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Dynamic surface error constrained adaptive fuzzy output-feedback control of uncertain nonlinear systems with unmodeled dynamics ☆

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A B S T R A C T

In this paper, an adaptive fuzzy output-feedback dynamic surface control (DSC) design with prescribed performance is investigated for a class of uncertain nonlinear systems in strict-feedback form. The considered nonlinear systems contain unknown nonlinear functions, unmodeled dynamics and immeasurable states. The fuzzy logic systems are used to model the unknown nonlinear system, and a fuzzy state observer is designed to estimate the immeasurable states. By transforming the errors into new virtual error variables, and based on DSC backstepping design technique and changing supply function, a new robust adaptive fuzzy output feedback control scheme is developed. It is proved that the proposed control approach can guarantee that all the signals of the resulting closed–loop system are bounded, and the dynamic surface errors are confined within the prescribed bounds for all times. Two simulation examples are provided to show the effectiveness of the proposed control approach.

1. Introduction

In the past decade, fuzzy logic systems and neural networks (NNs) theories have received much attention from various fields and also performed nice performance in various applications [1–3]. One important property of fuzzy logic systems and NNs is their universal approximation ability. In other words, fuzzy logic systems and NNs can be approximate any nonlinear functions within a required accuracy provided that enough fuzzy inference rules or NN node number are given. Based on the universal approximation theorem and by incorporating fuzzy logic systems or neural networks into adaptive control schemes, various adaptive fuzzy or NN backstepping control approaches for nonlinear systems have been developed [4–23]. Refs. [4–9] are for single-input and single-output (SISO) nonlinear systems and Refs. [10–16] are for multiple-input and multiple-output (MIMO) nonlinear systems, while Refs. [17–19] are for SISO nonlinear systems and large-scale nonlinear systems with immeasurable states, respectively. Furthermore, adaptive NN and fuzzy backstepping DSC schemes are proposed for uncertain nonlinear systems in Refs. [20–23]. Subsequently, the problem of 'explosion of complexity' inherent in the aforementioned adaptive fuzzy or NN control approaches were overcome. The main features of these adaptive approaches include the following: (i) They can deal with those nonlinear systems without satisfying the matching conditions (i.e., the unknown nonlinearities appear on the same equation as the control input in a state space representation); and (ii) they do not require the unknown nonlinear functions being linearly parameterized. Therefore, approximation-based adaptive fuzzy or NN backstepping control has attracted great interest in intelligent control community.

It is worth pointing out that the control methods [1–23] described previously suffer from their requirement only the unstructured uncertainties are assumed to be present in the nonlinear systems, while the dynamic disturbances and the unmodeled dynamics are neglected. The robust adaptive control for nonlinear systems with unmodeled dynamics is very important in control theory and applications. By using the small-gain theorem, changing supplying function or dynamical signal technique, several adaptive fuzzy or NN control approaches are proposed in [24–26] for a class of SISO nonlinear systems with unmodeled dynamics. The proposed adaptive control methods can not only guarantee the stability of the closed-loop system, but also have the robustness to the unmodeled dynamics. Although the above mentioned adaptive fuzzy or NN control design approaches satisfy the stability for infinite time from the Lyapunov stability theorem, and the tracking performance confined to a small residual set (its size depends on the design parameters and some unknown bounded terms), a prescribed transient and steady-state performance in finite time in these control schemes is very difficult to achieve without depending on trial and error.

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

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steady-state error. Prescribed performance issues are extremely challenging and difficult to be achieved, even in the case of the nonlinear behavior of the system in the presence of unknown uncertainties and external disturbances. A design solution called prescribed performance control for the problem has been proposed in [27] for a class of feedback linearization nonlinear systems and was extended to several classes of nonlinear systems in [28]. After Refs. [27] and [28], an adaptive NN decentralized control approach with prescribed performance is developed for a class of nonlinear large-scale systems with time delays in Ref. [29]. Its main idea is to introduce predefined performance bounds of the tracking errors, and is able to adjust control performance indices. However, to author's best knowledge, by far, the prescribed performance design methodology has not been applied to nonlinear strict-feedback systems with unknown functions, unmodeled dynamics and unmeasured states, which is important and more practical, thus has motivated us for this study.

