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Dynamic surface error constrained adaptive fuzzy output feedback control for switched nonlinear systems with unknown dead zone ☆

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ABSTRACT

This paper investigates the adaptive fuzzy output-feedback dynamic surface control (DSC) approach with prescribed performance for a class of uncertain switched nonlinear systems with unknown dead-zone. In this research, fuzzy logic systems are used to identify the unknown nonlinear functions, a fuzzy switched state observer is established to observe the unmeasured states. Based on DSC backstepping control design technique and incorporated by the predefined performance theory and the average dwell time method, a new adaptive fuzzy output-feedback control method is developed. It is proved that the proposed control approach can ensure that all the signals of the resulting closed-loop system are bounded, and the tracking errors are within the prescribed performance bounds for all times. Simulation studies illustrate the effectiveness of the proposed approach.

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1. Introduction

In the past decades, many approximation-based adaptive fuzzy or neural backstepping controllers have been developed for uncertain non-switched nonlinear systems [1–14]. For example, adaptive fuzzy or neural state-feedback controller have been designed in works [1–7] for nonlinear systems, while observer-based adaptive fuzzy output feedback control approaches have been proposed in works [8–14] for uncertain nonlinear systems by designing state observers. Meanwhile, in an effort to extend the backstepping control idea to larger classes of nonlinear uncertain systems, works [15–18] studied the control problem of nonlinear systems with unknown control directions, dead zones, time delays, and actuator faults, respectively. However, the above schemes are only focused on those non-switched nonlinear systems, instead of the switched nonlinear systems.

Recently, some results on adaptive control for switched systems have appeared in works [19–28]. Works [19–21] with the help of common Lyapunov function method have investigated state-feedback control schemes, for a class of nonlinear switched systems. Under the asynchronous switching, an adaptive state-feedback controller has been proposed in [22] for switched nonlinear systems. Based on multiple Lyapunov functions method, two switched adaptive control technique have been developed in [23,24] for a class of switched nonlinear systems. With all admissible switched strategy, an adaptive neural network feedback control scheme has been developed in [25] for nonlinear switched impulsive systems. By applying average dwell-time technique, works in [26,27] have been investigated switched adaptive control schemes for a class of switched nonlinear systems with time-varying delay, and a robust adaptive fuzzy output feedback control scheme has been constructed in [28] for a class of switched nonlinear systems with unknown dead-zone. Obviously, all the above mentioned adaptive control approaches can ensure that all the signals of the resulting closed-loop system are bounded. However, the tracking performance in the above control methods confined to converge to a small residual set, whose size depends on the design parameters and some unknown bounded terms, they cannot offer the guaranteed transient performance at time instants.

It should be mentioned that the practical engineering often requires the proposed control scheme to satisfy certain quality of the performance indices, such as overshoot, convergence rate, and steady-state error. Prescribed performance control (PPC) issues are extremely challenging and difficult to be achieved, even in the case of the nonlinear switched behavior of the system in the presence of unknown uncertainties and external disturbances. More

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recently, a robust adaptive control for SISO strict feedback nonlinear system and feedback linearizable nonlinear systems with PPC were investigated in [29] and [30]. An output feedback of robust adaptive control was considered in [31] with PPC based on dynamic surface approach. However, the prescribed performance design methodology still not be applied to switched nonlinear systems and the output feedback design for switched nonlinear systems with unknown dead zone is still a challenge.

In this paper, an adaptive fuzzy output feedback DSC design with prescribed performance is developed for a class of uncertain nonlinear systems unknown dead zone. Fuzzy logic systems are used to identifying the unknown nonlinear functions, and a fuzzy switched state observer is designed and thus via it the immeasurable states are obtained. The backstepping DSC design technique and incorporated by the prescribed performance technique, a new adaptive fuzzy prescribed performance output feedback tracking control method is developed. It is shown that all the signals of the resulting closed-loop system are bounded. Moreover, the tracking errors can be kept within the prescribed performance bounds for all the time. Compared with the existed results, the main advantages of the proposed control scheme include the following: (i) the new adaptive fuzzy controller has avoided the requirement that the states must be measurable in previous literatures [19–23], which addressed the adaptive fuzzy or neural control design problem for switched nonlinear systems (state estimation and observer-based stabilization become significant issues in [33,34]); and (ii) by introducing prescribed performance, the proposed adaptive DSC method can not only guarantee the stability of the whole switched control system, but also can ensure that the tracking error converges to a prescribed arbitrarily small residual set for all the times, which cannot be achieved in the previous literature [1–18].

