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Brief paper

Neural-networked adaptive tracking control for switched nonlinear pure-feedback systems under arbitrary switching[☆]

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ABSTRACT

This paper deals with the problem of adaptive tracking control for a class of switched uncertain nonlinear systems in pure-feedback form under arbitrary switching. Based on command filtered backstepping design and common Lyapunov function method, a robust adaptive neural-networked control scheme is proposed to guarantee that the resulting closed-loop system is asymptotically bounded with tracking error converging to a neighborhood of the origin. A universal formula for constructing common neural-networked stabilizing function and controller is designed. Differing from the existing results in the literature, the developed new design scheme only requires desired trajectory and common stabilizing functions/virtual control signals instead of them and their first derivatives at each step in backstepping design procedures, and does not need *a priori* knowledge of the signs of control gain functions. Simulation results illustrate the effectiveness of the proposed techniques.

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1. Introduction

It is well known that a switched system under arbitrary switching is asymptotically stable if and only if a common Lyapunov function exists for all subsystems (Farrell, Polycarpou, Sharma, & Dong, 2009; Jiang, Yang, & Cocquempot, 2011; Lian, Shi, & Feng, 2012; Liberzon, 2003; Mittal, Dwivedi, & Dwivedi, 2015; Wu, Cui, & Shi, 2012; Xu & Antsaklis, 2004; Zhang, Cao, & Wang, 2014). Recently, using the control Lyapunov function approach, some researchers investigated the stabilization problem of switched nonlinear systems under arbitrary switching (Ma, Dimirovski, & Zhao, 2013; Ma & Zhao, 2010; Wu, 2008, 2009). Based on the common control Lyapunov function (CCLF), the stabilization problem of switched nonlinear systems with two subsystems under arbitrary switching has been studied in Wu (2008). The robust $H\infty$ control problem of a class of switched nonlinear systems under arbitrary switching was investigated in Ma et al. (2013). In Wu (2009), the stabilization problem of a class of switched nonlinear systems in strict-feedback form under arbitrary switching was considered using both the backstepping method and the control Lyapunov function approach, and a universal formula for constructing stabilizing feedback laws was presented. In Ma and Zhao (2010), the global stabilization problem of switched nonlinear systems in lower triangular form under arbitrary switching was investigated. However, in the aforementioned results by Ma et al. (2013), Ma and Zhao (2010), Wu (2008, 2009), the considered system models must be known, i.e., system functions should be known in advance. If not, the corresponding CCLF cannot be found or constructed. Also it should be mentioned that, the systems presented in Ma et al. (2013), Ma and Zhao (2010), Wu (2008, 2009), are strict-feedback systems, which is a particular case of pure-feedback systems in a sense.

On the other hand, pure-feedback nonlinear systems have a more representative form than strict-feedback nonlinear systems, since such systems have no affine appearance of the state variables to be used as virtual controls and actual control (Ge & Wang, 2002; Tong, Li, & Shi, 2012; Wang, Hill, Ge, & Chen, 2006; Wang & Huang, 2002; Zhang & Ge, 2008). Thus, the stabilization problem of nonlinear pure-feedback systems, in particular, switched nonlinear pure-feedback systems, is more difficult and challenging

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as well, and stabilizing or controlling the switched nonlinear pure-feedback systems in general case is a motivation of this study.

It has been proved that adaptive backstepping technique is a powerful tool to solve tracking or regulation control problems of unknown nonlinear systems in or transformable to parameter strict-feedback form (Krstic, Kanellakopoulos, & Kokotovic, 2008; Wu, Xie, Shi, & Xia, 2009), where fuzzy logic systems (FLSs) or neural networks (NNs) are used to approximate unknown nonlinear functions (Wang & Huang, 2002; Zhou, Shi, Liu, & Xu, 2012; Zhou, Shi, Lu, & Xu, 2011). However, in standard backstepping design procedures, analytic computation of the first derivatives of virtual control signals α_i $(i = 1, 2, \ldots, n-1)$, i.e., $\dot{\alpha}_i$, is necessary. This limits the theoretical results' field of practical applications. Hence, how to avoid the computation of the derivatives of α_i, i.e., $\alpha_i^{(j)}$, $j \geq 2$, is a crucial issue in controller design, which is the other motivation of our current work. In addition, the aforementioned approaches required the knowledge of the desired trajectory $y_d(t)$ and the first n derivatives, i.e., $y_d^{(i)}(t)$, $i = 1, 2, \ldots, n$ should be available. It is important to note that in some important applications (e.g., land vehicle or aircraft) the desired trajectory may be generated by a planner, an outer-loop, or a user input device that does not provide its derivatives. Relaxing the condition also motivates our study in this paper.