In this paper, an adaptive fuzzy output-feedback control design with prescribed performance is developed for a class of uncertain SISO nonlinear systems. The considered systems contain unknown functions, unmodeled dynamics and unmeasured states. With the help of fuzzy logic systems identifying the unknown nonlinear systems, a fuzzy adaptive observer is developed to estimate the immeasurable states. The backstepping DSC design technique based on predefined performance bounds is presented to design adaptive fuzzy output feedback controller, and the stability of closed-loop system is proved by using the Lyapunov function method and changing supply function. Moreover, the dynamic surface errors are ensured to remain within the prescribed performance bounds. Compared with the existing results, the main advantages of the proposed control scheme are as follows: (i) the restrictive assumption in Refs. [4–16] that all state variables should be measured directly can be removed by designing a state observer; (ii) by introducing predefined performance, the proposed adaptive control method can ensure that the dynamic surface errors converge to a predefined arbitrarily small residual set for all times and (iii) by incorporated the dynamical signal and DSC design technique into the backstepping design method, the proposed control scheme can not only compensate the unmodeled dynamics, but also overcome the problem of 'explosion of complexity' inherent in the previous adaptive control approaches.

2. System descriptions and preliminaries

2.1. System descriptions and basic assumptions

Consider the following uncertain nonlinear systems with unmodeled dynamics:

$$\begin{cases} \dot{z} = q(z,y) \\ \dot{x}_1 = x_2 + f_1(x_1) + \Delta_1(z,x) \\ \dot{x}_i = x_{i+1} + f_i(\overline{x}_i) + \Delta_i(z,x), i = 2,\cdots,n-1 \\ \dot{x}_n = u + f_n(\overline{x}_n) + \Delta_n(z,x) \\ y = x_1 \end{cases} \tag{1}$$

where $\overline{x}_i = [x_1, x_2, \ldots, x_i]^T$, $i = 1, \ldots, n (x = \overline{x}_n)$; $x_i \in \Re$ are the state variables and $y \in \Re$ is system output, $z \in \Re^a$ is unmodeled dynamics; $u \in \Re$ is the control input, $f_i(\cdot)$ and $\Delta_i(\cdot)$ are unknown smooth functions.

Assumption 1. The unmodeled dynamics is exponentially input-to-state practically stable (exp-ISpS); i.e., the system $\dot{z} = q(z,y)$ has an exp-ISpS Lyapunov function $V_z(z)$, which satisfies [30,31]

$$\underline{\alpha}(|z|) \le V_z(z) \le \overline{\alpha}(|z|) \tag{2}$$

$$\frac{\partial V_z(z)}{\partial z} q(z,y) \le -\overline{c}_0 V_z(z) + \gamma_0(|y|) + d_0 \tag{3}$$

where $\underline{\alpha}(|z|)$, $\overline{\alpha}(|z|)$ are known functions of class k_∞ and $\overline{c}_0 > 0$, $d_0 > 0$ are known constants.

Lemma 1. *If the system $\dot{z} = q(z,y)$ is exp-ISpS, then for any constant $c_0 \in (0, \overline{c}_0)$, any initial condition $z_0 = z(t_0)$ and $r_0 > 0$, there exist a finite $T_0 = T_0(c_0, r_0, z_0) \ge 0$, and a non-negative function $D_0(t_0, t)$ defined for all $t \ge t_0$ and a dynamical signal described by*

$$\dot{r} = -c_0 r + x_1^2 \lambda(x_1^2) + d_0, \; r(t_0) = r_0 \tag{4}$$

such that for all $t \ge t_0 + T_0$, $D_0(t_0, t) = 0$, and for all $t \ge t_0$,

$$V_z(z) \le r(t) + D_0(t_0, t). \tag{5}$$

Assumption 2. For each $1 \le i \le n$, there exist unknown positive constants p_i^* such that [30–32]

$$|\Delta_i(z,x)| \le p_i^* \psi_{i1}(|z|) + p_i^* \psi_{i2}(y) \tag{6}$$

where $\psi_{i1}(|z|)$ and $\psi_{i2}(y)$ are known nonnegative increasing smooth functions with $\psi_{i1}(0) = \psi_{i2}(0) = 0$.

