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Stabilization of networked switched linear systems: An asynchronous switching delay system approach[☆]

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ABSTRACT

In this paper, we investigate the network-dependent hybrid controller design for a class of networked switched linear systems. Networks with limited bandwidth cause the asynchronous motions between switched subsystems and the candidate controllers in both the state measurement and the switching signal. We rewrite the original networked switched systems by sampled asynchronous switched systems with time-varying delays. Using the asynchronous switched delay system method, we give the co-design conditions on both the switching signal and the controllers which depend on the sampling time, the upper bound of network-induced delays, the bound of the asynchronous switching time ratio and the asynchronous occurring frequency, under which the networked switched system is exponentially stable.
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1. Introduction

The objective of this paper is stabilization of switched linear systems subjected to network-induced delays both in their state measurement and switching signal. Specifically, by "networked switched" here we mean that measurements being passed and switches being actuated from the system to the controller are sampled and delayed due to the transmission by networks with limited bandwidth, resulting in asynchronous communication. Our goal is to bring together switched systems and networked control, which have both enjoyed a lot of activity in the last two decades and made great impact on applications.

Networked control systems (NCSs) as an important class of feedback control systems, whose feedback paths are implemented by a real-time network, have drawn considerable attention [1–13]. This type of systems allows for reduced wiring as well as for lower installation cost. Since the network bandwidth is limited, once the data from sensors and actuators exchanged by networks, network-induced delays and packet dropout often occur. How to deal with these constraints to maintain the control performance can be found in the survey paper [3] and their references.

On the other hand, as a special class of hybrid systems, a switched system is a dynamical system that consists of a finite number of continuous variable subsystems and a rule that orchestrates switching between them [14–20]. It is widely used to model dynamical systems that exhibit mode switching due to jumping system parameters or changing environmental factors, such as the slippage of a legged robot and the gear switch of a car [18]. Meanwhile, there are a great variety of applications on switched systems in other fields, including manufacturing systems, auto-pilot design and chemical processes. But unlike non-switched systems, for different choice of the switching signal, switched systems might be asymptotically stable or unstable even if each subsystem is asymptotically stable. Such an example is given in [14]. Thus, we need to co-design the switching signal and the continuous control algorithms to obtain the performance of the system.

Recently, networked switched control systems (NSCSs), have attracted attention. See, for examples, [21–25]. The switched nature of the system enables one to capture many processes encountered in practice which allows one to incorporate scenarios where the controller is remotely located or how much the network-induce delay is permitted. A networked switched system is not a simple combination of switched systems and networked systems. In fact, a networked switched system is a hybrid system that consists of a finite number of continuous variable subsystems, sampled state measurement and a rule orchestrates switching between them. There are distinct features of networked switched systems, such as sampling, network-induced delay and switching. A brand new one is simultaneously design switching signal and controllers for the system subject to sampling and network-induced delay. To

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reveal the relationship among sampling, network-induced delay and switching is a completely new issue that is studied in this paper. Since switched systems arise from the interaction between a discrete switching signal and continuous control algorithms in dynamical systems, both the design of switching signal and continuous control algorithms will be affected by networks. On one hand, if the performance (e.g. stability) of each subsystem subjected to the imperfect network-induced factor is guaranteed, it does not mean the stability of switched systems can be obtained. For example, most of literature on networked non-switched systems focus on system sampling, transmission data via network suffered from network-induced delays and packet dropout, and then design a single controller which can deal with all the above imperfect network-induced factors to preserve the stability of NCS. While in the switched system case, if a switched plant controlled by a single well-designed networked controller switches to a new mode, the closed-loop system may be destabilizable since the controller design does not take the system switching into account. Therefore, the existing methods for networked non-switched systems are not effective to networked switched systems. On the other hand, the traditional switched system theory is built based on the perfect information transmission of the system. Once such a system exchanges data via networks with limited bandwidth, network-induced delays or packet dropout will lead to the imperfect transmission and even destroy the system performance. Specifically, when the switching signal is subjected to network-induced delays or packet dropout, it is even worse and much more difficult to deal with. In this case, mismatch between subsystems and their candidate controllers can be inevitable, even the system is destabilized by the designed switching signal. Moreover, due to the uncertainty of the network transmission, neither the arrival of the state measurement nor how to switch is known to the hybrid controller a prior. Thus, how to design network-dependent switching signal and the continuous feedback control for networked switched systems becomes an urgent problem to be solved.

