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Non-fragile reliable sampled-data controller for nonlinear switched time-varying systems

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This paper addresses dissipative-based stability analysis and robust mixed non-fragile reliable control design for an uncertain nonlinear switched system. In particular, actuator failures and time-varying delay with a known upper bound on the sampling intervals are taken into account of the considered system. By using a matrix inequality approach and by constructing a proper Lyapunov–Krasovskii functional that utilizes the complete available information about the actual sampling pattern and time-varying delay, we formulate stability conditions and a control design procedure in the form of linear matrix inequalities for obtaining the required result. More precisely, a dissipative based non-fragile reliable sampled-data controller is designed such that the resulting closed-loop switched system is reliable in the sense that it is exponentially stable and satisfies certain dissipative performance index under the given conditions. It should be mentioned that the implemented Lyapunov functionals are more general since they incorporate the nonlinearities of the system model in its design. Further, the performance of the proposed controller is demonstrated through a numerical example to show the validity and applicability of the proposed design technique.

1. Introduction

As it is known that switched systems are a kind of hybrid systems, which contain a finite number of subsystems along with a switching rule that provides the switching route among them. For the past twenty years, the problems related to stability analysis and control synthesis of switched systems have received a lot of attention due to their importance in both theory and applications [1–4]. Niu and Li [5] developed a neural-network-based control scheme for the tracking control problem of nonlinear switched systems in the presence of uncertain input time delay and external time-varying disturbances. The H_∞ control problem for a class of stochastic switched nonlinear systems is investigated in [6] by employing the average dwell-time approach. By using parallel distributed compensation design technique and single Lyapunov function method, a new set of sufficient conditions is obtained in [7] in terms of linear matrix inequalities (LMIs) for the construction of robust fuzzy controller which ensures the asymptotic stability of control system. An adaptive fuzzy fault-tolerant control scheme is proposed in [8] for ensuring the asymptotic stability of the switched fuzzy systems by using parallel distributed compensation design scheme and the online estimation of actuator faults. Tian et al. [9] proposed a sojourn-probability-dependent method to investigate the robust H_∞ control problem for a class of switched systems with input delays, where the robust H_∞ control feedback gains were derived by using the cone complement linearization method.

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On the other hand, a sampled-data system is a control system in which a continuous-time plant is controlled with a digital device and it is possible to obtain higher performance in sampled-data control system than with analog control systems [10]. For the past few decades, the stability analysis and controller synthesis problems of sampled-data control systems have attracted much attention due to the widespread use of their applications [11,12]. Several approaches have been developed to study the sampled-data control systems combined with LMI approach and Lyapunov–Krasovskii functionals [13,14]. Qiu and Cao [15] studied the sampled-data control problem of linear continuous-time systems subject to uncertain sampling periods in which a novel time-dependent Lyapunov functional in the framework of input delay approach was used to obtain the required results. Seuret and Briat [16] obtained a set of conditions for stability analysis of asynchronous sampled-data systems with uncertainties and input delay in the looped-functional framework. The mixed passive and H_∞ filtering problem for uncertain semi-Markovian jump delayed systems subject to sensor failures is reported in [17], where the parameter uncertainties are assumed to occur in random fashion with two stochastic variables that are mutually independent and satisfy certain probability distributions. Moreover, the failure of control components is unavoidable due to environmental disturbances in real world problems. The main aim of reliable control design is that which could guarantee stability and desired performances of closed-loop systems not only when all control components operate properly but also in the presence of actuator failures [18]. Nowadays, reliable control design with the use of Lyapunov function and LMI approach for uncertain control systems has attracted significant attention and several fruitful results have been presented in the literature, for instance, see [19,20]. In [21], the robust reliable dissipative control problem for a class of uncertain dynamical systems with possible actuator failures is discussed, where the reliable control law is designed based on input delay approach in presence of nonlinear actuator faults. Li et al. [22] reported the issues of reliable stabilization and H_∞ control design for switched nonlinear systems with actuator failures.

