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Exponential stability of hybrid switched nonlinear singular systems with time-varying delay

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Abstract

We address exponential stability of switched nonlinear singular systems with time-delay in which delay is time varying and presents in the states. For switched nonlinear singular time-delay systems with average dwell-time switching signals, we provide sufficient conditions, in terms of linear matrix inequalities (LMIs) to guarantee the exponential stability of such systems. By using Lyapunov–like Krasovskii approach, the relationship between the average dwell-time of the switched nonlinear singular time-delay system and the exponential decay rate of differential and algebraic states is given. A numerical example is also included to illustrate the effectiveness of the results proposed in this paper.

1. Introduction

Switched system is an important class of hybrid dynamical systems, which is composed of a family of continuous-time or discrete-time subsystems and a rule orchestrating the switching among them. For switched systems, due to the complicated behavior caused by the interaction between the continuous dynamics and discrete switching, the problem of stability is more difficult to study and has a strong engineering background. In recent years, switched systems have been widely studied and many interesting results have been reported in

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the literature [1–6]. Since delays are often the main cause of instability and poor performance of dynamic systems, how to deal with time-delay has been also a hot topic in the stability analysis of switched time-delay systems. Several useful results have been reported in the literature such as the stability and stabilization analysis [7,8], observer-based tracking problem [9], output feedback control [10], H_∞ control design and filtering [11–14], exponential stability with stable and unstable subsystems [15], and exponential stability of delayed neural networks [16].

As a crucial factor, switching signals determine the dynamic behavior of a switched system in most cases. As a class of typical constrained switching signals, the average dwell-time switching means that the number of switches in a finite interval is bounded and the average time between consecutive switching is not less than a constant [17]. The average dwell-time switching can cover the dwell-time switching, and its extreme case is actually the arbitrary switching [17]. Therefore, it is of practical and theoretical significance to prove the stability of switched systems with average dwell-time, and the corresponding results have been available in [18,19] for discrete-time version, [20,21] for continuous-time version, and [22] for relevant applications. For more results of stability of switched systems, we refer the readers to [23,24] and the references cited therein.

Singular systems, such as robotics, power systems, networks, economical systems and highly interconnected large-scale systems, have been extensively studied in the past decades due to the fact that singular models describe physical systems more directly and generally than regular state-space ones [25]. Many fundamental system theories developed for regular state-space system have been successfully extended to their counterparts for singular system, for example, controllability and observability [26], the Lyapunov stability [27,28], robust stability and stabilization [29,30], singular time-delay systems [31–33], and optimal control [34].

When partial or total subsystems of a switched system are singular systems, the switched system becomes a class of switched singular systems. Owing to switches among multiple singular subsystems, it is inevitably difficult to analyze and synthesize such systems. There are some papers which have presented stability analysis of the switched singular system [35–40], but the simultaneous presence of switching signals with average dwell-time, time-delay, and nonlinearities have not been fully investigated. However, to the best of our knowledge, the delay range-dependent stability problem for switched nonlinear singular time-delay systems has not been fully investigated yet, which will be challenging due to the difficult extension of the existing stability results and has motivated us to carry out the present study.

In this paper, we are seeking for a switching signal based on the average dwell-time constraint able to exponentially stabilize the switched nonlinear singular time-delay system. The parameters of this signal are determined and the exponentially stability is proved. First, some properties of switched nonlinear singular time-delay systems are introduced and discussed. Then, the most important section is presented. In this section, with the help of the average dwell-time approach, a class of switching signals is found under which the switched nonlinear singular time-delay system is exponentially stable. The linear matrix inequality (LMI)-based existence conditions of such a stability analysis are derived by the introduction of free-weighting matrices. Some additional instrumental matrix variables are introduced which makes the stability analysis feasible.

The organization of the paper is as follows. The preliminaries are stated in Section 2, followed by the main result in Sections 3 and 4. A numerical example is presented in Section 5. Finally, we conclude the paper in Section 6 with a discussion of future work.

Notation: Throughout this paper, $\Re^n$ and $\Re^{n\times m}$ denote the n dimensional Euclidean space and the set of all $n\times m$ real matrices, respectively. The superscript "T" denotes the