Nonlinear Analysis: Hybrid Systems 13 (2014) 2–21

Contents lists available at ScienceDirect

Nonlinear Analysis: Hybrid Systems

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

Robust stabilization for uncertain switched neutral systems with interval time-varying mixed delays

Hamid Ghadiri[a,*], Mohammad Reza Jahed-Motlagh[b], Mojtaba Barkhordari Yazdi[c]

[a] Department of Electrical Engineering, College of Engineering, Tehran Science and Research Branch, Islamic Azad University, Tehran, Iran

[b] Complex Systems Research Laboratory, Iran University of Science and Technology, Tehran, Iran

[c] Electrical Engineering Department, Shahid Bahonar University of Kerman, Iran

A R T I C L E I N F O

Article history:
Received 8 July 2013
Accepted 17 March 2014

Keywords:
Uncertain switched neutral systems
Time-varying delay
Dynamic output feedback
Exponential stability
Stabilization

A B S T R A C T

This paper deals with the problems of exponential stability and stabilization of uncertain switched neutral systems (USNSs) with interval time-varying mixed delays. Interval time-varying delay exists in the state, derivatives of the state (neutral), and the output. This research emphasizes the cases where uncertainties are norm-bounded time-varying in the model. First, sufficient conditions are proposed in terms of a set of linear matrix inequalities (LMIs) to guarantee exponential stability using the average dwell time (ADT) approach and the piecewise Lyapunov function technique. Then, the corresponding conditions are obtained for the stabilization via a dynamic output feedback (DOF) controller. The problem of uncertainty in the system model is solved by designing the DOF controller and applying the Yakubovich lemma. Since the conditions obtained are not represented by LMI form, decoupling between the Lyapunov function and the system matrices is generated using the proposed slack matrix variable, and a new condition is obtained. Finally, numerical examples are given to determine the effectiveness of the proposed theorem.

1. Introduction

The delay phenomenon exists in many practical and engineering systems such as chemical processes, nuclear reactors, electrical systems, and biological systems [1–3]. It is a well-known fact that the presence of delay may cause systems to perform poorly and to even be unstable [4]. Many researchers have extensively studied the fundamental theoretical and practical problem of stability analysis of time-delay systems (TDSs) (see [5,6] and the references cited therein).

In some practical systems, the delay exists not simply in the state, but also in the derivatives of the state. This class of TDSs are referred to as neutral systems (NSs). Neutral delays usually arise when state-derivative feedback or output-derivative feedback is provided in systems which have delay in the input. The presence of this type of delay can improve the performance of the closed-loop system. Sometimes, achieving better performance requires that the delay be considered in the derivatives of the state of open-loop model [7]. NSs have a variety of applications. Examples can be found in the areas of population model [8], transmission line oscillator [9], partial element equivalent circuits [10], DC–DC converters [11], and drilling systems [7].

* Corresponding author. Tel.: +98 2813365404.
E-mail addresses: h.ghadiri@srbiau.ac.ir, h_gh_3418@yahoo.com (H. Ghadiri), jahedmr@iust.ac.ir (M.R. Jahed-Motlagh), barkhordari@uk.ac.ir (M. Barkhordari Yazdi).

http://dx.doi.org/10.1016/j.nahs.2014.03.001
1751-570X/

Many attempts have been made in the previous research to analyze NSs with constant time-delays [12–15]. However, in many practical NSs, time-delays are usually time-varying, which can even result in massive changes to the dynamics of NSs in some cases. Lately, the NSs with time-varying delays have been the subject of study in [2–4,16–20]. Interval time-varying delay is a time delay which varies at an interval where the lower bound is not limited to zero. Networked control systems (NCSs) constitute a prime example of dynamical systems with interval time-varying delay [21,22]. Obviously, it is more difficult to analyze and synthesize systems with time-varying delays, especially when such delays are interval and the output consists of time-varying delay functions. Presence of time-varying delays in the outputs and states of the system makes the problem even more complicated.

This paper considers interval time-varying delay in the state, the derivatives of the state (neutral), and the output of the system. On the other hand, switched systems have been widely used in modeling various dynamical systems such as chemical processes [23], communication networks [24], electrical systems [25], and mechanical systems [26].