Assumption 3. There exist known constants m_i, $i = 1, 2, \cdots, n$ such that for $\forall X_1, X_2 \in R^i$, the following inequalities hold [25]

$$|f_i(X_1) - f_i(X_2)| \le m_i ||X_1 - X_2|| \tag{7}$$

where $||X||$ denotes the 2-norm of a vector X.

2.2. Prescribed performance

According to Ref. [28], the prescribed performance is achieved by ensuring that each error $s_i(t)$ evolves strictly within predefined decaying bounds as follows:

$$-\delta_{i\,\min} h_i(t) < s_i(t) < \delta_{i\,\max} h_i(t), \quad \forall t \ge 0, \tag{8}$$

where $1 \le i \le n$, $\delta_{i\,\min}$ and $\delta_{i\,\max}$ are design constants, and the performance functions $h_i(t)$ are bounded and strictly positive decreasing smooth functions with the property $\lim_{t\to\infty} h_i(t) = h_{i,\infty}$; $h_{i,\infty} > 0$ is a constant. The performance functions are usually chosen as the exponential form $h_i(t) = (h_{i,0} - h_{i,\infty}) e^{-n_i t} + h_{i,\infty}$, where n_i, $h_{i,0}$, and $h_{i,\infty}$ are strictly positive constants, $h_{i,0} > h_{i,\infty}$, and $h_{i,0} = h_i(0)$ is selected such that $-\delta_{i\,\min} h_i(0) < s_i(0) < \delta_{i\,\max} h_i(0)$ is satisfied. The constant $h_{i,\infty}$ denotes the maximum allowable size of $s_i(t)$ at steady state that is adjustable to an arbitrary small value reflecting the resolution of the measurement device. The decreasing rate n_i represents a lower bound on the required speed of convergence of $s_i(t)$. Furthermore, the maximum overshoot of $s_i(t)$ is prescribed less than $\max\{\delta_{i\,\min} h_i(0), \delta_{i\,\max} h_i(0)\}$. Therefore, choosing the performance function $h_i(t)$ and the constants $\delta_{i\,\min}$, $\delta_{i\,\max}$ determines the performance bounds of the error $s_i(t)$ appropriately.

To represent Eq. (8) by an equality form, an error transformation is employed as

$$s_i(t) = h_i(t) \Phi_i(\zeta_i(t)), \quad \forall t \ge 0$$
$$\Phi_i(\zeta_i) = \frac{\delta_{i\,\max} e^{\zeta_i} - \delta_{i\,\min} e^{-\zeta_i}}{e^{\zeta_i} + e^{-\zeta_i}} \tag{9}$$

Since the function $\Phi_i(\zeta_i)$ is strictly monotonic increasing, its inverse function can be expressed as

$$\zeta_i(t) = \Phi_i^{-1}\left(\frac{s_i(t)}{h_i(t)}\right) = \frac{1}{2} \ln \frac{\Phi_i - \delta_{i\,\min}}{\delta_{i\,\max} - \Phi_i} \tag{10}$$

and

$$\dot{\zeta}_i(t) = \upsilon_i \left(\dot{s}_i(t) - \frac{\dot{h}_i s_i(t)}{h_i} \right) \tag{11}$$

with $\upsilon_i = \frac{1}{2h_i}\left[\frac{1}{\Phi_i + \delta_{i\,\min}} - \frac{1}{\Phi_i - \delta_{i\,\max}}\right]$.