In the existing literature, when the maximal delay is less than one sample period and the system switched is synchronous with the sampling, switched systems with uncertain time varying feedback delays is expressed as a problem of stabilizability for uncertain systems with polytopic uncertainties, and robust stabilization conditions under arbitrary switching is presented in [21]. But the conditions under an arbitrary switching signal are obviously strict. How to obtain the switching conditions for switched linear systems that take the network-induced constraints into account is of great importance. The NCSs with time-varying transmission intervals as a discrete-time switched linear uncertain system is studied in [26] and the state-dependent switching signal is given to be regarded as quadratic protocols. And new stability conditions are given using a polytopic system with norm-bounded uncertainty. [23] addresses the system state measurement suffered from network-induced delay and packet dropout, sufficient conditions for exponentially stabilization of the system are obtained. However, network-induced delays in the switching signal are not taken into account. [24] is concerned with the network-induced delay in the switching signal, and presents the asynchronous switching protocol to stabilize the system but not gives the design method for hybrid controllers. [25] studies the stabilization of switched linear systems with sampling and quantization, but the network-induced delay and asynchronous switching are not mentioned. As for the design of switching signal, the average dwell time technique [20] is an efficient tool in analyzing and designing switched systems. Using this method, [16] converses a non-switched system with the controller failure and the time-varying delay into a switched system, sufficient conditions for switched delay system are presented. [27] gives the stabilization conditions of sampled-data non-switched control systems with control inputs missing. But neither of the results can be applied to the switched plant, while stability of non-switched systems can trivially be deduced by eliminating the switching aspect of the problem. About the study of asynchronous switching, [17] investigates the asymptotical stability of switched control systems under the asynchronous switching signal; however, sampling and network-induced delays are not mentioned. [28] gives sufficient conditions for stabilization of switched linear neutral system under asynchronous switching, but the results are not applicable to switched systems subjected to network-induced delays and the proposed conditions are delay-independent. Although there are some literature to address the asynchronous switching for switched systems [17–32], none of them can be applied to the networked switched systems.

Combining the switching between different modes of operation and the transmission delay nature of the communication link between the system and the controller, in this paper we design an asynchronous hybrid controller to exponentially stabilize a networked switched linear system. Here "hybrid" means that the controller in the low layer is continuous state feedback and how to switch is given in the high layer by the proposed asynchronous switching ratio and asynchronous occurring frequency relationship between systems switched and controllers switching. But different from the traditional asynchronous switched systems, networked switched systems must take the system sampling into account. However, the study of asynchronous switched systems emphasizes the interaction between the continuous dynamics and the asynchronous switching signal. The main drawback of traditional asynchronous switching theory is that the variation of system state is continuous. While in practice or implementation of the digital platform, all measurements are only taken at discrete sampling instants, and control action must be piecewise constant. Furthermore, as we all known, sample period is one of the most important factors for stability, and switched systems are no exception. Therefore, sampling must be considered for networked switched systems. In addition, as for the network-induced delay both in the state measurement and the switching signal, it is difficult to co-design the controller and the switching signal for the system with feedback delay. Thus in the existing literature, the result on asynchronous switching systems with system state delay cannot be applied to networked switched systems as well.

The paper is organized as follows. Firstly, we analyze the transmission time of a switched linear control system suffered from the network-induced delays, and then formulate the closed-loop system by an asynchronous switched system with time-varying feedback delays. Thirdly, using the Lyapunov-like-Krasovskii technique, we give sufficient conditions to exponentially stabilize the system. Finally, we present an example to illustrate the efficiency and feasibility of the proposed method and consequently give the conclusions.

Notations: Suppose $\tau_{\max} > 0$ and $h_s > 0$ are given positive real numbers, $\mathrm{R} = (-\infty, +\infty)$, $\mathrm{R}_+ = (0, +\infty)$, R^n is an n-dimensional linear vector space over the reals with norm $\|\cdot\|$, $\mathrm{C}_n = C([-(\tau_{\max} + h_s), 0])$ is the Banach space of continuous functions mapping the interval $[-(\tau_{\max} + h_s), 0]$ into R^n with the topology of uniform convergence.

2. Problem formulation

The system to be controlled is a switched linear system described by

$$\dot{x}(t) = A_{\sigma(t)}x(t) + B_{\sigma(t)}u_{\sigma(t)}(t), \quad x(0) = x_0 \tag{1}$$

where $x(t) \in \mathrm{R}^n$ is the state, $u(t) \in \mathrm{R}^m$ is the control input, $\{(A_p, B_p) : p \in \Upsilon\}$ is a collection of matrix pairs defining the individual subsystems of the switched system, Υ is a finite index

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