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Stabilization and robustness analysis of multi-module impulsive switched linear systems

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ABSTRACT

In this work, a class of multi-module impulsive switched linear systems are formulated and their stabilization and robustness issues are studied. A pathwise state-feedback impulsive switching scheme is proposed and proven universal in sense that any asymptotically stabilizable impulsive switched linear system admits such a mechanism steering the system asymptotically stable. It is interesting to find that the designed scheme is flexible in avoiding Zeno phenomena and accommodating perturbations. That motivates us to conduct robustness analysis of the considered system under structural perturbations, unstructural perturbations and impulsive switching signal perturbations. Finally, a numerical example is provided to illustrate the effectiveness of the approach.
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1. Introduction

Hybrid dynamical systems exhibit the interaction of continuous-time dynamics and discrete-event dynamics and draw increasing attention in biology, engineering and many other fields [1,2]. As one typical class of hybrid systems, switched systems include a two-level structure with the lower lever governed by a set of modes and the upper level orchestrated by the switching among the modes [3,4]. Impulse is another hybrid dynamic that models a system whose state is discontinuous at some discrete instants [5,6]. As is known, switching and impulse widely exist in engineering, biology and many other practical systems [7–11]. Switching and impulse are naturally combined to form a more comprehensive model, i.e., impulsive switched systems. In [12], the authors derived some sufficient conditions for stability analysis and control synthesis of switched impulsive nonlinear systems. A set of readily computable conditions in terms of linear matrix inequalities were developed in [13] for exponential stability with the L_2-gain condition of nonlinear impulsive switched systems. Exponential stabilization problem was studied in [14] for a class of multi-module impulsive switched linear systems via a periodic switching scheme. Some other relevant topics concerned with input-to-state stability and finite-time stability of impulsive switched systems can be found in [8,15,16] and references therein.

Note that, for an autonomous impulsive switched system, a standard problem is the stabilization design that finds a proper impulsive switching law steering the system asymptotically stable. Some classical stabilizing methods can be found for switched linear systems, such as (average) dwell-time switching [17–21], state-space-partitioned switching [22–24] and combined switching [25–27]. One can see a survey paper [28] for more related details. Moreover, a multiple discontinuous Lyapunov function approach was proposed in [29] recently to reduce the dwell time. Note that conventional switching law is usually purely time-driven or state-feedback. Time-driven switching law is not universal for the stabilization issue, though it is well-defined as it is independent of the system dynamics. On the other hand, state-feedback switching law is

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robust with perturbations but usually cannot avoid Zeno behavior. In [30], the authors presented a pathwise state-feedback switching scheme, which achieves the merits of both mixed time-driven method and state-feedback method. The priority of the pathwise state-feedback scheme motivates our research to some extent. On the other hand, a universal method addressing the stabilization problem for generic impulsive switched linear systems is still lost in existing work [12,31–33]. The discontinuous dynamics caused by impulse leads to the stabilization problem a more challenging topic. In general, it is very hard to establish some necessary and sufficient stabilization criteria and construct proper impulsive switching laws for the impulsive switched linear systems. Moreover, impulsive switching signal perturbation analysis of the proposed scheme is also required, especially when time delay and measurement errors occur in practical systems. However, there are limited results conducting this problem.

In this work, we mainly study the stabilization and robustness problems for a class of impulsive switched linear systems, where the impulse inputs are subject to multi-module constraints [34]. The system framework is interesting in representing a wide class of impulsive switched systems when only a finite set of impulse modules are available, such as the multi-mode propulsion systems in flexible small satellite missions [35,36]. Such systems are designed to offer a range thrust and total spacecraft velocity change options to meet specific mission objectives, e.g., orbit insertion, state-keeping and attitude control. Motivated by the advantages of the pathwise state-feedback switching scheme introduced in [30], we extend it to an impulsive switching mechanism for the considered impulsive switched systems. Under the proposed method, we prove that any asymptotically stabilizable impulsive switched system admits such an impulsive switching control law that steers the system asymptotically stable. In this work, it only requires the norm of state vector decreases along a sequence formed by the starting instant of concatenated impulsive switching path, which is a relatively simple identifying way.

