



Observer-based sensor fault-tolerant control for semi-Markovian jump systems



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ARTICLE INFO

Article history:

Received 11 September 2015

Accepted 6 April 2016

Keywords:

Fault tolerant control

State estimation

Sliding mode control

Semi-Markovian jump system

Sensor fault

ABSTRACT

This paper investigates the state estimation and fault-tolerant control problems for a class of semi-Markovian jump systems with external disturbance and sensor fault. In this study, the original system is decomposed into two subsystems, where disturbance only exhibits in the first subsystem, and sensor fault only exists in the second subsystem. Two new observers are designed to eliminate the effects of fault and disturbance, respectively. Then, an observer-based sliding mode control scheme is proposed to stabilize the fault closed-loop system and the reachability of the proposed sliding mode surface can be guaranteed. By transforming the time-varying transition rate into convexification of the polytopic-type form, sufficient conditions for the existence of the gain of the observer and controller are obtained through solving a set of linear matrix inequalities. Finally, two numerical examples where the first one contains three modes and the second one is the linearized model of an F-404 aircraft engine system, are presented to illustrate the effectiveness of the proposed control method.

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1. Introduction

In modern industrial processes, actual systems are very vulnerable to various types of malfunction, resulted from component and interconnection failures, unexpected changes in external surroundings, etc [1,2]. Since component failures can degrade the system performance, even lead to the instability, it is thus significant to enhance the safety and reliability criterion for practical systems [3,4]. In order to improve the safe degree of the operation performance, the investigation on fault-tolerant control (FTC) problem for the overall control systems with sensor/actuator failures has received considerable attention during the past two decades [5,6]. Besides, external disturbances usually exhibit in industrial systems, hence it is necessary to investigate disturbance rejection techniques in the fault systems [7]. Due to the fact that sliding mode control (SMC) is an effective control approach against external disturbances and faults, it has been successfully incorporated to deal with the FTC problem [8,9].

System states are generally not measurable in practice, which makes it impossible to implement a full state feedback stabilization scheme [10,11]. Therefore, state estimation is of great importance in signal processing domain, and has been a focus of increasing research investigation in both theoretical and practical areas [12]. Since unknown component failures and external disturbances usually cause performance degradation of the observer, fault-tolerant observer has thus received a lot of attention, and a number of desirable results have been reported over the past several decades [13,14].

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On the other hand, due to the powerful modeling ability of the random abrupt variations in their structures, a great deal of attention has been focused on Markovian jump linear systems (MJLSs) in recent years [15–17]. MJLSs are a special class of stochastic dynamic systems, where the switching behavior is determined by a Markov chain [18,19]. Hence, it achieves many applications in control systems, such as power systems, robot manipulator systems and networked control systems [20–22]. A great number of important results on stability analysis, controller design of MJLSs have been addressed [23–25].

Various approaches for FTC problems of MJLSs have been presented in the existing literature: [26] studied the sliding mode observer technique to solve the sensor fault problem for MJLSs without uncertainties or external disturbances. Then the robustness of the method was later improved in [2,27,28], using an augmented descriptor system consisted of states, faults and disturbances to estimate faults and design the controller. However, the observer of the augmented descriptor system in those results has a very high dimension. In addition, the condition that, the derivative of the disturbances and sensor faults is demanded to be bounded in [28], is not always satisfied especially when the disturbances and faults are discontinuous. [29] also proposed an adaptive fault-control method for Markovian jump systems with time-varying delay, but it can only minimize the effects of uncertainties and disturbances on the fault system.

