Fault-Tolerant Control System Design for Nonlinear System with Actuator Faults

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Abstract

This article deals with observer-based integrated robust fault estimation and accommodation design problems for nonlinear system. The environmental disturbance torque, actuator faults, sensor faults and model uncertainties are considered. Firstly, we propose the augmented fault estimation observer (AFEO) to guarantee the convergence of H_∞ performance index of fault estimation and to restrict the influence of uncertainties with respect to the fault estimation error as well. We then design the fault accommodation which is based on the dynamic output feedback to keep the stability of the closed-loop system while malfunctioning. AFEO and dynamic output feedback fault tolerant controller (DOFFTC) are separately designed. Their performances are separately considered. Finally, we propose a simulation result of the micro-satellite attitude control system to demonstrate the effectiveness of the presenting method.

Keywords: augmented fault estimation observer, H_∞ performance index, dynamic output feedback fault tolerant controller.

1. Introduction

The main missions of the satellite include communication, navigation, earth observation, and so on. The attitude control system is one of the most important subsystems of the satellite which requires high performance and excellent functionality. Different kinds of unavoidable malfunctions will occur in a harsh mission environment such that some performances will become poorer and even shut down the whole system. The fault diagnosis theory might be one of the most efficient methodologies among all attitude control design theories. It can provide reliable attitude control when component faults or malfunctions occur. Therefore, many contributions are made to the satellite attitude control problem on the basis of fault diagnosis theory [1-5].

There are three types of fault diagnosis (FD) method: signal-based, knowledge-based, and model-based. Three essential tasks are included in the basic FD strategy: fault detection, fault isolation, and fault estimation. Due to the increased requirements of performance, safety, and reliability, the model-based fault detection and isolation are getting concerned in the last two decades [1-8].

Fault estimation is the most common method among these model-based methods [1]. It uses filters to generate residuals and then to set a threshold according to these residuals to detect the faults. Recently, with the developments of robust control theory and $H\infty$ optimal control theory, more methods have been proposed to solve the robust fault detection and isolation (RFDI) problems. The goal of the robust fault detection is to distinguish faults effects and effects of uncertain signals and perturbations, which is different from the robust control. Therefore, the performance of the RFDI system is measured by the appropriate trade-off between robustness and sensitivity.

This article is divided into two parts. The microsatellite H∞ robust fault detection filter (RFDF) design problem is introduced in the first part. The second part discusses the microsatellite fault-tolerant control problem. In the first part, the microsatellite is considered as a nonlinear system with external disturbance input. The aim of this part is to design a stable RFDF system with $\boldsymbol{H}_\infty$ performance for the microsatellite. The system is described by a state space model formed by the linear terms combining with the nonlinear terms which satisfy the Lipschitz condition. The residual model is used to simplify the RFDF design problem to the standard H∞ model matching problem in this article. The performance index used to design the reference residual model considers the robustness to the disturbances and the sensitivity to the faults. In [3], the RFDF system was designed with a similar performance index without considering the failure of the sensor, hence, it cannot deal with the condition when both actuators and sensors malfunctions. We apply a linear matrix inequalities (LMIs) method in $\boldsymbol{H}_\infty$ optimization technique to the RFDF design problem in this article.

In the second part, fault detection and isolation are considered to be the most important tasks and also are the main concern in references. The accurate and immediate fault estimation helps to reconstruct fault parameters (and/or) signals, hence, it plays a critical role in the fault-tolerant control system. Even though the fault effects can be accommodated in the corresponding control reconfiguration in the fault-tolerant control system, the existences of disturbances, noises, and model uncertainties make the fault estimation design becomes more difficult.

There are three main contributions of this paper. Firstly, we propose a multi-objective augmented fault estimation observer (AFEO). This observer contains exponential stability and $\boldsymbol{H}_\infty$ performance, which not only guarantees the convergence speed of fault estimation but also limits the influence of uncertainty as much as possible. Secondly, it is well known that traditional multi-objective design methods generate stability for the system when faults occur, and the detailed design steps of the strategy are given based on LMIs. The third is to consider uncorrelated actuator failure and sensor failure issues at the same time. It is worth noting that AFEO and DOFTC are independently designed from the perspective of the entire design process. To avoid the coupling problem caused by observer state feedback and to help the estimation of design parameters, the performances of AFEO and DOFTC are simultaneously considered. As far as we know, no reference about fault estimation and accommodation control problem has been reported.

This article is organized as follows. The description of the system refers to Section 2. A new type of augmented fault estimation observer (AFEO) is designed for a class of uncertain Lipschitz nonlinear systems in Section 3, which can provide an H_∞ performance index to estimate the fault vector. We propose a new fault accommodation design method based on dynamic output feedback and present a result of an actual system in Section 4. At the end, the conclusion of this article.

