Aerospace Science and Technology 75 (2018) 245–253

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Spacecraft attitude fault-tolerant control based on iterative learning observer and control allocation

Qinglei Hu *, Guanglin Niu, Chenliang Wang

School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China

ARTICLE INFO

Article history:
Received 15 August 2017
Received in revised form 25 December 2017
Accepted 26 December 2017
Available online 3 February 2018

Keywords:
Fault tolerant control
Spacecraft
Iterative learning observer
Control allocation
Actuator fault

ABSTRACT

In this paper, an observer-based fault-tolerant control scheme is proposed for the attitude stabilization of rigid spacecraft in the presence of actuator fault, configuration misalignment, input saturation and even external disturbances simultaneously. More specifically, an iterative learning observer is firstly developed to estimate the torque deviation and steer the estimation errors into some small residual sets. And also the detailed derivations of the observer are provided, along with a thorough analysis for the associated ultimate bounded stability and estimation error convergence property. Then, an integral-type sliding mode control law is designed to produce the three-axis virtual control signals with the desired performance for being distributed among the individual actuators. Under this, a robust control allocation algorithm is developed to map the virtual control demand onto individual actuator in an optimal manner, which takes into account the estimation uncertainties and ensures some fault-tolerant ability. The key feature of the proposed strategies is that the whole closed-loop fault tolerant control system can be guaranteed theoretically to be stable by the development of Lyapunov methodology. Numerical simulation results are presented to illustrate and highlight the fine performance benefits obtained using the proposed schemes.

1. Introduction

Attitude stabilization is one of the most significant missions for spacecraft on-orbit operation. The spacecraft dynamics are strongly nonlinear and subject to various disturbances from space environment. In addition, regarding the control torque produced by actuators of spacecraft, a complication arises from the fact that input is upper-bounded by a constant. Although a large amount of approaches have been developed to address these problems [1–4], most of the existing results ignore actuator faults in the attitude stabilization system, and the actuator faults may cause three-axis instability and even a total loss of the spacecraft. Hence, fault-tolerant control is one of the most significant issues that should be handled in attitude stabilization.

Generally speaking, fault-tolerant control can be classified into two categories, i.e., passive approaches and active approaches [5]. The passive fault-tolerant control considers a presumed set of system component failures and uses actuator redundancy. Sliding mode control has attracted extensive interest in fault-tolerant control [6–10]. Particularly, the integral-type sliding mode control provides a proper sliding manifold, where the stability can be proved from the beginning of the process and the reaching phase is eliminated. However, passive fault-tolerant control without faults estimation is only valid for presumed faults. In contrast to the passive tolerant control, active fault-tolerant control compensates for the faults by synthesizing or selecting the new controller online and requires the fault diagnosis mechanism. Patton et al. [11] proposed the robust fault detection and isolation for faults on the thrusters. Ref. [12] employed a two-stage Kalman filter to estimate the actuator and sensor faults. Ref. [13] presented an integrated fault diagnosis by state augmentation. An iterative neuron PID observer was proposed and used for the fault detection and diagnosis spacecraft attitude control systems in [14]. A supervision scheme consisting of fault detection, isolation and control reconfiguration was developed in [15] for attitude control system with reaction wheels, while a second order nonlinear sliding mode observer was proposed in [16]. Ref. [17] proposed a method consisting of a fault detector for robust and quick fault detection, two-stage hierarchical isolation strategy for fault isolation. Sliding mode and learning approaches were employed to develop a novel and practical model-based robust fault diagnosis schemes in [18] for various satellite control systems. Xiao et al. [19] designed a terminal sliding mode observer which can estimate the reaction wheel faults and external disturbances in finite time. A sliding mode observer was developed with reaction wheel dynamics in [20] to detect the

---

* Corresponding author.
E-mail address: huql_buaa@buaa.edu.cn (Q. Hu).

https://doi.org/10.1016/j.ast.2017.12.031
1270-9638/

anomalies and faults. On account of the limited computing capability of computer on spacecraft, an iterative learning observer was investigated in [21] to estimate both time-varying and constant faults. Unfortunately, external disturbances are not considered in the above results. In addition, these results only addressed a single type of actuator fault, and there are few control schemes able to handle configuration misalignment and the loss of actuator effectiveness simultaneously in the presence of external disturbances.

To make effective use of the redundancy of actuators, control allocation is utilized to distribute the virtual control signals to each actuator in the best manner while taking into account the constraints. There are some interesting results available for control allocation. The pseudo-inverse method [22] with a configuration matrix is the main method in the early research. However, this method cannot make full use of the remaining control power for fixed allocation. At present, some other control allocation strategies have been proposed, such as the daisy chain allocation method [23], the linear or nonlinear programming method [24], and the dynamic control allocation method [25]. But these strategies [23–25] have not considered the situation that there exist actuator faults, so some schemes are developed to allocate the control torque incorporated with actuator faults information. In Ref. [26], the robust least-square control allocation was proposed for the flight fault tolerant control system. Taking into account the unknown disturbances and inertia uncertainty, a novel fault-tolerant control law incorporating on-line control allocation was developed in [27]. Considering fault estimation error, a robust control allocation strategy was proposed in [28]. A constrained control allocation technique was designed in [29] with the ability to comprise several control effectors into only three aerodynamic moments around the body axes.