The rest of the paper is organized as follows: The problem statement and preliminaries in Section 2. The switched fuzzy state observer design is given in Section 3. The adaptive fuzzy output-feedback controller design and stability analysis are in Section 4. The simulation example is given in Section 5, and followed by Section 6 which concludes the work.

2. Problem statement and preliminaries

2.1. System statement and assumptions

Consider the following uncertain switched nonlinear system with unknown dead-zone:

$$\begin{cases} \dot{x}_i = x_{i+1} + f_{i,\sigma(t)}(\underline{x}_i) + d_{i,\sigma(t)}(t), \\ i = 1, \dots, n-1, \\ \dot{x}_n = D_{\sigma(t)}(u_{\sigma(t)}) + f_{n,\sigma(t)}(x) + d_{n,\sigma(t)}(t), \\ y = x_1 \end{cases} \tag{1}$$

where $\underline{x}_i = [x_1, x_2, \dots, x_i]^T \in \Re^i$, $i = 1, 2, \dots, n$, $x = \underline{x}_n$, are the states, $y \in \Re$ is the output. The function $\sigma(t) : [0, \infty) \to M = \{1, 2, \dots, m\}$ is a switching signal which is assumed to be a piecewise continuous (from the right) function of time. Moreover, $\sigma(t) = k$ implies that the kth subsystem is active. $f_{i,\sigma(t)}(\underline{x}_i)$ $(i = 1, 2, \dots, n)$ are unknown smooth nonlinear functions. $d_{i,\sigma(t)}(t)$ $(i = 1, 2, \dots, n)$ are dynamic disturbances and satisfy $|d_{i,\sigma(t)}(t)| \le \overline{d}_{i,\sigma(t)}$ with $d_{i,\sigma(t)}$ being known constants. $D_{\sigma(t)}(u_{\sigma(t)}) \in \Re$ is output of the dead zone. In addition, we assume that the state of systems (1) does not jump at the switching instants, i.e., the solution is everywhere continuous, which is a standard assumption in the switched system literatures [26,27].

Similar to [15,32], the output of the dead zone $D_{\sigma(t)}(u_{\sigma(t)})$:

$$D_{\sigma(t)}(u_{\sigma(t)}) \triangleq \begin{cases} m_{r\sigma(t)}(u_{\sigma(t)} - d_{r\sigma(t)}) & \text{if } u_{\sigma(t)} \ge d_{r\sigma(t)} \\ 0 & \text{if } -d_{l\sigma(t)} < u_{\sigma(t)} < d_{r\sigma(t)} \\ m_{l\sigma(t)}(u_{\sigma(t)} + d_{l\sigma(t)}) & \text{if } u_{\sigma(t)} \le -d_{l\sigma(t)} \end{cases} \tag{2}$$

where $u_{\sigma(t)} \in \Re$ is the input to the dead zone; $m_{r\sigma(t)}$ and $m_{l\sigma(t)}$ denote the slope of the dead zone; $d_{r\sigma(t)}$ and $d_{l\sigma(t)}$ represent the dead zone width parameters.

The assumptions for switched system and the dead zone are the following.

Assumption 1 (*Tong and Li [15], Han and Lee [32]*). The dead zone outputs $D_{\sigma(t)}(u_{\sigma(t)})$ are not available for measurement. The dead zone parameters $m_{r\sigma(t)}$, $m_{l\sigma(t)}$, $d_{r\sigma(t)}$ and $d_{l\sigma(t)}$ are unknown, but their signs are known ($m_{r\sigma(t)} > 0$, $m_{l\sigma(t)} > 0$, $d_{r\sigma(t)} \ge 0$ and $d_{l\sigma(t)} \ge 0$, respectively).

Assumption 2 (*Tong and Li [15], Han and Lee [32]*). Dead zone slopes are bounded by known constants $m_{r\min\sigma(t)}$, $m_{r\max\sigma(t)}$, $m_{l\min\sigma(t)}$ and $m_{l\max\sigma(t)}$ such that $0 < m_{r\min\sigma(t)} \le m_{r\sigma(t)} \le m_{r\max\sigma(t)}$ and $0 < m_{l\min\sigma(t)} \le m_{l\sigma(t)} \le m_{l\max\sigma(t)}$.

