Nonlinear Analysis: Hybrid Systems 27 (2018) 239–257

Contents lists available at ScienceDirect

Nonlinear Analysis: Hybrid Systems

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

Output regulation of switched nonlinear systems using incremental passivity[☆]

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ARTICLE INFO

Article history:
Received 25 September 2016
Accepted 21 August 2017
Available online 16 October 2017

Keywords:
Switched nonlinear systems
Incremental passivity
Error-dependent switching law
Error-feedback output regulation
Switched internal model

ABSTRACT

This paper studies the global output regulation problem for a class of switched nonlinear systems using incremental passivity, even though the output regulation problem for none of subsystems is solvable. Firstly, a concept of incremental passivity for switched nonlinear systems without the requirement of the incremental passivity property of individual subsystem is introduced. This incremental passivity property is shown to be invariant under compatible feedback interconnection. Secondly, a switched nonlinear system is rendered to be incrementally passive by the design of a set of dynamic error feedback controllers and a dynamic switching law. In particular, an error-dependent switching law is designed to guarantee a specific class of switched systems incrementally passive. Thirdly, the incremental passivity for switched nonlinear systems is applicated to solve the global output regulation problem by the dual design of the composite switching law and error feedback controllers. The key idea is to design an incrementally passive switched internal model. Two examples including a Switched Chua's Circuit are presented to illustrate the effectiveness of the proposed approach.

1. Introduction

The output regulation problem is one of the most fundamental problems in control theory and engineering. The output regulation, in general, aims to track exosystem-generated reference signals asymptotically and reject the effect of exosystem-generated disturbances. This problem for nonlinear systems has been well investigated [1–3].

The passivity theory, proposed by Willems [4], is effective tool for solving the output regulation problem [5–7]. To investigate a more extensive class of physical systems with an equilibrium point or not, [8,9] extended the conventional passivity property to incremental passivity. A state space form of incremental passivity definition and some related preliminary results were given in [10–13]. For an incrementally passive system, the storage function can be chosen as an incremental Lyapunov function for incremental stability analysis [12,13] and convergence analysis [14]. In addition, according to the invariance of incremental passivity under feedback interconnection, once the incremental passivity property of a nonlinear system is assured, an incrementally passive feedback controller can be designed to drive the trajectories to converge to a steady-state solution. Therefore, incremental passivity was used to solve the output regulation problems [10,11]. Incremental passivity theory was applied to the synchronization analysis problem of coupled oscillators [12–14] and the analysis of electrical circuits [15].

☆ This work was supported by the National Natural Science Foundation of China under Grant 61773098; 111 Project, Grant/Award Number: B16009.
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https://doi.org/10.1016/j.nahs.2017.08.011
1751-570X/

On the other hand, a great amount of attention has been paid to switched systems due to their wide existence in many practical fields [16–22], such as mechanical systems [23,24], and electrical systems [17] and so on. Switched systems are composed of a family of continuous-time subsystems and a rule that governs the switching among them [25]. The output regulation problem for switched systems is much more difficult than that for non-switched systems because of the interactions of continuous dynamics and discrete dynamics. Several methods were adopted to deal with switched system, such as the common Lyapunov function technique [26], the multiple Lyapunov functions method [27,28], the average dwell time approach [23,29–31] and so on.

Passivity property is also useful for switched nonlinear systems as non-switched systems. Passivity concepts of switched nonlinear systems and the corresponding feedback passification and passivity-based stabilization problems were investigated in [24,32,33]. The incremental passivity was still important for switched nonlinear systems [34–36]. Incremental passivity theory and the incremental passivity-based output tracking for switched nonlinear systems were investigated using multiple storage functions and multiple supply rates in [34]. But the adjacent storage functions are connected at the switching times, which is a strong requirement. In [35], a more general incremental passivity concept of switched nonlinear systems which allow the storage functions to increase at the switching times was proposed. A state-dependent switching law is designed to render a switched system incrementally passive. Moreover, the output regulation problem for switched nonlinear systems was solved using the established incremental passivity. However, when the whole states information is unavailable for measurements, the output regulation problem for switched nonlinear systems has not been investigated using incremental passivity theory. The difficulty in solving the output regulation problem for switched nonlinear systems is the design of the internal model and error-dependent switching laws.

Motivated by the above discussion, we will generalize the results on incremental passivity and global output regulation in [10] to switched nonlinear systems. Compared with the existing literatures, the results of this paper have four distinct features. First, when the whole states information is unavailable for measurements, a set of dynamic feedback controllers for subsystems and a dynamic switching law are designed using error information to render the resulting closed-loop system incrementally passive. In particular, an error-dependent switching law is designed to guarantee a specific class of switched systems incrementally passive. Second, a switched regulator and a composite switching law are designed to solve the output regulation problem. Compared with conventional regulator, the switched regulator is parallel interconnections of the incrementally passive switched internal model and a switched stabilizer rendering the controlled plant incrementally passive (together with the linear error feedback controllers). The internal model and the stabilizer can be designed independently. Third, compared with the switched internal model designed in [23], the incrementally passive switched internal model is allowed to switch asynchronously with the controlled plant, which increases the freedom of design greatly. The internal model property is not required for each subsystem of the switched internal model. Finally, compared with [23,28,29], once the incremental passivity property of the controlled plant is assured, the stabilizer is designed as a set of the linear error feedback controllers. Thus, this paper does not need to verify that all the solutions converge to the steady-state solution, while we only have to verify the regulated outputs converge to zero directly.

2. Problem formulation and preliminaries

Consider a switched nonlinear system described by

$$\begin{aligned} \dot{x} &= f_\sigma\left(x, u_\sigma, \omega\right), \\ e &= h_\sigma\left(x, \omega\right), \end{aligned} \tag{1}$$

where $x \in R^n$ is system state, $u_i \in R^m$ is the input vector of the ith subsystem, $e \in R^m$ is the measured regulated output/error and $\sigma(t) : [0, \infty) \to I = \{1, 2, \ldots, M\}$ is the switching signal which is assumed to be a piecewise constant function and has a finite number of switchings on any finite time interval [25]. The exogenous signal $\omega(t)$ including exogenous commands, exogenous disturbances is generated by the exosystem

$$\dot{\omega} = s(\omega), \quad \omega(t_0) \in W, \tag{2}$$

where $W \subset R^s$ is a given positively invariant set of initial conditions. It is assumed that any solution $\omega(t)$ starting from $\omega(t_0) \in W$ is bounded for all $t \geq t_0$. f_i , h_i and s are smooth functions.

Corresponding to the switching signal, the switching sequence is described by

$$\Sigma = \left\{(i_0, t_0), (i_1, t_1), \ldots, (i_k, t_k), \ldots \middle| i_k \in I, k \in N\right\}, \tag{3}$$

where t_0 is the initial time, and N denotes the set of nonnegative integers. When $t \in [t_k, t_{k+1})$, $\sigma(t) = i_k$, that is, the i_k-th subsystem is active. For any $j \in I$, let

$$\Sigma_j = \left\{ t_{j_1},\ t_{j_2},\ \cdots t_{j_n} \cdots ;\ i_{j_q} = j,\ q \in N \right\} \tag{4}$$

be the sequence of switching times when the jth subsystem is switched on, and thus

$$\left\{ t_{j_1+1},\ t_{j_2+1}, \ldots t_{j_n+1}, \ldots ;\ i_{j_q} = j,\ q \in N \right\} \tag{5}$$