In this paper, an observer-based fault-tolerant control scheme is proposed for rigid spacecraft attitude stabilization in the presence of actuator faults, configuration misalignment, external disturbances and input saturation as well. Firstly, an iterative learning observer is developed to estimate the torque deviation and guarantees that the estimation errors of the torque deviation and the angular velocity converge to some small residual sets. Then, the virtual control based on integral-type sliding mode manifold is developed, which is able to ensure that all signals of the closed-loop system are globally uniformly bounded. Finally, based on the virtual controller and the iterative learning observer, a robust control allocation algorithm is developed to distribute the virtual control law to each actuator in an optimal manner with fault-tolerant ability. The proposed fault-tolerant control scheme is analytically verified and illustrated via simulation results. The main contributions of this study, relative to other works, are as follows:

- Proposing an iterative learning observer which contains the sign function to estimate the torque deviation caused by actuator faults. Particularly, the sign function used in the observer could decrease the computing complexity for only need to compare the size between the angular velocity of the spacecraft and its estimate value.
- The faults estimation information is introduced in robust control allocation strategy, which could achieve better fault-tolerant ability than the existing methods.

The rest of this paper is organized as follows. In Section 2, the control problem is formulated. Section 3 gives the design of the iterative learning observer. In Section 4, the virtual control law and robust control allocation strategy are proposed. Simulation results are presented in Section 5 to illustrate the effectiveness of the proposed scheme. Finally, we conclude in Section 6.

2. Problem formulation

The attitude dynamics and kinematics of the rigid spacecraft are governed by Euler's rotational equations of motion, given by

$$J\dot{\omega} = -S(\omega)J\omega + \tau + d \tag{1}$$

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

$$\dot{q}_v = \frac{1}{2}\big(q_0 I_{3\times 3} + S(q_v)\big)\omega \tag{3}$$

where $J \in \mathbb{R}^{3\times 3}$ is the total inertia matrix, $\omega = [\omega_1, \omega_2, \omega_3]^T$ denotes the angular velocity of the spacecraft in the body-fixed frame, $\tau \in \mathbb{R}^3$ denotes the control torque, $d \in \mathbb{R}^3$ denotes the external disturbance torque, the unit quaternion $q = [q_0, q_v^T]^T = [q_0, q_1, q_2, q_3]^T$ is a four-dimensional vector representing the orientation of the body frame and satisfies the unit-norm constraint $q_0^2 + q_v^T q_v = 1$, $I_{3\times 3}$ is the 3×3 identity matrix, and $S(\omega)$ and $S(q_v)$ are given by

$$\begin{aligned} S(\omega) &= \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix}, \\ S(q_v) &= \begin{bmatrix} 0 & -q_3 & q_2 \\ q_3 & 0 & -q_1 \\ -q_2 & q_1 & 0 \end{bmatrix}. \end{aligned} \tag{4}$$

Similar to [30], the actual control torque generated by reaction wheels with faults and configuration misalignment can be modeled by

$$\begin{aligned} \tau &= (D_0 + \Delta D)E(t)u_c \\ &= (D_0 + \Delta D)u_c + (D_0 + \Delta D)\underbrace{\big(E(t) - I_{m\times m}\big)u_c}_{\tau_f} \\ &= D_0 u_c + (D_0 + \Delta D)\tau_f + \Delta D u_c \end{aligned} \tag{5}$$

where $D_0 \in \mathbb{R}^{3\times m}$ is the nominal control torque distribution matrix with $m > 3$ the number of actuators, $\Delta D \in \mathbb{R}^{3\times m}$ denotes the configuration matrix of misalignment, $E(t) = \mathrm{diag}(e_1(t), e_2(t), \ldots, e_m(t)) \in \mathbb{R}^{m\times m}$ represents the loss of effectiveness for actuators with $0 \le e_i(t) \le 1$ $(i = 1, 2, \ldots, m)$, u_c denotes the control signal commanded by the controller and delivered to actuators, and τ_f denotes the deviation value caused by actuator faults. Note that $e_i(t) = 1$ indicates the ith actuator operates normally, $0 < e_i(t) < 1$ implies that the ith actuator partially loses its power, and $e_i(t) = 0$ indicates the ith actuator fails completely. Substituting Eq. (5) into Eq. (1), the spacecraft attitude dynamics can be rewritten as

$$J\dot{\omega} = -S(\omega)J\omega + D_0 u_c + (D_0 + \Delta D)\tau_f + \Delta D u_c + d \tag{6}$$

The following assumption is made, which is mild for the external disturbance.

Assumption 1. The external disturbance d is bounded, i.e., there exists a constant $d_{\max}$ such that $\|d\| \le d_{\max}$.

The objective is to propose a control scheme such that all signals of the closed-loop system are uniformly ultimately bounded and the attitude vector q_v and relative angular velocity ω converge asymptotically to zero, regardless of the actuator faults, external disturbances and actuator saturation.