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Controller design for discrete-time hybrid linear parameter-varying systems with semi-Markov mode switching

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Abstract

The paper is concerned with the stability and stabilization problems for a family of hybrid linear parameter-varying systems with stochastic mode switching. The switching phenomenon is modeled by a semi-Markov stochastic process which is more generalized than a Markov stochastic process. With the construction of a Lyapunov function that depends on both the parameter variation and operating mode, numerical testable stability and stabilization criteria are established in the sense of σ-error mean square stability with the aid of some mathematical techniques that can eliminate the terms containing products of matrices. To test the effectiveness of the designed stabilizing controller, we apply the developed theoretical results to a numerical example.

1. Introduction

Hybrid systems are initially referred to a class of systems that contain both continuous and discrete dynamics, which have been widely utilized to analyze the dynamical interaction between continuous and discrete signals in one research framework. Nowadays, physical systems with multiple operating modes are generally regarded as hybrid systems that have been well recognized as an effective means of modeling a variety of systems with complex switching dynamics, and numerous studies have been carried out since 2000s [1–5]. In the area of

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industrial electronics, hybrid systems can be found in motor drives [6,7], converter circuits [8,9], active power filters [10], electrical networks [11], and so on. Due to the generality of hybrid systems, the stability analysis and control synthesis procedures are often difficult to be addressed, which motivates the research interests in both academic and industrial communities.

On another research forefront, linear parameter-varying (LPV) systems have achieved great development in both theories and applications so far, which is motivated by their powerful capability of describing systems containing parameters with smooth variations, modeling the gain-scheduled control systems and approximating nonlinear systems. For quite a few years, a large number of researches have been reported on the stability and control issues of LPV systems, [12–15], and some theories have been applied in the field of industrial applications, such as hypersonic aircrafts [14], active magnetic bearing systems [16], missile autopilot systems [17,18] and coupled-tank processes [20]. It is noteworthy that many practical systems may encounter abrupt changes in system parameters or structures, while most of the developed methodologies for LPV systems are not applicable to those systems with nonsmooth and/or stochastic switchings in parameters. To tackle such a problem, it is of necessity to investigate the so-called hybrid linear parameter-varying (HLPV) systems defined as a class of multi-mode LPV systems that can switch from one to another operating mode [19], which is not only significant in theoretical study but also in practical engineering.

In most of the existing studies on HLPV systems with stochastic mode switchings, Markov stochastic process is adopted to describe the mode-switching phenomenon, which requires the sojourn time of each operating mode to be subject to exponential distribution in continuous-time domain and geometric distribution in discrete-time domain [21]. The corresponding systems, that is Markov jump systems (MJSs), have been well recognized as an effective means to model systems that have different system modes and may switch among them stochastically. During the past decades, numerous studies on the issues of stability, control and filtering issues for MJSs have been launched [22–34]. However, Markov stochastic processes, including the nonhomogeneous Markov case in which the transition probabilities are time-varying, are not always acceptable in practice due to the fact that the practical sojourn time may not be confined to neither of the two distribution types [35]. As semi-Markov stochastic process does not have the restriction on sojourn time, this type of stochastic process is more general and powerful in the aspect of modeling stochastic mode switchings than Markov stochastic process. Recent years have witnessed a growing interest in the stability and control issues of systems with semi-Markov switching by considering certain sojourn-time probability density functions [36–39], assuming upper and lower bounds of time-varying transition probabilities a priori [40,41], or with the aid of semi-Markov kernel [42–46].

In reality, the semi-Makov model has been uesed to multiple-bus systems [47], maneuvering target tracking systems [48,49], biological systems [50] over the past decades. Nonetheless, to the best of the authors' knowledge, no insightful investigations have been reported on the issue of HLPV systems with semi-Markov mode switching so far, which motivates us for the present work.

Based on the above discussions, the paper aims to address the stability analysis and controller design problems for discrete-time HLPV systems with stochastic switching that is considered to be governed by a semi-Markov chain. The main contribution lies in the employment of semi-Markov stochastic process to model the phenomenon of stochastic switching such that the designed controller can stabilize a wider scope of HLPV systems. The remainder of this paper is summarized as follows. In Section 2, the preliminaries and problem formulation are introduced. In Section 3, the development of stability conditions and the design