrate the efficiency of the proposed event-triggered attitude control law, and data to be sent over the communication channel under the proposed attitude control scheme is greatly reduced.

The remaining parts of this paper are organized as follows. Section 2 introduces the attitude dynamics of spacecraft. Section 3 presents the problem formulation. Section 4 proposes an event-triggered controller design scheme for attitude stabilization, and the stability analysis of the resulting closed-loop system is also given in this section. Section 5 presents the simulation results, while the conclusions are drawn in Section 6.

2. Spacecraft attitude dynamics

With the assumption of rigid body movement, the kinetics of a spacecraft can be established from Euler's moment equation as (Ahmed et al., 1998):

$$\boldsymbol{J}\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega}^{\times}\boldsymbol{J}\boldsymbol{\omega} + \boldsymbol{u} + \boldsymbol{d} \tag{1}$$

where $\boldsymbol{\omega} = \boldsymbol{\omega}(t) \in \mathbb{R}^3$ denote the body angular velocity of the spacecraft with respect to the inertial frame $\mathcal{I}$, expressed in the body-fixed frame $\mathcal{B}$; $\boldsymbol{J} = \boldsymbol{J}^T \in \mathbb{R}^{3\times3}$ denotes the positive-definite inertia matrix of the spacecraft. $\boldsymbol{u} = \boldsymbol{u}(t) \in \mathbb{R}^3$ denotes the control torque expressed in the body-fixed frame $\mathcal{B}$; $\boldsymbol{d} \in \mathbb{R}^3$ denotes the external disturbances expressed in the body-fixed frame $\mathcal{B}$; The notation $\boldsymbol{\omega}^{\times}$ for the vector $\boldsymbol{\omega} = [\,\omega_1 \quad \omega_2 \quad \omega_3\,]^T$ is employed to denote the skew-symmetric matrix as below

$$\boldsymbol{\omega}^{\times} = \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix}$$

The nonlinear differential equations that govern the kinematics of the rigid spacecraft in terms of quaternion are described as follows (Ahmed et al., 1998):

$$\dot{\boldsymbol{q}}_v = \frac{1}{2}(\boldsymbol{q}_v^{\times} + q_0\mathbf{I}_3)\boldsymbol{\omega} \tag{2}$$

$$\dot{q}_0 = -\frac{1}{2}\boldsymbol{q}_v^T\boldsymbol{\omega} \tag{3}$$

$(\boldsymbol{q}_v, q_0) \in \mathbb{R}^3 \times \mathbb{R}$ denotes the unit quaternion representing the orientation of a body-fixed frame $\mathcal{B}$ with respect to an inertial frame $\mathcal{I}$ and satisfies the constraints $\boldsymbol{q}_v^T\boldsymbol{q}_v + q_0^2 = 1, \boldsymbol{q}_v \in \mathbb{R}^3$ and $q_0 \in \mathbb{R}$ denote the vector and scalar components, respectively; $\mathbf{I}_3$ denotes the 3×3 identity matrix.

Property 1. *The inertia matrix of spacecraft* $\boldsymbol{J}$, *which is symmetric and positive-definite, satisfies the following bounded condition*:

$$J_{\min}\|\boldsymbol{x}\|^2 \leqslant \boldsymbol{x}^T\boldsymbol{J}\boldsymbol{x} \leqslant J_{\max}\|\boldsymbol{x}\|^2, \quad \forall \boldsymbol{x} \in \mathbb{R}^3 \tag{4}$$