Nonlinear Analysis: Hybrid Systems 23 (2017) 91–110

Contents lists available at ScienceDirect

Nonlinear Analysis: Hybrid Systems

journal homepage: www.elsevier.com/locate/nahs

Fault-tolerant synchronization for nonlinear switching systems with time-varying delay

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ARTICLE INFO

Article history:
Received 1 March 2016
Accepted 22 June 2016

Keywords:
Fault-tolerant synchronization
Switching system
Time-varying delay
Impulsive feedback control
Fault model
Fault estimator

ABSTRACT

This paper studies fault-tolerant synchronization for nonlinear switching systems with time-varying delay using impulsive feedback control. Both faults and disturbances in the drive system are taken into account. In order to deal with these faults, we adopt an input–output fault model by which faults are regarded as outputs corresponding to inputs that approach zero as time goes to infinity. Based on this principle, by using an observer-based fault estimator with output feedback controllers and impulsive state feedback controllers, we design a fault-tolerant synchronization scheme, by which the synchronization can be eventually reached no matter whether there are faults, disturbances in the drive system or not. The problem of design is formulated so as to find control gain matrices in the controllers such that the trivial solution of the error system is globally attractive and the L_2 norm of the error between fault and its estimation is bounded by that of the vector consisting of the fault input and disturbance. Several criteria for this problem are derived in terms of linear matrix inequalities. Finally, a hybrid Chua's circuit is used to illustrate the effectiveness of the proposed method.

1. Introduction

Synchronization has gained significant attention over the past couple of decades due to its important applications in a variety of engineering and control fields, such as information processing [1,2], secure communication [3–5], and fault-tolerant control [6]. In [1], Xie et al. introduced a mixed (generalized plus identical) synchronization scheme that could be applied to store and encode arbitrary signals. The adaptive synchronization problem of the drive-driven type chaotic systems via a scalar transmitted signal was studied and the proposed method was employed in a secure communication system [3]. In [6], a fault-tolerant scheme for master–slave synchronization of the Lur'e system, was proposed, by which the synchronization could be achieved no matter whether there were faults occurring in the master system or not.

Switching systems, consisting of a family of subsystems and a switching law that determines which subsystem is active during a certain time interval [7], have been used as an important framework for the purpose of synchronization in recent years [8–11]. This is because, except for the importance of synchronization itself, switching systems play an essential role in modeling many real-world systems with switchings such as biochemical processes, chemical processes, transportation and communication systems [12–14]. And newly, a framework that modeled a class of cyber–physical switching vulnerabilities in smart grid systems was presented in [15], in which the mathematical model was a switching system describing different dynamical behaviors of the physical quantities of generator phase angle and frequency led by different loads. Similar to the need of switchings in practice, time delay is also usually taken into consideration to make models closer to practical facts.

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http://dx.doi.org/10.1016/j.nahs.2016.06.005

For instance, in [16], the presence of transmission delay and sampling delay in chaos-based secure communication systems by employing impulsive synchronization was studied. Michiels et al. [17] studied the stability of a linear system with a point-wise time-varying delay, which was inspired by the existence of the time-varying delay representing the time taken by the cutting inserts for one revolution of the workpiece when considering the dynamics of rotating cutting machines.

There have been a few works on the problem of synchronization for switching systems with time delay via different control methods such as [8,9]. In [8], the synchronization of complex spatio-temporal switching network with time delays was investigated based on passive control method. Adaptive control was employed in [9] to achieve the robust synchronization for a class of delayed complex networks with switching topology. Except for these control methods, impulsive control, arising naturally in a wide variety of applications such as orbital transfer of satellite [18–20] and management of ecosystems [21,22], also has attracted much attention in controlling switching systems, see [23,10,24,25]. Specifically, in [23,10], new hybrid impulsive control strategies for nonlinear systems were developed by using multiple Lyapunov functions; in [24], Shi et al. investigated the hybrid impulsive control problem of switched singular systems aiming to compress their inconsistent state jumps when switch occurs between two different singular subsystems; in [25], the problem of fault estimator design for switched time-delay systems with impulsive control was investigated, using multiple Lyapunov–Krasovskii functionals. However, except [25], few results have been proposed for impulsive control of switching systems with time delay, especially when faults and disturbances are taken into account.