Switched systems are a class of hybrid systems which consist of a family of subsystems and which are controlled by switching laws [27]. The previous research on switched systems has generally focused on two major problems. First, from a practical point of view, a large class of physical systems are naturally multi-model whose behavior is represented by several dynamic models. Second, from a control perspective, for complex systems and systems with large uncertainties, designing a multi-controller is better than a controller [12,28].

Delays also appear in switched systems; hence the term switched time-delay systems (STDSs). There are numerous applications for such systems, including water quality control, electric power systems, productive manufacturing systems, and cold steel rolling mills [29].

Switched neutral systems (SNSs) constitute a multidisciplinary research area borrowing ideas from many diverse fields. For example, stability and stabilization problems were studied in [2,12,13,16], H_∞ control problem was discussed in [14], and state feedback (SF) control was addressed in [12,13,15]. In practice, it is often not possible to obtain full information on the state variables to use them for feedback control. This makes it necessary to study the stabilization problem of the dynamic output feedback (DOF) for this case [15].

Another point is that the application of any output feedback controller to STDSs and SNSs would result in a closed-loop system with interval time-varying delays, and this will cause problems when an attempt is made to derive stabilizability conditions for the purpose of finding controller parameters. For example, [30] proposed an output feedback controller for stabilization and H_∞ control of switched linear systems with time-varying uncertainties. Study [31] was concerned with the problem of H_∞ control for switched linear systems by DOF controller in terms of linear matrix inequalities (LMIs).

In most of the studies into SNSs, stability analysis is considered as a major control problem. For stability analysis of switched delay systems under arbitrary switching, often the common Lyapunov function (CLF) is used, but it should be noted that this may lead to conservatism. Furthermore, arbitrary switching has limited applicability because it requires all the subsystems to be stable. The multiple Lyapunov function (MLF) [15], the dwell time (DT) approach [4,15,17], and the average dwell time (ADT) approach [2,14] have been proposed as effective tools for reducing conservatism in the cases where some subsystems are unstable.

The studies into switched systems with time-delay (whether neutral or non-neutral) have proposed some other popular approaches for this purpose: the model transformation method [5], the free-weighting-matrix method [15,17,18, 32], Leibniz–Newton formula [15,16], the slack matrix [33], and choosing the appropriate Lyapunov–Krasovskii function [4,28,32,34–36].

Uncertain factors such as environment noise, uncertain parameters, and disturbance are commonly encountered in various practical and engineering systems, and this makes it very difficult to develop an exact mathematical model. Also, it has been shown that the existence of uncertainty invariably causes poor performance and even instability of control systems. Therefore, robust control of uncertain switched neutral systems (USNSs) is very important in theory and application (see [34,37] and the references cited therein). However, the stability and stabilization problem of USNSs has been minimally considered in the literature. Study [12] investigated the stabilizing SF controller for robust stabilization of a class of USNSs with constant mixed delays and time-varying structured uncertainties based on the CLF and formulated stability conditions in terms of LMIs. The LMI approach is an efficient and popular tool proposed by [38] to solve stability analysis.

In [16], the problem of exponential stability was studied for USNSs with time-varying structured uncertainties. In the study mentioned, the neutral delay was considered constant based on the Razumikhin-like approach under arbitrary switching. Sufficient conditions were obtained in [4] for exponential stability for SNSs with time-varying state delay, constant neutral delay, and norm-bounded uncertainty based on the ADT approach and the Lyapunov–Krasovskii functions. The authors in [2], proposed exponential stability criteria for USNSs with norm-bounded time-varying uncertainties, nonlinear perturbations, and interval neutral time-varying delay by using the ADT approach and the piecewise Lyapunov functional technique.

Besides, switched nonlinear systems or nonlinear systems with neutral delay have been regarded as SNSs or NSs under additive nonlinear perturbations which have been the subject of investigation in many previous studies (e.g., [2,7,18–20]).

To the best of our knowledge, the problem of stability and stabilization of SNSs via DOF controllers with uncertainties has received little attention in the previous research, and this motivated the present research.

In this paper, we consider the problems of exponential stability and stabilization of USNSs with interval time-varying mixed delays that exist in the state, derivatives of the state (neutral), and the output. Using the ADT approach and the piecewise Lyapunov function technique, sufficient conditions are suggested to guarantee the exponential stability. Then, the