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Reliable control of a class of switched cascade nonlinear systems with its application to flight control

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ABSTRACT

This paper considers the reliable control problem of a class of uncertain switched cascade nonlinear systems. A new state-feedback control method is proposed for global stabilization of the nonlinear switched systems against actuator faults with the existence of structural uncertainties. Compared with the existing results of switched systems, this paper mainly features on: (1) the proposed controller can stabilize a class of nonlinear systems with actuator faults and its nominal systems (i.e., without actuator faults) without necessarily changing any structures and/or parameters of the proposed controllers; (2) the proposed method treats all actuators in a unified way without necessarily classifying all actuators into faulty actuators and healthy ones; (3) the proposed method is independent of arbitrary switching policies. The simulation studies on a numerical example and on longitudinal dynamics of an F-18 aircraft operating on different heights show and further validate the effectiveness of the proposed method.

1. Introduction

Switched systems are a special class of hybrid dynamic systems. It consists of a limited number of subsystems, one of which is activated for a specific time interval under a switching law to achieve certain target [1,2]. As high performance requirements of control systems for handling nonlinearities, uncertainties and operating condition variations and also fault-induced dynamic changes, much attention has been paid on switched systems and available results on switched systems have been applied widely and practically [2–10]. However, most of the existing results are presented on theoretical research of switched linear systems and their applications [2,4,6]. Since the nature of hybrid dynamic systems containing discrete and continuous states is inherently nonlinear, studies of switched nonlinear systems have become one of the key topics in the control community [4,11].

Undoubtedly, stability is the first requirement for a system to work normally; thus, stability of switched systems is the first and important task in researches on switched systems. Due to the complexity of switched nonlinear systems, the available results on stability of switched nonlinear systems are limited; see [3,12–18] and the references therein as examples. Thus, switched nonlinear systems with special structures are explored for stability-related problems [3,15–18]. Namely, Ref. [15] considered a class of cascade nonlinear systems by switching gains of controllers of the linear subsystems to achieve invariant control and semi-globally asymptotic stability, and was experimentally used in vehicle rollover avoidance [19]. The result in [15] was extended to a multiple-input case in [16]. Ref. [3] studied quadratic stability of a class of switched nonlinear systems without control input. Ref. [17] considered adaptive neural control for a class of switched nonlinear systems in strict

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lower triangular form. Work in [18] concerned global stabilization for a class of switched nonlinear feedforward systems. As shown by these results, stability of switched nonlinear systems with special structures is still an important research area.

On the other hand, maintenances or repairs in the highly automated industrial systems cannot be always achieved immediately; thus a reliable control system is desirable to tolerate failures of actuators or sensors within a pre-specified subset of all actuators or sensors, while retaining desired control system properties such as preserving safety and reliability of the systems [20]. Briefly speaking, reliable control is to design fault-tolerant control systems using certain robust control techniques, initially defined as integrity control [21], later as reliable control [20], and more generally as passive fault-tolerant control [22] against actuator and/or sensor faults. However, reliable control, similar to robust control techniques, has a fixed controller structure to ensure the insensitiveness of the control system to a specific fault or a class of specific faults. That is, it can guarantee the system stability and other expected performances whether or not the fault occurs. Reliable control also does not need online knowledge of faults; thus neither fault detection nor diagnosis of the controlled system is needed. These features make reliable control attract more and more attention [6,23–28,22,29,30,20,31–34,21,35]. Refs. [6,25–28] designed passive fault-tolerant controllers for nonlinear systems with actuator faults to guarantee reliable stability of the systems. Their common feature is that actuators are decomposed into two parts, one of which is susceptible to faults, and the other of which is robust to faults, to compensate for actuator faults effectively. However, in order to implement the controllers, the two-part decomposition has to be known in advance. It is in general difficult to obtain it practically due to the randomness and uncertainty of faults occurrence although failures modes and their effects analysis can be carried out from reliability engineering aspects. The work in [20] presented centralized and decentralized design methods to achieve reliable controls. The authors of [31] proposed a heuristic approach to the design of linear multivariable interacting control systems, [32–34,21] designed several compensators to realize reliable stabilization of the plant, and [35] gave a design method for linear state feedback systems based on a solution of a Riccati-type equation to possessing integrity. The common feature is that they dealt with non-switched systems.

From the above analysis on switched systems and fault-tolerant control, *reliable control of switched nonlinear systems* is one of the promising research interests due to the fact that many practical systems can be cast into such hybrid dynamic systems [24,9,30,36–38]. Compared with available results on switched systems and traditional fault-tolerant control, there are very few results on fault-tolerant control of switched nonlinear system [6,39,40]. Ref. [6] gave a sufficient condition on robust fault-tolerant control of a class of nonlinear switched systems by decomposing actuators into two parts, in the same way as [26], i.e., one part is robust to actuator faults, and the other is susceptible to actuator faults. Thus, the method in [6] has the above-mentioned disadvantages on fault modeling and characterization. In addition, structural uncertainties of input matrices were not considered for this class of nonlinear switched systems in [6]. In [39], by combining the safe-parking method and the reconfiguration-based approach the authors proposed two switching strategies to realize fault-tolerant controls of a class of switched nonlinear systems against actuator faults. However when actuator faults occur, the two methods both need to determine reparation time for faulty actuators, which is not easy to acquire in many real-world scenarios. Ref. [40] considered an observer-based fault-tolerant control of a class of switched nonlinear systems with external disturbances. From a system structure's point of view, the nonlinear item in this paper is connected to the system in a parallel way, which can be directly compensated for by control signals. However, it is worth noting that fault-tolerant control for cascade nonlinear systems is much more complicated, where the nonlinear term, as a nonlinear subsystem, is cascaded to the other subsystems.

On the other hand, flight control is a good example and has been paid much attention for new reliable control methods to be applied to since such an application initiated and has been a main move of fault-tolerant control research and application since 1980s [22,41,42]. Recent research results on robust adaptive flight control are surveyed in [42]. Following this trend, this paper will apply the reliable control method to the longitudinal control of an F-18 aircraft model used in [41].

This paper considers the problem of robust fault-tolerant control of a class of switched cascade nonlinear systems with structural uncertainties existing in both system matrices and input matrices, and proposes a fault-tolerant control method for this class of switched systems by using common Lyapunov function techniques and applies it to the longitudinal control of an F-18 aircraft. The main features and contributions of this paper are highlighted as follows:

(1) The proposed method can guarantee the system stability and other performances whether or not the fault occurs, i.e., works on both the switched nonlinear systems with actuator faults and its nominal systems without necessarily changing any structures and/or parameters of the proposed controllers.

(2) The proposed method, in a unified way, treats all actuators without necessarily classifying all actuators into faulty actuators and robust ones as in [26–28], for easy and practical applications.

(3) The proposed method does not need online knowledge of faults; thus neither fault detection nor diagnosis of some subsystems are needed.

(4) The proposed method is independent of arbitrary switching signals.

The layout of the paper is as follows. Section 2 presents the problem statement. The details about designing the controllers of the nonlinear switched systems and its stability analysis are presented in Section 3. A numerical example and the longitudinal dynamics of an F-18 aircraft are given in Section 4. Section 5 concludes the paper.