In terms of practical significance, except for the effect of switching, delay and impulsive control, the influence of fault and disturbance is also worthy of consideration, because the occurrence of a fault is always inevitable, for instance, the component failure in a circuit and the unknown input in a control system caused by malfunctions in sensors or other unknown reasons. In order for reliability of synchronization schemes, it is necessary to take faults and disturbances into consideration, and to design schemes to be fault-tolerant. These years, there have been some results of fault-tolerant or fault-related control such as [6,25–28]. The essence of fault-tolerant is to guarantee both stability and L_2 norm bound constraint for error system. In [25], authors considered the impulsive control for linear switched time-delay systems.

However, there is an issue in dealing with the change of the value of the multiple Lyapunov–Krasovskii functional at each impulsive instant, since the value of the functional changes due to the change of positive matrices contained in the functional (see (35)–(37)) rather than remains unchanged as stated under (11) in [25]-"Since $V_{2,i}(t, x_t)$ and $V_{3,i}(t, x_t)$ are defined in terms of integrals which will remain continuous over t_k". In fact, the difficulty goes far beyond this. In [26,27], authors studied fault estimator design and fault detection filter design for switched nonlinear systems using Lyapunov–Krasovskii functional, respectively. There is a much more serious problem to be further investigated in guaranteeing the L_2 norm bound constraint. To be exact, the average dwell time could not be directly substituted into the integral in (36) of [27]. Thus, the constraint failed to be satisfied. To avoid the same problem of the L_2 norm bound constraint, in some related areas such as disturbance attenuation [29], L_2 gain analysis [30] and H_∞ model reduction [31], authors adopted a weighted norm-$\int_0^\infty e^{-\lambda t} z^T(t)z(t)dt$. Unfortunately, this changed the original meaning of the L_2 norm bound constraint. Therefore, it is a technical challenge to prove the L_2 norm bound constraint in fault-tolerant control of switching systems with time delay by using the multiple Lyapunov–Krasovskii functional.

Motivated by the practical significance and the existing theoretical problems, we shall investigate the problem of fault-tolerant synchronization for nonlinear switching systems with time-varying delay using impulsive feedback control. In this paper, the change of the value of the Lyapunov–Krasovskii functional at each impulsive instant will be taken into consideration (see (30)–(40)). Also, the challenge in dealing with the L_2 norm bound constraint will be overcome by using the relation between the switching number and the minimum dwell time, maximum dwell time (see (55)–(59)). Moreover, we will consider some special cases (see the cases: $0 < \mu < 1$, in Theorem 3.1, Theorem 3.2, Corollaries 3.2 and 3.3) which were overlooked before (only the case: $\mu \le 1$, was considered in [27,29–31]).

The rest of this paper is organized as follows. In Section 2, we establish a fault-tolerant synchronization scheme for nonlinear switching systems with time-varying delay, explaining why this scheme is fault-tolerant, and formulate the problem of fault-tolerant synchronization as to find control gain matrices such that the trivial solution of the error system is globally attractive and the L_2 norm bound constraint, related to the synchronization errors, and fault input and disturbance, is satisfied. In Section 3, main results for deriving these control gain matrices are proposed and proven. In Section 4, the implementations of synchronization for a switching Chua's circuit with time-varying delay in different cases are used to illustrate the effectiveness of the proposed method. Finally, conclusion is given in Section 5.

2. Preliminaries and problem statement

Consider the following synchronization scheme using impulsive feedback control

$$\mathscr{D}_0: \begin{cases} \dot{x}(t) = A_{\sigma(t)}x(t) + A_{1\sigma(t)}x(t-\tau(t)) + G_{1\sigma(t)}g_1(t, X(t)) \\ y(t) = C_{\sigma(t)}x(t) + G_{2\sigma(t)}g_2(t, X(t)) \\ x_{t_0} = x(t_0+\theta) = \phi(\theta), \quad \theta \in [-d, 0], \end{cases} \tag{1}$$

$$\mathscr{R}_0: \begin{cases} \dot{\hat{x}}(t) = A_{\sigma(t)}\hat{x}(t) + A_{1\sigma(t)}\hat{x}(t-\tau(t)) + G_{1\sigma(t)}g_1(t, \hat{X}(t)) + u(t) \\ \hat{y}(t) = C_{\sigma(t)}\hat{x}(t) + G_{2\sigma(t)}g_2(t, \hat{X}(t)) \\ \hat{x}_{t_0} = \hat{x}(t_0+\theta) = \varphi(\theta), \quad \theta \in [-d, 0], \end{cases} \tag{2}$$