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Simultaneous state and actuator fault estimation for satellite attitude control systems

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Abstract In this paper, a new nonlinear augmented observer is proposed and applied to satellite attitude control systems. The observer can estimate system state and actuator fault simultaneously. It can enhance the performances of rapidly-varying faults estimation. Only original system matrices are adopted in the parameter design. The considered faults can be unbounded, and the proposed augmented observer can estimate a large class of faults. Systems without disturbances and the fault whose finite times derivatives are zero piecewise are initially considered, followed by a discussion of a general situation where the system is subject to disturbances and the finite times derivatives of the faults are not null but bounded. For the considered nonlinear system, convergence conditions of the observer are provided and the stability analysis is performed using Lyapunov direct method. Then a feasible algorithm is explored to compute the observer parameters using linear matrix inequalities (LMIs). Finally, the effectiveness of the proposed approach is illustrated by considering an example of a closed-loop satellite attitude control system. The simulation results show satisfactory performance in estimating states and actuator faults. It also shows that multiple faults can be estimated successfully.

1. Introduction

A satellite attitude control system is an essential subsystem for accomplishing successful space missions. Due to the increasing requirement for high safety and reliability, fault diagnosis for satellite attitude control systems has been an important research topic. Fruitful results can be found in many researches.[1–3]

During the last two decades, model-based fault diagnosis techniques have been widely researched and applied in modern systems.[4,5] Generally speaking, model-based fault diagnosis strategy performs three essential tasks: fault detection, fault isolation and fault estimation.[6,7] Fault estimation is the superior lever of the three tasks. Accurate fault estimation implies that it not only detects and isolates the fault automatically, but also provides details of the fault, such as the size and time-varying behavior of the fault. Besides, once a fault is determined, fault tolerant control can be adopted to compensate for it, which requires a simultaneous state and fault estimation.[8,9] Thus, state estimation observers that can provide the

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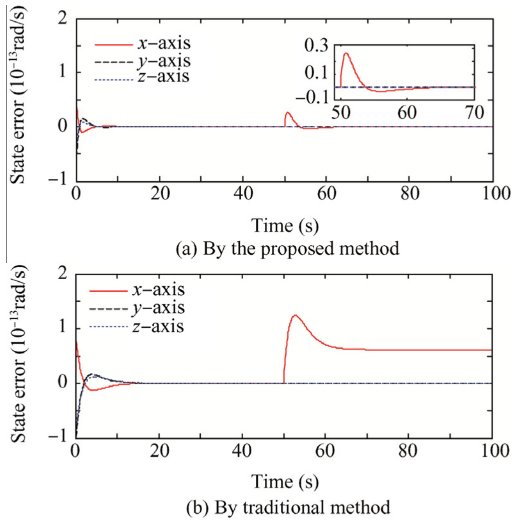

Fig. 1 State estimation errors in Case 1 by different methods.

required state and fault information within one design have attracted a lot of attention.

Much research effort has been devoted in this area and fruitful results have been published. To mention a few, proportional multi-integral observers were designed in Refs.[10,11] to achieve fault estimation for linear and nonlinear descriptor system. In Refs.[12,13], actuator fault estimation based on neural network was considered. In Refs.[14,15], adaptive observer technique has been used to estimate fault. In Refs.[16,17], fault estimation is investigated by sliding mode observers.

Among various approaches developed in the past, the augmented observer has attracted increasing attention due to its simplicity and the potential for simultaneously estimate system states and faults. The main idea of this kind of observer lies in addressing the faults as additional state variables. Accordingly, a variety of important results have been reported in the literature. For example, the actuator fault estimation based on augmented observer has been addressed in Refs.[18,19] for linear time invariant systems, and in Ref.[20] for linear parameter-varying systems. Fault diagnosis using augmented observer for rotor systems and satellite attitude control systems have been investigated in Refs.[21,22] and Refs.[23,24], respectively. In Ref.[25], a nonlinear augmented observer is designed and applied to a quadrotor aircraft. There are also much literature which can be viewed as the transformations of the augmented observers, such as Refs.[26,27]. However, the traditional augmented observer is conservative as the faults are assumed to be slowly-varying. In this situation, the constant fault estimation is guaranteed to be unbiased, but it fails to deal with the rapidly-varying fault. Besides, systematic and convenient approaches for the design of nonlinear augmented observers remain lacking in the available literature.

