Neurocomputing 196 (2016) 42–52

Contents lists available at ScienceDirect

Neurocomputing

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

Adaptive finite-time tracking control for a class of switched nonlinear systems with unmodeled dynamics

Jun Mao, Zhengrong Xiang*, Shipei Huang

School of Automation, Nanjing University of Science and Technology, Nanjing, 210094, People's Republic of China

A R T I C L E I N F O

Article history:
Received 17 November 2015
Received in revised form
17 February 2016
Accepted 25 February 2016
Available online 8 March 2016

Keywords:
Switched systems
Nonlinear systems
Unmodeled dynamics
K-filters
Dynamic surface control

A B S T R A C T

In this paper, an adaptive tracking control scheme is proposed for a class of switched nonlinear systems with state and input unmodeled dynamics. The unmodeled dynamics are dealt with by introducing a first-order filter and a dynamic signal. K-filters are used to estimate the unmeasured states, and the dynamic surface control (DSC) technique is employed to construct the controller to avoid the explosion problem of complexity. By choosing an appropriate common Lyapunov function, the boundedness of all closed-loop signals is proved, and the tracking error can converge to a small neighborhood of zero in finite time under arbitrary switchings. Finally, a simulation example is provided to show the feasibility and validity of the proposed method.

1. Introduction

Over the past years, switched systems have become an emerging hot research topic due to their board applications in control fields, such as spacecraft control [1] and vehicle control [2,3]. Switched system means a hybrid system that is composed of a family of continuous-time and discrete-time subsystems and a rule orchestrating the switching between the subsystems. Stabilization and tracking are fundamental problems in the research field of switched nonlinear systems [4–20]. Many significant methods have been proposed to solve these problems, such as common Lyapunov function method, multiple Lyapunov function method and dwell-time approach [6,14,15,17,18,20]. For example, common Lyapunov function method was employed to solve the tracking control problem of switched nonlinear systems in strict feedback form [14,17,18]. Adaptive tracking control for switched nonlinear systems in lower-triangular form was investigated in [6] by exploiting multiple Lyapunov function method. By using the dwell-time approach, adaptive control for uncertain switched nonlinear systems was studied in [15,20], where fuzzy sets [21,22] and neural networks [19,23–25] are used to approximate unknown nonlinearities.

As is well known, unmodeled dynamics widely exist in many practical nonlinear systems, which can severely degrade the system performance. Therefore, how to handle unmodeled dynamics is a meaningful topic when one investigates the system stability. Generally speaking, unmodeled dynamics include state unmodeled dynamics [5,6,15,20,25–32] and input unmodeled dynamics [33–38]. State unmodeled dynamics denote the parts of invalid modeling during the parameterization, a few approaches were proposed to handle the adverse effects caused by them. In [5,6,20,26,27,29–32], the state unmodeled dynamics were dominated by introducing available dynamic signals. In [15,28], several specific Lyapunov functions were selected to remove the state unmodeled dynamics. On the other hand, input unmodeled dynamics mean modeling errors or external disturbances act upon the controller. In [33–38], a first-order filter was introduced to generate a dynamic signal to overcome the input unmodeled dynamics, which were of relative degree zero and minimum-phase.

In recent years, finite-time stabilization and finite-time tracking have drawn considerable attention due to theirs practical importance [1,16–18,39–42]. The aim of finite-time stabilization or tracking is to design the control law to make system states or tracking errors converge to the origin or the small neighborhood of it in finite time. In [39], the problem of global finite-time stabilization for a class of stochastic nonlinear systems was solved. In [16–18], finite-time stabilization was studied for several classes of switched nonlinear systems in strict feedback form. Finite-time tracking and stabilization control for spacecraft systems were respectively investigated in [1] and [40]. In [41,42], adaptive finite-time tracking and stabilization control schemes were respectively proposed for multi-agent and autonomous systems. However, finite-time tracking control for switched nonlinear systems with

* Corresponding author.
E-mail address: xiangzr@mail.njust.edu.cn (Z. Xiang).

http://dx.doi.org/10.1016/j.neucom.2016.02.035
0925-2312/

unmodeled dynamics was not investigated until now, which motivates the present study. The main contributions of this paper are summarized as follows:

(i) An adaptive finite-time tracking control scheme is proposed for a class of switched nonlinear systems with unmeasured states and unmodeled dynamics. K-filters are used to estimate the unmeasured states, and a filter is introduced to counteract the influence of input unmolded dynamics. Moreover, dynamic surface control (DSC) is used to overcome the limitation of "explosion of complexity".
(ii) Compared with previous results [29–31,33–35], the restrictions on the control coefficients and the reference signals are relaxed. In this paper, the upper bound of control coefficient is unknown and the second derivative of the reference signal is not required to be bounded.
(iii) An output feedback controller and adaptive laws are constructed to guarantee that the tracking error can converge to a small neighborhood of zero in finite time rather than in infinite time presented in [20,29–31,33–35].

The rest of this paper is organized as follows. In Section 2, the problem statement and preliminaries are given. In Section 3, system parameterization and K-filters design are presented. In Section 4, a control scheme is developed for switched systems by using the DSC technique. Section 5 gives stability analysis. Simulation results are presented in Section 6. Section 7 summarizes the main conclusions.

Notations: R^+ denotes the set of all non-negative real numbers; R^n denotes the real n-dimensional space; $R^{m\times n}$ denotes the real $m\times n$ dimensional matrix; $R^+_{odd} \triangleq \{q\in R: q>0$ and q is a ratio of odd integers$\}$; $e_i, i=1,2,\ldots,n$, denotes the n-dimensional vector with the ith element being one, and other elements being all zeros; K function denotes the set of all continuous functions which are strictly increasing and vanishing at zero; K_∞ function denotes the set of all functions which are class K functions and unbounded, C^i stands for a set of functions with continuous ith partial derivatives, $\|\cdot\|$ represents the Euclidean norm.

2. Problem statement and preliminaries

Consider the following switched nonlinear system with state and input unmodeled dynamics:

$$\begin{cases} \dot z = q(z,y), \\ \dot x_1 = x_2 + f_{1,\sigma(t)}(y) + \Delta_{1,\sigma(t)}(z,y,t), \\ \dot x_2 = x_3 + f_{2,\sigma(t)}(y) + \Delta_{2,\sigma(t)}(z,y,t), \\ \vdots \\ \dot x_\rho = x_{\rho+1} + f_{\rho,\sigma(t)}(y) + \Delta_{\rho,\sigma(t)}(z,y,t) + b_{m,\sigma(t)}v, \\ \vdots \\ \dot x_{n-1} = x_n + f_{n-1,\sigma(t)}(y) + \Delta_{n-1,\sigma(t)}(z,y,t) + b_{1,\sigma(t)}v, \\ \dot x_n = f_{n,\sigma(t)}(y) + \Delta_{n,\sigma(t)}(z,y,t) + b_{0,\sigma(t)}v, \\ y = x_1. \end{cases} \tag{1}$$

The minimal realization of input ummodeled dynamics is represented as

$$\begin{cases} \dot \xi = A_{\Delta,\sigma(t)}(\xi) + b_{\Delta,\sigma(t)}u, \\ v = C_{\Delta,\sigma(t)}(\xi) + d_{\Delta,\sigma(t)}u, \end{cases} \tag{2}$$

where $x=[x_1,x_2,\ldots,x_n]^T\in R^n$ and $u\in R$ are the unmeasured system states and input respectively. $y\in R$ is the measured system output; $\sigma(t):[0,+\infty)\to M=\{1,2,\ldots,m\}$ is the switching signal and all system states do not jump at each switching instant, $t_0=0$; For any $i=1,2,\ldots,n, k=1,2,\ldots,m$, $f_{i,k}(\cdot)$ is the unknown smooth nonlinear function; $z\in R^{n_0}$ is the state unmodeled dynamics; $\Delta_{i,k}(z,y,t), i=1,2,\ldots,n$, is the external dynamic disturbance, which is an unknown smooth nonlinear function; $q(z,y)$ is the unknown continuous function; $v\in R$ is the unmeasured signal which acts upon the nonlinear system; $\xi\neq 0\in R^q$ is the input unmodeled dynamic; $A_{\Delta,k}(\cdot)$, $b_{\Delta,k}$ are unknown vectors; $C_{\Delta,k}(\cdot)$ is an unknown function and $d_{\Delta,k}$ is an unknown constant. $b_{i,k}\neq 0, i=1,2,\ldots,n$, is the unknown control coefficient; $\rho+m=n$.