In practical situations, it is shown that the existence of small uncertainties in controllers during their design could also make closed-loop system unstable and such controllers are often called as fragile. It is therefore necessary to consider a robust controller that ensures the closed-loop system stability and performance level when the controller gains change in the predefined admissible range [23]. In particular, desirable controllers should be able to provide safe tuning margins and tolerate some possible amount of uncertainties in their coefficients. In [24], the finite-time dissipativity-based non-fragile control problem of Takagi–Sugeno fuzzy time-varying delay system is investigated, where closed-loop system is finite-time bounded and satisfies certain dissipative control index for all uncertainties under the developed conditions. Li et al. [25] designed a non-fragile state estimator such that the augmented estimation error system of discrete-time neural networks subject to Markovian jump parameters and unreliable communication links is stochastically finite-time stable in the mean-square sense with a prescribed $l_2 - l_\infty$ performance index level. A time-dependent Lyapunov functional utilizing the entire available information of the sampling pattern is constructed in [26] to derive a set of sufficient conditions for non-fragile stochastic passivity of Markovian jump systems with aperiodic sampling.

It is known that dissipativity concept developed by Willems [27] is one of the most important and desirable system properties for nonlinear systems. In recent years, dissipativity and passivity-based control problems of switched systems have attracted much attentions (see [28,29] and references therein). The dissipativity for switched discrete-time nonlinear systems based on multiple energy storage functions and supply rates is reported in [30], where a new set of sufficient conditions guaranteeing the dissipativity of switched system is given under some switching law. Xiang et al. [31] studied the dissipativity and dwell-time configurations of discrete-time switched system in which the dissipativity and the desirable induced Lyapunov stability of switched systems are established by imposing certain condition on multiple energy storage functions at switching instants. However, up to now, no work has been reported on dissipative analysis for nonlinear switching system with nonlinear actuator failures and external disturbances via non-fragile reliable sampled-data control. Motivated by this consideration, in this paper, we address the issues of dissipative based exponential stability analysis and mixed non-fragile reliable control for a nonlinear switched system subject to actuator failures. By implementing Wirtinger's inequality, a new set of sufficient conditions is developed which ensures that the resulting closed-loop system is exponentially stable. Moreover, the main contributions of this present paper are given as follows:

(i) A novel non-fragile reliable controller design involving nonlinear actuator faults is proposed for an uncertain nonlinear switched system subject to time-varying delay and exogenous disturbance under sampled-data control law.
(ii) By employing a continuous Lyapunov functional which makes use of the available information of the sampling pattern, sufficient conditions for robust exponential stability and dissipativity of the resulting closed-loop system are established with a satisfied performance index level.
(iii) Design of the proposed switched non-fragile reliable state feedback controller is then provided in terms of LMIs based on the established stability conditions.

2. Problem formulation and preliminaries

Let us consider an uncertain nonlinear switched system with time-varying delay and disturbance whose dynamics can be described by the following equations:

$$\begin{aligned}\dot{x}(t) = {} & [A_{\sigma(t)} + \Delta A_{\sigma(t)}(t)]x(t) + [A_{d\sigma(t)} + \Delta A_{d\sigma(t)}(t)]x(t-h(t)) + [B_{\sigma(t)} + \Delta B_{\sigma(t)}(t)]u^F_{\sigma(t)}(t) \\ & + [D_{\sigma(t)} + \Delta D_{\sigma(t)}(t)]\omega(t) + [L_{\sigma(t)} + \Delta L_{\sigma(t)}(t)]f_{\sigma(t)}(x(t)), \qquad (1) \\ z(t) = {} & C_{\sigma(t)}x(t) + G_{\sigma(t)}u_{\sigma(t)}(t) + N_{\sigma(t)}\omega(t), \\ x(t) = {} & \phi(t), \quad t \in [-h, 0],\end{aligned}$$