2. Micro-satellite Attitude Control System Model

By using the well-known Euler's moment equation, we can describe the dynamic characteristics of a rigid microsatellite in a circular orbit in terms of a nonlinear equation of motion [1]:

$$J\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega}^{\times} J\boldsymbol{\omega} + \boldsymbol{\tau}_w + \boldsymbol{\tau}_u \tag{1}$$

where $\boldsymbol{J} = \text{diag}\left\{J_x, J_y, J_z\right\}$ are inertia moments of the satellite along principal axes; $\boldsymbol{\omega}$ are the angular velocity of the body-fixed reference frame. $\boldsymbol{\tau}_w$ are space disturbance torques and $\boldsymbol{\tau}_u$ are the control torques along principal axes. Denotes a skew-symmetric matrix which is given by

$$\boldsymbol{\omega}^{\times} = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix} \tag{2}$$

Satellite attitude kinematics can be obtained as follows [2]:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \frac{1}{\cos\phi} \begin{bmatrix} \left(\omega_{box}\cos\theta + \omega_{boy}\sin\theta\right)\phi \\ \omega_{box}\cos\phi + \left(\omega_{box}\sin\theta - \omega_{boz}\sin\theta\right) \\ \omega_{boz}\cos\theta - \omega_{box}\sin\theta \end{bmatrix} \tag{3}$$

where ϕ, θ and ψ were roll angle, pitch angle, yaw angle along principal axes, respectively. $\omega_{bo} = \begin{bmatrix} \omega_{box} & \omega_{boy} & \omega_{boz} \end{bmatrix}^T$ the angular velocity of a body-fixed reference frame of a satellite with respect to an orbit reference frame expressed in the body-fixed reference frame. $\boldsymbol{\omega} = \omega_{bo} + T_{bo}\omega_{oi}$, where T_{bo} is the attitude transformation matrix. ω_0 is the constant orbital rate, and $\omega_{oi} = [0 \quad -\omega_0 \quad 0]$ is the orbit angular velocity.

Consider the satellite is moving in a small angle maneuver. According to Eq. (1), Eq. (2) and Eq. (3), satellite attitude control system (ACS) model with actuator and sensor faults are established into the following equations:

$$\begin{cases} \dot{x}(t) = Ax(t) + B_w w(t) + B_u u(t) + g(x,t) \\ \qquad + \psi(x,u,t) + F_a f_a(t) \\ y(t) = Cx(t) + F_s f_s(t) \end{cases} \tag{4}$$

$$\dot{z}(t) = -A_z z(t) + A_z y(t) \tag{5}$$

where $x = [\phi \quad \theta \quad \psi \quad \omega_x \quad \omega_y \quad \omega_z]^T$ is state variable vector, $w = [w_x \quad w_y \quad w_z]^T$ denotes the disturbance torque which is consist of gravitational perturbation solar radiation pressure, electromagnetic force, $u = [u_x \quad u_y \quad u_z]^T$ represents the input vector, $f_a(t)$ denotes actuator fault, and $f_s(t)$ is the a sensor fault. The system matrix can be expressed as

$$A = \begin{bmatrix} 0 & 0 & \omega_0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ -\omega_0 & 0 & 0 & 0 & 0 & 1 \\ 3\omega_0^2(J_z - J_y)J_x^{-1} & 0 & 0 & 0 & 0 & 0 \\ 0 & 3\omega_0^2(J_z - J_x)J_y^{-1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$, \quad g(t,x) = \begin{bmatrix} 0 \\ \omega_0 \\ 0 \\ \omega_y\omega_z(J_z - J_y)J_x^{-1} \\ \omega_x\omega_z(J_x - J_z)J_y^{-1} \\ \omega_x\omega_y(J_y - J_x)J_z^{-1} \end{bmatrix} \quad , \quad C = I_6 \quad ,$$

$$B_u = B_w = F_a = \begin{bmatrix} 0_{3\times3} \\ \boldsymbol{J}^{-1} \end{bmatrix}, F_s = I_6 .$$

Assume the microsatellite is moving in a small angle maneuver, hence, the nonlinear function $g(x,t)$ is locally Lipschitz nonlinear with a Lipschitz constant l_c , which means,

$$\|g(t,x_1) - g(t,x_2)\| \le l_c \|x_1 - x_2\| \tag{6}$$

We can have the augmented system by inserting Eq. (5) into

$$\begin{cases} \dot{x}(t) = Ax(t) + B_w w(t) + B_u u(t) + g(x,t) \\ \qquad + \psi(x,u,t) + F_a f_a(t) \\ \dot{z}(t) = A_z Cx(t) - A_z z(t) + A_z F_s f_s(t) \end{cases} \tag{7}$$

$$\begin{bmatrix} \dot{x}(t) \\ \dot{z}(t) \end{bmatrix} = \begin{bmatrix} A & 0 \\ A_z C & -A_z \end{bmatrix}\begin{bmatrix} x(t) \\ z(t) \end{bmatrix} + \begin{bmatrix} B_w \\ 0 \end{bmatrix} w(t) + \begin{bmatrix} B_u \\ 0 \end{bmatrix} u(t) + \begin{bmatrix} F_a & 0 \\ 0 & A_z F_s \end{bmatrix}\begin{bmatrix} f_a(t) \\ f_s(t) \end{bmatrix} + \begin{bmatrix} g(x,t) + \psi(x,u,t) \\ 0 \end{bmatrix} \tag{8a}$$

$$y(t) = [C \quad 0]\begin{bmatrix} x(t) \\ z(t) \end{bmatrix} + [0 \quad F_s]\begin{bmatrix} f_a(t) \\ f_s(t) \end{bmatrix} \tag{8b}$$