The dead zone inverse technique is useful for compensating the dead zone effect [15,32]. Setting $u_{d\sigma(t)}$ as the control input from the controller to achieve the control objective for the plant without a dead zone, the following control signal $u_{\sigma(t)}$ is generated according to the certainty equivalence dead zone inverse:

$$u_{\sigma(t)} = D^{-1}_{\sigma(t)}(u_{d\sigma(t)}) = \frac{u_{d\sigma(t)} + \hat{d}_{mr\sigma(t)}}{\hat{m}_{r\sigma(t)}} \delta_{\sigma(t)} + \frac{u_{d\sigma(t)} + \hat{d}_{ml\sigma(t)}}{\hat{m}_{l\sigma(t)}} (1 - \delta_{\sigma(t)}) \tag{3}$$

where $\hat{m}_{r\sigma(t)}$, $\hat{m}_{l\sigma(t)}$, $\hat{d}_{mr\sigma(t)}$ and $\hat{d}_{ml\sigma(t)}$ are estimates of $m_{r\sigma(t)}$, $m_{l\sigma(t)}$, $m_{r\sigma(t)} d_{r\sigma(t)}$ and $m_{l\sigma(t)} d_{l\sigma(t)}$, respectively, and

$$\delta_{\sigma(t)} = \begin{cases} 1 & \text{if } u_{d\sigma(t)} \ge 0 \\ 0 & \text{if } u_{d\sigma(t)} < 0 \end{cases} \tag{4}$$

The resulting errors between $u_{\sigma(t)}$ and $u_{d\sigma(t)}$ are given by

$$\begin{aligned} D_{\sigma(t)}(u_{\sigma(t)}) - u_{d\sigma(t)} &= \left(\tilde{d}_{mr\sigma(t)} - \frac{u_{d\sigma(t)} + \hat{d}_{mr\sigma(t)}}{\hat{m}_{r\sigma(t)}} \tilde{m}_{r\sigma(t)} \right) \delta_{\sigma(t)} + \varepsilon_{d\sigma(t)} \\ &\quad + \left(\tilde{d}_{ml\sigma(t)} - \frac{u_{d\sigma(t)} + \hat{d}_{ml\sigma(t)}}{\hat{m}_{l\sigma(t)}} \tilde{m}_{l\sigma(t)} \right) (1 - \delta_{\sigma(t)}) \end{aligned} \tag{5}$$

where $\tilde{m}_{l\sigma(t)} = \hat{m}_{l\sigma(t)} - m_{l\sigma(t)}$, $\tilde{m}_{r\sigma(t)} = \hat{m}_{r\sigma(t)} - m_{r\sigma(t)}$, $\tilde{d}_{ml\sigma(t)} = \hat{d}_{ml\sigma(t)} - d_{ml\sigma(t)}$ and $\tilde{d}_{mr\sigma(t)} = \hat{d}_{mr\sigma(t)} - d_{mr\sigma(t)}$ are parameter errors. $\varepsilon_{d\sigma(t)}$ can be expressed as $\varepsilon_{d\sigma(t)} = -m_{r\sigma(t)} \chi_{r\sigma(t)} (u_{\sigma(t)} - d_{r\sigma(t)}) - m_{l\sigma(t)} \chi_{l\sigma(t)} (u_{\sigma(t)} - d_{l\sigma(t)})$ and $\varepsilon_{d\sigma(t)}$ is bounded:

$$\chi_{r\sigma(t)} = \begin{cases} 1, & \text{if } 0 \le u_{\sigma(t)} < d_{r\sigma(t)} \\ 0, & \text{otherwise} \end{cases}, \quad \chi_{l\sigma(t)} = \begin{cases} 1, & \text{if } d_{l\sigma(t)} < u_{\sigma(t)} < 0 \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

2.2. Prescribed performance

According to [29], the prescribed performance is achieved by ensuring that each tracking error $\nu(t) = y - y_r$ $(i = 1, 2, \dots, n)$ evolves strictly within prescribed decaying bounds as follows:

$$-\delta_{\min} \mu(t) < \nu(t) < \delta_{\max} \mu(t), \quad \forall t \ge 0, \tag{7}$$

where $\delta_{\min}$ and $\delta_{\max}$ are design constants, and the performance functions $\mu(t)$ are bounded and strictly positive decreasing smooth functions with the property $\lim_{t \to \infty} \mu(t) = \mu_\infty$; $\mu_\infty > 0$ is a constant. In this paper, the performance functions are chosen as the exponential form $\mu(t) = (\mu_0 - \mu_\infty) e^{-at} + \mu_\infty$, where a, μ_0 and μ_∞ are strictly positive constants, $\mu_0 > \mu_\infty$ and $\mu_0 = \mu(0)$ are selected such that $-\delta_{\min} \mu(0) < \nu(0) < \delta_{\max} \mu(0)$ is satisfied. Furthermore, the maximum overshoot of $\nu(t)$ is prescribed less than

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