In this paper, a robust adaptive control scheme is proposed for switched uncertain nonlinear pure-feedback system to guarantee that the tracking error converges to a neighborhood of the origin. Compared with existing results in the literature, the following contributions are worth to be emphasized: (1) Unlike Wu (2008) where special certain switched nonlinear systems were considered and common stabilization functions α_i are assumed to be existent and known, a universal formula for constructing NNs-based common stabilizing functions and controller is firstly proposed for a class of switched uncertain pure-feedback systems by combination of the capability of NNs approximation, adaptive command filtered backstepping recursive design and the common Lyapunov function method in this paper; (2) In contrast with the existing results such as Ge and Wang (2002); Tong et al. (2012); Wang et al. (2006); Wang and Huang (2002); Zhang and Ge (2008) where the desired trajectory and its first n derivatives, i.e., $y_d^{(i)}(t)$, $i = 0, 1, \ldots, n$ should be available, only the desired trajectory is necessary for the control scheme presented in this paper, which is more reasonable in practical applications. The theoretic results of this paper are thus valuable in a wide field of practical applications; (3) Compared with the existing works concerning the standard backstepping design, the control scheme presented in this paper does not need the computation of the first derivatives of virtual control signals at each step in backstepping design procedures, which decreases the computation complexity; and (4) Different from Ma et al. (2013), Ma and Zhao (2010), Wu (2008, 2009), where all system functions are known, the system functions considered in this paper are unknown. In particular, the signs of control gain functions in this paper are also unknown.

2. Problem statement and preliminaries

2.1. Problem statement

Considers the following switched systems:

$$\begin{cases} \dot{x}_i = f_i^{\sigma(t)}(\bar{x}_i, x_{i+1}) + d_i^{\sigma(t)}(t), \quad i = 1, 2, \ldots, n-1 \\ \dot{x}_n = f_n^{\sigma(t)}(\bar{x}_n, u^{\sigma(t)}) + d_n^{\sigma(t)}(t) \\ y = x_1 \end{cases} \tag{1}$$

where $\bar{x}_i = (x_1, \ldots, x_i)^T \in R^i$, $i = 1, \ldots, n$ is the state; $\sigma(t)$: $[0, +\infty) \to M = \{1, 2, \ldots, m\}$ is the switching signal; $u^k \in R$ is the input of the kth subsystem; $f_i^k(\bar{x}_i, x_{i+1}) \in R$, $i = 1, \ldots, n$, $\forall k \in M$ are the unknown smooth functions with $x_{n+1} = u^k$; $d_i^k(t)$, $i = 1, \ldots, n$, $\forall k \in M$ denote the unknown dynamic disturbances.

Control objective is to design a common adaptive controller for system (1) under arbitrary switching such that output y can track accurately the desired trajectory y_d as possible regardless of unknown dynamic disturbances $d_i^k(t)$, $i = 1, \ldots, n$, $\forall k \in M$.

Lemma 1 (*Polycarpou & Ioannou, 1995*). *For* $\forall x \in R$, $|x| - \tanh(x/\delta)x \leq 0.2785\delta$, *where* $\delta > 0$.

Assumption 1. There exist unknown constants $D_i^k > 0$, $i = 1, \ldots, n$, $\forall k \in M$, such that $|d_i^k(t)| \leq D_i^k$.