Besides, MJLSs have strong restrictions in applications since the jump time of a Markov chain is exponentially distributed [30]. Semi-Markovian process is a general continuous stochastic process whose sojourn-time follows different probability distribution, such as Weibull distribution and Gaussian distribution [31]. Therefore, semi-Markovian jump linear systems (S-MJLSs) are more general than MJLSs in modeling practical systems due to its relaxed conditions on the probability distributions. Different from constant transition rates in MJLSs, S-MJLSs are characterized by a fixed matrix of transition probabilities and a matrix of sojourn time probability density functions, which means that the transition rates in S-MJLSs are time-varying [32]. In this sense, MJLSs are a special case of S-MJLSs, and it is more difficult and practicable to investigate the analysis and synthesis problems for S-MJLSs. Considerable research results have been reported on this general topic. [30] considered the robust stabilization problems of S-MJLSs by partitioning the sojourn-time h into subsections, and the conservativeness of the sufficient condition can be reduced effectively. [33] studied stability and stabilization for a class of discrete-time S-MJLSs. [34] investigated the state estimation and stabilization for the phase-type S-MJLSs. [31,35] addressed the stochastic stability of semi-Markovian jump systems with delays. [36] studied the quantized control design problem for a class of S-MJLSs with repeated scalar nonlinearities.

Since the memoryless restriction cannot be often satisfied in the practical engineering, the Markovian model would not be applicable [37]. In contrast, the corresponding semi-Markov processes can generally accommodate different types of the randomly happening system variations, so some interesting results have also been produced in the FTC problems of S-MJLSs model: [38] studied the reliability evaluation problem of FTC systems using semi-Markovian model; [37] applied semi-Markov process in the FTC schemes for actuation faults with the complete measurable states. However, to the authors' best knowledge, there are few results available in the existing literature on the state estimation and sensor FTC problems simultaneously for S-MJLSs. Thus, how to estimate states in the S-MJLSs with external disturbance and sensor faults, and how to establish a stochastic admissibility condition for the fault systems are the key problems.

Based on the aforementioned statements, the paper investigates the state estimation and FTC problems for a class of S-MJLSs with external disturbance and sensor fault. The main contribution of the present work lies in the following features.

- (1) The original S-MJLSs is transformed into two subsystems, where the first one has the external disturbance but free from sensor faults and the second one only includes sensor faults. Then two robust observers are designed for each subsystem. By the discontinuous term in each observer, the effects of disturbance and sensor fault on state estimation are eliminated. The proposed scheme can estimate states accurately without a high dimension in observer and weaken the restrictions on the disturbance and fault.
- (2) Based on the estimation, an integral-type SMC scheme against faults and disturbances is developed to solve the FTC problem for S-MJLSs. It is shown that the proposed FTC method can stabilize the state estimate space and the estimation error space, and the reachability of the resulting sliding mode dynamics are guaranteed.

The rest of the paper is structured as follows: Section 2 briefly describes the required mathematical preliminaries. It is followed by providing the main results in Section 3. In Section 4, two examples are provided to demonstrate the effectiveness of the proposed methods. Finally, Section 5 concludes the paper.

Notation: The notations used in this paper are standard. $\mathbf{R}^n$ denotes the n -dimensional Euclidean space. $\mathbf{R}^{m \times n}$ is the set of all $m \times n$ real matrices. $(\Omega, \mathcal{F}, \mathcal{P})$ denotes a complete probability space, in which Ω is the sample space, $\mathcal{F}$ is the σ algebra of subsets of the sample space, and $\mathcal{P}$ is the probability measure on $\mathcal{F}$. $\mathbb{E}\{\cdot\}$ is the mathematical expectation. $\|\cdot\|$ and $|\cdot|$ denote the Euclidean norm and 1-norm of a vector respectively. Given a symmetric matrix A , the notation $A > 0$ (< 0) means that A is a positive definite matrix (negative definite, respectively). I_n represents an identity matrix with dimension n . $*$ stands for the matrix entries implied by symmetry in a symmetric matrix.

2. Problem formulation and preliminaries

Consider a class of semi-Markovian jump linear systems (S-MJLSs), defined on a complete probability space $(\Omega, \mathcal{F}, \mathcal{P})$:

$$\begin{aligned}\dot{x}(t) &= A(r(t))x(t) + B(u(t) + d(t)) \\ y(t) &= Cx(t) + D_s f_s(t)\end{aligned}\tag{1}$$

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