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Resilient dissipative dynamic output feedback control for uncertain Markov jump Lur'e systems with time-varying delays

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ABSTRACT

The resilient dissipative dynamic output feedback control problem for a class of uncertain Markov jump Lur'e systems with piecewise homogeneous transition probabilities and time-varying delays in the discrete-time domain are examined in this study. The designed controller can tolerate additive uncertainties in the controller gain matrix, which result from controller implementations. The time-varying delays are also supposed to be mode-dependent with lower and upper bounds known a *priori*. By constructing a Lyapunov–Krasovskii functional candidate, the sufficient conditions regarding the existence of desired resilient dissipative controllers are obtained in terms of linear matrix inequalities, thereby ensuring that the resulting closed-loop system is stochastically stable and strictly dissipative. Two numerical examples were established to illustrate the effectiveness of the proposed theoretical results.

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1. Introduction

Recent decades have witnessed an increasing interest from the control research community in the study of hybrid systems generally, and, more specifically, in a special subclass called Markov jump systems (MJSs) [1]. The motivation for this class of systems is that the Markov chain can model abrupt changes in the dynamics of the system due to, for instance, environmental disturbances, component failures or repairs, and changes in subsystems interconnections (see e.g. [2–6] and the references therein). Transition probabilities (TPs), which are a crucial factor in the jumping process, govern the complex dynamic behavior of MJSs. The TPs discussed in the extant literature are assumed to be time-invariant or homogeneous, however, such assumptions cannot always be satisfied in practical engineering problems [7,8]. Nonlinearities also universally exist in practical systems. Accordingly, nonlinear control has been an increasingly hot topic over recent decades.

Among different descriptions of nonlinearities, the so-called sector nonlinearity has garnered significant research attention; for example, nonlinear perturbations under a flying aircraft are modeled as sector-bounded nonlinearity in the aircraft

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autopilot system [9,10]. In addition, actuator or sensor saturations [11,12] can be decomposed into a linear term and a sector-bounded nonlinearity term. Such nonlinear systems formed as a result of the feedback interconnection of a linear system and a sector-bounded nonlinearity, are directly related to the so-called Lur'e problem [13]. Very recently, stochastic systems (e.g., Markov jump systems) with sector-bounded nonlinearity garnered extensive research attention [11,12,14–16]. By employing a stochastic Lur'e type Lyapunov function, Gonzaga and Costa [11] addressed the problem of control synthesis for a class of discrete-time Markov jump Lur'e systems with control saturation; the convex optimization problems subject to linear matrix inequalities (LMIs) constraints were solved in order to maximize an estimate of the domain of stochastic stability and to minimize the l_2-gain from the disturbance to the output.

It has been well recognized that time delays, which are inherent features of many physical processes, are significant sources of instability and poor performances. Considerable attention has been devoted to the analysis and synthesis of time-delayed systems [17–19]. Many researchers have recently focused on Markov jump systems with time-delay [4,5,15,20,21]. For instance, Cao and Lam [20] designed an H_∞ state-feedback controller for uncertain MJLSs with time delay in the continuous-time domain. A similar methodology was also used to deal with the discrete-time case [21]. When all state variables are not available for the feedback, it is necessary to design an output feedback controller [22–26]. Yu et al. [24] investigated delay-dependent H_∞ output feedback control problems where a cone complementarity linearization (CCL) procedure was needed to solve the LMIs for continuous-time MJLSs with time-varying delays. By considering linear fractional uncertainties, Huang et al. [26] studied the robust control problem for continuous-time MJLSs where both a state feedback controller and dynamic output feedback controller were proposed in terms of LMIs. Importantly, these studies were conducted based on an implicit assumption that the controller can be precisely implemented. Uncertainties may occur, however, in the implementation of the designed controller whether or not it is effectively designed. To this effect, the controller should be designed to be insensitive to some amount of errors with respect to its gain, i.e., the designed controller must be resilient or non-fragile. It is also necessary to design a controller able to tolerate a certain level of controller parameter variations, which is known as the non-fragile control problem [27,28]. Li and Jia [27] designed a dynamic output feedback controller (DOFC) with additive gain variations for continuous-time time-delay linear systems, effectively obtaining a delay-dependent stability criterion via the LMI approach.

On another research front, the dissipative theory has played an important role in system analysis and synthesis since the concept of dissipative dynamical systems was introduced [29]. The dissipative theory provides a framework for the design and analysis of control systems under the input–output description [30] based on energy-related considerations, which not only generalizes basic tools including the passivity theorem, bounded real lemma, and the circle criterion, but also provides a more flexible, less conservative robust control design as it allows a better trade-off between gain and phase performances. There have been a number of studies on dissipative control [31–35]: For example, for continuous-time linear time-delay systems, Li et al. [35] designed the dissipative state feedback controller and DOFC where the sufficient conditions for the existence of the quadratic dissipative controllers are obtained through an LMI approach. Relatively few studies have been conducted on the resilient dissipative dynamic output feedback control problem for uncertain Markov jump Lur'e systems with time-varying delays, however.

In this study, the resilient dissipative DOFC problem was investigated for uncertain Markov jump Lur'e systems with time-varying delays in the discrete-time domain. The state delay was assumed to be time-varying and with minimum and maximum bounds; the parameter uncertainties are assumed to be norm-bounded; and the sector nonlinearities appear in the system states and controller states. The controller as-designed is assumed to include additive gain variations resulting from controller implementations. An effective LMI approach is proposed here with resilient output feedback controllers such that the resulting closed-loop system is stochastically stable and strictly dissipative, irrespective of parameter uncertainties, sector nonlinearities, and time-varying delays. Sufficient conditions for the existence of the desired controller are proposed in terms of LMIs; and the explicit expressions of resilient controller gain matrices are obtained simultaneously. A numerical example is provided to show the feasibility and effectiveness of the proposed method.

The remainder of this paper is organized as follows: In Section 2, the mathematical model of the underlying Markov jump Lur'e systems is introduced and some preliminary results are given for problem formulation. Section 3 provides the $(\mathcal{Q}, \mathcal{S}, \mathcal{R})$-$\gamma$-dissipative analysis results for the resulting closed-loop systems. A robust resilient dissipative DOFC is discussed in Section 4. Section 5 provides a numerical example to demonstrate the effectiveness of the proposed method; Section 6 gives a brief summary and conclusion.

Notation: The notation $\|\cdot\|$ refers to the Euclidean vector norm. $l_2[0, \infty)$ is the space of summable infinite sequence over $[0, \infty)$, and for $v = \{v(k)\} \in l_2[0, \infty)$, its norm is given by $\|v\|_2 = \sqrt{\sum_{k=0}^{\infty} |v(k)|^2}$. For notation $(\Omega, \mathcal{F}, \mathcal{P})$, Ω represents the sample space, $\mathcal{F}$ is the σ-algebra of subsets of the sample space and $\mathcal{P}$ is the probability measure on $\mathcal{F}$. $\Pr(\cdot)$ means the occurrence probability of the event "$\cdot$". $\mathcal{E}\{\cdot\}$ stands for the mathematical expectation. In symmetric block matrices or long matrix expressions, $*$ marks terms that are introduced by symmetry and $\mathrm{diag}\{\cdots\}$ marks the block-diagonal matrix; I and 0 represent the identity matrix and zero matrix, respectively.

2. Problem formulation and preliminaries

Consider the following class of discrete-time uncertain Markov jump Lur'e time-delay systems defined on a probability space $(\Omega, \mathcal{F}, \mathcal{P})$:

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