To the convenience purpose, we re-express Eq. (8) as

$$\dot{\bar{x}} = \bar{A}\bar{x} + \bar{B}_w w + \bar{B}_u u + \bar{F}\bar{f} + \bar{g} \tag{9a}$$

$$y = \bar{C}\bar{x}(t) + \bar{E}\bar{f} \tag{9b}$$

where $\bar{x} = [x^T \quad z^T]^T$ represents the new state, $\bar{f} = [f_a^T \quad f_s^T]^T$, $\bar{A} = \begin{bmatrix} A & 0 \\ CA_z & -A_z \end{bmatrix}$, $\bar{B}_w = \begin{bmatrix} B_w \\ 0 \end{bmatrix}$, $\bar{B}_u = \begin{bmatrix} B_u \\ 0 \end{bmatrix}$, $\bar{F} = \begin{bmatrix} F_a & 0 \\ 0 & A_z F_s \end{bmatrix}$, $\bar{g}(x,u,t) = \begin{bmatrix} g(x,t) + \psi(x,u,t) \\ 0 \end{bmatrix}$

$$[0 \quad F_s] = [0 \quad A_z^{-1}]\begin{bmatrix} F_a & 0 \\ 0 & A_z F_s \end{bmatrix} = \bar{E} .$$

3. Nonlinear Fault Estimation Observer

The nonlinear fault estimation observer is described as

$$\begin{aligned} \dot{\hat{\bar{x}}}(t) &= \bar{A}\hat{\bar{x}}(t) + \bar{g}(t, \hat{\bar{x}}(t)) + \bar{B}_u u(t) \\ &\quad + \bar{F}\hat{\bar{f}}(t) - L(\hat{y}(t) - y(t)) \end{aligned} \tag{10}$$

$$\hat{y}(t) = \bar{C}\hat{\bar{x}}(t) + \bar{E}\hat{\bar{f}}(t) \tag{11}$$

$$\dot{\hat{\bar{f}}}(t) = \hat{\bar{f}}(t) - F(\hat{y}(t) - y(t)) \quad (12)$$

where $\hat{\bar{x}}(t) \in \mathbb{R}^{n+p}$ is the state vector, $\hat{y}(k) \in \mathbb{R}^{p}$ is the output vector, $\hat{\bar{f}}(t) \in \mathbb{R}^{q+r}$ is the estimation vector of $\bar{f}(t)$, $L \in \mathbb{R}^{(n+p)\times p}$ and $F \in \mathbb{R}^{(q+r)\times p}$ are matrix parameters waited to be determined.

Therefore, from the dynamical error function (12) we have

$$\dot{e}_x(t) = (\bar{A} - L\bar{C})e_x(t) + (\bar{F} - L\bar{E})e_f + G(t,x,\hat{x}) - \bar{B}_w w - (\bar{A}\bar{x} + \bar{B}_w w + \bar{B}_u u + \bar{F}\bar{f} + \bar{g}(t,x(t))) \quad (13)$$

$$G(t,x,\hat{x}) = \bar{g}(t,x(t)) - \bar{g}(t,\hat{x}(t))$$

$$e_y(t) = \hat{y}(t) - y(t) = \bar{C}e_x(t) + \bar{E}e_f(t) \quad (14)$$

4. *H∞* Robust Fault Estimation Observer Design

Combining Eq. (14) and Eq. (15), we can obtain the augmented error system,

$$\begin{bmatrix} \dot{e}_x(t) \\ \dot{e}_f(t) \end{bmatrix} = \left(\begin{bmatrix} \bar{A} & \bar{F} \\ 0 & I \end{bmatrix} - \begin{bmatrix} L \\ H \end{bmatrix} \begin{bmatrix} \bar{C} & \bar{E} \end{bmatrix} \right) \begin{bmatrix} e_x(t) \\ e_f(t) \end{bmatrix} + \begin{bmatrix} \bar{B}_w & 0_{\times n} \\ 0 & -I_{q+r} \end{bmatrix} \begin{bmatrix} w(t) \\ \Delta f(t) \end{bmatrix} + \begin{bmatrix} I_n \\ 0_{(q+r)\times n} \end{bmatrix} G(t, x(t), \hat{x}(t)) \quad (16)$$

and

$$e_y(t) = \begin{bmatrix} \bar{C} & \bar{E} \end{bmatrix} \begin{bmatrix} e_x(t) \\ e_f(t) \end{bmatrix}.$$

5. Conclusion

This paper proposes a structure combined with robust fault estimation and fault-tolerant accommodation for the microsatellite attitude control system. It is designed on the basis of the observer and the Lipschitz condition which constrains the nonlinear terms of the system. We study a new multi-objective fault estimation method to improve the fault estimation performance. This new method has the property of low conservative compared to other traditional methods. We then propose an integrated system which is composed of fault estimation observer and fault-tolerant controller. The uncoupling characteristic of this integrated system allows us to design the two parts separately.

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