Inspired by the research problems above, in this paper, a nonlinear augmented observer is designed and applied to satellite attitude control systems. Unlike in Refs.[23,24], the Takagi-Sugeno fuzzy model is used to linearise the satellite attitude dynamics or only slowly-varying fault is considered. The augmented observer proposed in this paper can handle the estimation problem for a large class of actuator faults. Moreover, no equivalent transformations are needed for obtaining this observer. Our design uses only original coefficient matrices, thus the observer is convenient and reliable in computations.

In summary, the main contributions of this paper are as follows: (1) a new nonlinear augmented observer with a novel structure is proposed to estimate states and actuator faults for satellite attitude control systems; (2) the observer parameters can be computed directly using linear matrix inequalities (LMIs) with original coefficient matrices; (3) multiple rapidly-varying faults can be estimated within one design.

The rest of this paper is organized as follows. Section 2 briefly describes problem statement. In Sections 3 and 4, the design of the augmented observers is developed in detail for two cases, respectively. Section 3 concerns with the ideal case in which the finite times derivatives of the faults is assumed to be zero piecewise. Section 4 deals with the general case that the finite times derivatives of the faults is not null but bounded and disturbances cannot be neglected. Simulations are provided in Section 5 via an example of a satellite attitude control system. Conclusions are drawn in Section 6.

Notation. The notation used in the present paper is fairly standard. $\mathbf{R}^n$ denotes the n-dimensional Euclidean space, and $\mathbf{R}^{n\times m}$ is the set of all real matrices of dimension $n\times m$. $\boldsymbol{P}>\mathbf{0}$ means that $\boldsymbol{P}$ is real symmetric and positive definite. $\|\cdot\|$ stands for the usual L_2 norm. $\lambda_{\max}(\boldsymbol{X})$ and $\lambda_{\min}(\boldsymbol{X})$ denote the maximum and minimum eigenvalues of $\boldsymbol{X}$. The symmetric terms in a symmetric matrix are denoted by "$*$".

2. Problem formulation

Consider a nonlinear dynamic system with actuator fault as

$$\begin{cases} \dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{\Phi}(\boldsymbol{x}) + \boldsymbol{B}\boldsymbol{u}(t) + \boldsymbol{E}\boldsymbol{d}(t) + \boldsymbol{L}\boldsymbol{f}(t) \\ \boldsymbol{y}(t) = \boldsymbol{C}\boldsymbol{x}(t) \end{cases} \tag{1}$$

where $\boldsymbol{x}(t)\in\mathbf{R}^n$ is the system state vector; $\boldsymbol{u}(t)\in\mathbf{R}^m$ and $\boldsymbol{y}(t)\in\mathbf{R}^p$ are the input and the output vectors, respectively; $\boldsymbol{d}(t)\in\mathbf{R}^l$ is the unknown disturbance vector and it is assumed to be L_2 norm bounded; $\boldsymbol{f}(t)\in\mathbf{R}^k$ is the unknown vector that represents all possible actuator faults; $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$, $\boldsymbol{E}$ and $\boldsymbol{L}$ are known constant real matrices of appropriate dimensions, and the pair $(\boldsymbol{A},\boldsymbol{C})$ is observable; the nonlinear vector function $\boldsymbol{\Phi}(\boldsymbol{x})$ is assumed to be Lipschitz nonlinear with a Lipschitz constant γ, i.e.,

$$\|\boldsymbol{\Phi}(\boldsymbol{x})-\boldsymbol{\Phi}(\hat{\boldsymbol{x}})\| \leqslant \gamma\|\boldsymbol{x}-\hat{\boldsymbol{x}}\| \tag{2}$$

where $\hat{\boldsymbol{x}}$ is the estimation of $\boldsymbol{x}$.

In this paper, our goal is to develop a new augmented observer to estimate system states and fault simultaneously. And then an effective way to calculate the design parameters is given. First, Section 3 discusses an augmented observer for an ideal case in which system disturbances are neglected and $\boldsymbol{f}(t)$ is assumed to be in a general form as follows:

$$\boldsymbol{f}(t) = \boldsymbol{F}_0 + \boldsymbol{F}_1 t + \boldsymbol{F}_2 t^2 + \ldots + \boldsymbol{F}_{q-1} t^{q-1} \tag{3}$$

where $\boldsymbol{F}_i$ $(i=0,1,\ldots,q-1)$ are unknown constant vectors. One can see that the qth derivative of $\boldsymbol{f}(t)$ with respect to time is zero (i.e., $\boldsymbol{f}^{(q)}=\mathbf{0}$). And then, Section 4 discusses a robust augmented observer for a more general case in which the system is subjected to disturbances and $\boldsymbol{f}^{(q)}$ is not null but bounded. One can see that the fault considered in this paper may be unbounded.