Further, we address robustness problem of nominal impulsive switched linear system under structural perturbations, unstructural perturbations and impulsive switching signal perturbations. Note that, the cases when subsystems are against structural and unstructural perturbations can be handled via conventional method while the case of impulsive switching signal perturbations is a new topic that awaits more attention. The motivation of robustness against impulsive switching signal perturbation is stated as below. In practice, we usually cannot implement an impulsive switching signal precisely due to time delay and inexact online measure, and impulse/switching devices might not manipulate in certain cases [37]. From the viewpoint of stabilizing design, we also prefer to an impulsive switching law that still works under small perturbations. By defining the distance between perturbed and nominal impulsive switching path/signal through time variation and ignoring the dynamic difference between the system matrices for simplicity, we prove that the proposed pathwise state-feedback control law is robust against impulsive switching perturbations.

The main contributions of this work can be stated as below. First, we propose a universal impulsive switching scheme and establish a necessary and sufficient criteria for the multi-module impulsive switched systems, which greatly reducing conservatism of many existing results. Second, we conduct robustness analysis for the considered system under (un)structural perturbations and especially impulsive switching signal perturbations. Third, we extend the results into [30,37,38] to a more comprehensive model and increase more available degrees of freedom for stabilizing design.

2. Problem formulation and preliminaries

Consider a continuous-time impulsive switched linear system formed by

$$\begin{cases} \dot{x}(t) = A_\sigma x(t), & t \neq t_k, \\ x(t^+) = U(x(t^-)), & t = t_k, \end{cases} \tag{1}$$

where $x(t) \in \mathbf{R}^n$ is the system state, $\sigma : [0, +\infty) \to \{1, 2, \dots, s\}$ is the switching signal, $\{t_k\}_{k=1}^{\infty}$ is impulse/switching instant sequence satisfying $0 < t_1 < t_2 < \cdots$, and $U(x) \in \{B_1x, B_2x, \dots, B_mx\}$ is the impulse input dependent on the state. We suppose that the system state is continuous from the right hand.

Throughout this work, an impulsive switching path defined over a time interval $[t_s, t_f)$ is a sequence of triples as

$$p_{[t_s,t_f)} = \{t_s|(\tau_1, A_{l_1}, B_{j_1}), \dots, (\tau_v, A_{l_v}, B_{j_v})\},$$

where t_s (t_f) is the starting (ending) time of the path, τ_q is the qth impulse/switching interval, A_{l_q} and B_{j_q} are the activated constituent subsystem and impulse mode respectively, $q = 1, 2, \dots, v$. We will omit t_s in the brace when it is zero.

For an impulsive switching signal, it can be seen as an impulsive switching path defined over an infinite time horizon. An impulsive switching control law for system (1) is a rule that generates an impulsive switching path/signal for certain initial configurations. In this sense, an impulsive switching control law can be defined as $\{p^x : x \in \mathbf{B}_\delta\}$, where $\mathbf{B}_\delta$ is the ball centered at the origin with radius δ. An impulsive switching path/signal is said to be well defined if only a finite number of impulse/switching occurs during any finite time interval.

For clarity, we denote $\phi(t; x_0, p)$ by the state of system (1) at time t under impulsive switching path p and initial state $x(0) = x_0$; $\Phi(t, p)$ stands for the state transition matrix that corresponds to p with $\phi(t; x_0, p) = \Phi(t, p)x_0$; $|\cdot|$ is any given vector norm in $\mathbf{R}^n$, and $\|\cdot\|$ is the induced matrix norm; $\rho(\cdot)$ is the spectral radius of the matrix in $\mathbf{R}^{n\times n}$; Ø symbols an empty set; $\mathbf{H}_1 = \{x \in \mathbf{R}^n \parallel x| = 1\}$; $S_1 - S_2$ stands for a set $\{s \in S_1 : s \notin S_2\}$ for any $S_1, S_2 \subset \mathbf{R}^n$; $\overline{S}$ denotes the closure of a set $S \subset \mathbf{R}^n$; E_n denotes the $n \times n$ unit matrix. By a class $\mathcal{K}$ function $\alpha(q)$, $q \geq 0$, we mean that it is a continuous and strictly increasing function with $\alpha(0) = 0$, and a class $\mathcal{K}_\infty$ function is an unbounded class $\mathcal{K}$ function. A class $\mathcal{KL}$ function $\beta(q, t)$

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