Assumption 2. $\frac{\partial f_i^k(\bar{x}_i, x_{i+1})}{\partial x_{i+1}} \neq 0$, $i = 1, \ldots, n$, $\forall k \in M$, are unknown, and there exist unknown real constants $g_{i0}^k > 0$ such that $|\frac{\partial f_i^k(\bar{x}_i, x_{i+1})}{\partial x_{i+1}}| \leq g_{i0}^k$. Let $g_m = \max_{i \in I, k \in M}\{g_{i0}^k\}$, $I = \{1, 2, \ldots, n\}$. In addition, the signs of $\frac{\partial f_i^k(\bar{x}_i, x_{i+1})}{\partial x_{i+1}}$ are unknown.

Assumption 3. For $t \geq 0$, the desired trajectory $y_d(t)$ is bounded, continuous and available, and $\dot{y}_d(t)$ is bounded but may be not available, i.e., there exists an unknown constant $M_y > 0$ such that $|\dot{y}_d(t)| \leq M_y$.

Remark 1. In the literature, the existing results concerning trajectory tracking problem require the classical assumption that the desired trajectory $y_d(t)$ and the first n derivatives, i.e., $y_d^{(i)}(t)$, $i = 0, 1, \ldots, n$ should be available. Just stated in Introduction section, in some important applications, its derivatives are not available. Thus, Assumption 3 in this paper is more reasonable in practical applications.

2.2. Nussbaum-type gain

Any continuous function $N(s) : R \to R$ is a function of Nussbaum type if it has the following properties:

(1) $\lim_{s \to +\infty} \sup \frac{1}{s} \int_0^s N(\varsigma) d\varsigma = +\infty$;
(2) $\lim_{s \to -\infty} \inf \frac{1}{s} \int_0^s N(\varsigma) d\varsigma = -\infty$.

For example, $e^{\varsigma^2} \cos((\pi/2)\varsigma)$ verify the above properties and are thus Nussbaum-type functions (Khalil, 1992). The even Nussbaum function $e^{\varsigma^2} \cos((\pi/2)\varsigma)$ is used throughout this paper.

Lemma 2 (*Ye & Jiang, 1998*). *Let $V(\cdot)$ and $\varsigma(\cdot)$ be smooth functions defined on $[0, t_f)$ with $V(t) \geq 0$, $\forall t \in [0, t_f)$, and $N(\cdot)$ be an even smooth Nussbaum-type function. If the following inequality holds:*

$$V(t) \leq c_0 + \int_0^t (\underline{g} N(\varsigma) + 1)\dot{\varsigma} d\tau, \quad \forall t \in [0, t_f)$$

where $\underline{g} \neq 0$ is a constant, and c_0 represents a suitable constant, then $V(t)$, $\varsigma(t)$ and $\int_0^t \underline{g} N(\varsigma)\dot{\varsigma} d\tau$ must be bounded on $[0, t_f)$.

Lemma 3 (*Ge, Hong, & Lee, 2004*). *Let $V(\cdot)$ and $\varsigma(\cdot)$ be smooth functions defined on $[0, t_f)$ with $V(t) \geq 0$, $\forall t \in [0, t_f)$, and $N(\cdot)$ be an even smooth Nussbaum-type function. For $\forall t \in [0, t_f)$, if the following inequality holds,*

$$V(t) \leq c_0 + e^{-c_1 t} \int_0^t \underline{g}(\tau) N(\varsigma)\dot{\varsigma} e^{c_1 \tau} d\tau + e^{-c_1 t} \int_0^t \dot{\varsigma} e^{c_1 \tau} d\tau$$

where constant $c_1 > 0$, $\underline{g}(\cdot)$ is a time-varying parameter which takes values in the unknown closed intervals $I := [l^{-1}, l^{+1}]$ with $0 \notin I$, and c_0 represents some suitable constant, then $V(t)$, $\varsigma(t)$ and $\int_0^t \underline{g}(\tau) N(\varsigma)\dot{\varsigma} d\tau$ must be bounded on $[0, t_f)$.

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