Remark 1. It should be emphasized that switched system (1) and (2) does not have strict feedback or pure feedback structures studied in [10,15–18]. Furthermore, due to the existence of the state and input unmodeled dynamics, finite-time tracking control for switched system (1) and (2) becomes more difficult.

The objective is to design a controller and adaptive laws for switched system (1) and (2) such that the output y follows the specified desired trajectory y_r, and the tracking error can converge to a small neighborhood of zero in finite time under arbitrary switchings.

Assumption 1 (*Zhang and Xia [29,30], Xia and Zhang [31]*). The external disturbance $\Delta_{i,k}(z,y,t), i=1,2,\ldots,n$, is an unknown smooth function satisfying

$$|\Delta_{i,k}(z,y,t)| \le \phi_{i1,k}(\|z\|) + \phi_{i2,k}(\|y\|),$$

where $\phi_{i1,k}(\cdot)\ge 0$ is an unknown increasing function and $\phi_{i2,k}(\cdot)\ge 0$ is an unknown smooth function.

Assumption 2 (*Xia et al. [33], Chen et al. [34,35]*). The input ummodeled dynamics (2) has relative degree zero, that is, $d_{\Delta,k}\neq 0$, and there exists an unknown positive constant $\overline{C}_k>0$ such that $|C_{\Delta,k}(\xi(t))| \le \overline{C}_k\|\xi(t)\|$.

Assumption 3 (*Zhang and Xia [29,30], Xia and Zhang [31]*). The system $\dot z = q(z,y)$ is exponentially input-state-practically stable (exp-ISPS), that is, there exists a C^1 function $V_0(z)$ such that

$$\overline{\alpha}_1(\|z\|) \le V_0(z) \le \overline{\alpha}_2(\|z\|), \tag{3}$$

$$\frac{\partial V_0(z)}{\partial z} q(z,y) \le -cV_0(z) + \gamma(\|y\|) + d, \tag{4}$$

where $\overline{\alpha}_1(\cdot),\overline{\alpha}_2(\cdot)$ and $\gamma(\cdot)$ are the class K_∞ functions, $c>0, d\ge 0$ are constants.

Assumption 4 (*Xia et al. [33], Chen et al. [34,35]*). For input unmodeled dynamics (2), there exists a C^1 function $\overline{V}(\xi)$ satisfying

$$\beta_1\|\xi\|^2 \le \overline{V}(\xi) \le \beta_2\|\xi\|^2,$$
$$\frac{\partial \overline{V}(\xi)}{\partial \xi} A_{\Delta,k}(\xi) \le -2\delta_{0,k}\overline{V}(\xi),$$
$$\left\|\frac{\partial \overline{V}(\xi)}{\partial \xi}\right\| \le \beta_3\|\xi\|,$$

where $\beta_1>0, \beta_2>0, \beta_3>0$ and $\delta_{0,k}>0$ are constants.

Assumption 5. The desired trajectory $x_r=[y_r,\dot y_r]^T\in\Omega_r$ is known, where $\Omega_r=\{x_r: y_r^2+\dot y_r^2\le D_0\}$, and D_0 is a constant.

Remark 2. In [10,29–31,33–35], the upper bounds of control coefficients should be known, and the second derivative of tracking signals was required to be bounded, which are somewhat strict. In this paper, we relax these restrictions, and do not require any information about the second derivative of tracking signals.

Lemma 1 (Krstic et al. [26]). *If V_0 is a C^1 function for a system $\dot z = q(z,y)$ such that (3) and (4) hold, then, for any constant $\overline{c}^*\in(0,c)$, any initial instant $t_0\ge 0$, any initial condition $z_0=z(t_0), \gamma_0>0$, any continuous function $\overline{\gamma}(\|y\|)$ satisfying $\overline{\gamma}(\|y\|)\ge\gamma(\|y\|)$, there exist a finite constant $T_0=\max\{0,\ln(V_0(z)/\gamma_0)/(c-\overline{c}^*)\}\ge 0$, a function $D(t_0, t)\ge 0$ and an unmeasured dynamic signal described by*