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Observer-based adaptive prescribed performance tracking control for nonlinear systems with unknown control direction and input saturation

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ABSTRACT

In this paper, the problem of observer-based adaptive tracking control is investigated for a class of nonlinear systems with unknown control direction, input saturation and tracking error constraint. The Nussbaum function is employed to address the unknown control direction and a state observer is constructed by neural networks (NNs) to estimate the unmeasurable states. A new error constraint transformation is proposed to guarantee that the tracking error satisfies the prescribed performance. Then, a novel adaptive prescribed performance neural network (NN) output feedback tracking control method is designed. It is proved that the designed controller can guarantee the boundedness of all the signals in the closed-loop system and the prescribed time-varying tracking performance. Finally, simulations on two examples are performed to illustrate the efficiency of the proposed control method.

1. Introduction

Recently, due to the unique properties of neural networks (NNs) and fuzzy logic systems (FLSs), NNs and FLSs have been in rapid progress and applied widely to approximate any unknown smooth nonlinear function [1–3]. To solve the unknown nonlinearity in control design of nonlinear systems, many control approaches based on NNs or FLSs have been proposed in [4–10]. An NN based robust adaptive decentralized control method was designed for interconnected nonlinear systems in [11]. In [12], an adaptive actor-critic NN control scheme was presented for continuous-time nonlinear systems with input quantization. In [13], a novel adaptive NN active control approach was presented for large-scale nonlinear systems with nonstrict-feedback form.

Note that many practical systems have the requirement that the control design should satisfy certain performance. However, many previous designed control methods only can guarantee the asymptotic convergence of the closed-loop system signals through Lyapunov method. In such a situation, performance constraint was presented to guarantee the performance requirement. The demand of control system performance improvement motivates the development of control methods to deal with the performance constraint problem. Up to now, there have been mainly three methods to deal with the performance constraint problem, which include a barrier Lyapunov function (BLF) method [14], a funnel control method [15] and an error transformation method [16]. A logarithmic function was proposed to deal with the output constraint problem in [14]. The error constraint was handled by using a proper funnel boundary in [15]. In [16], the error constraint was satisfied by presenting a prescribed performance function and conducting an error transformation. Recently, many research results have been published to settle the performance constraint problem with an error transformation method, see [17–20] and the references therein.

In addition, the control system inputs are normally limited by saturation, dead-zone or backlash. The input saturation may potentially and severely influence the system performance, even cause system instability. To address the tremendous challenge brought by the problem of control input saturation, in the past decades, several control design methods have been studied in [21–25]. Furthermore, the control input direction unknown is another commonly encountered problem in control design. Hence, it is meaningful to research on the control direction unknown problem [26–30]. In [27], a popular method using the Nussbaum function was proposed to solve the control direction unknown problem. A global

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adaptive control scheme using the Nussbaum function was designed for nonlinear systems in [28]. Effective adaptive NN control schemes based on the Nussbaum function were proposed in [29,30].

It is known that the control problem for linear systems [31,38] and the control problem for nonlinear systems [3] are two main research directions of control theory. While, it is the fact that nonlinearities exist in a variety of practical systems, for examples, hydraulic equipment systems, chemical process reactor systems, electrical network systems and so forth. Hence, the research for nonlinear systems is a significative problem. At the same time, many real systems confront the situation that some of the system states are unknown and unavailable. Then, the study of state estimator which is employed to estimate the unmeasured states has attracted many attentions [32–37]. Furthermore, the tracking control problem is often encountered in practical systems, then it is of great practical significance to solve the tracking control problem [9,12,16,21,38]. To the best of our knowledge, the published works have investigated the control problem of nonlinear systems with control direction unknown, but there is no work published for nonlinear systems with unavailable states, unknown control direction and performance constraint.

Motivated by the earlier observations, the adaptive NN control with prescribed performance is proposed for a class of strict-feedback nonlinear systems. The considered nonlinear system consists of unavailable states, input saturation, unknown nonlinearities and unknown control direction. The unknown smooth nonlinearities are identified by NNs and the control direction unknown problem is processed through the Nussbaum function. An observer based on NNs is proposed for estimation of the unavailable system states and a new error constraint transformation is used to guarantee the prescribed time-varying performance. An effective adaptive prescribed performance NN output feedback tracking control approach is designed. The stability of the closed-loop system is guaranteed through Lyapunov theory. The main contributions of this paper are summarized as follows:

(1) Compared with [7], the unknown nonlinear functions are not needed to satisfy the Lipschitz condition in this paper.
(2) Compared with [16], a new error constraint transformation is proposed, which does not need the calculation of inverse function and logarithmic function.
(3) The designed output feedback control scheme can tackle the effect of input saturation and unknown control direction, and guarantee the prescribed tracking performance.

The rest of this paper is organized as follows. Problem statement and preliminaries are given in Section 2. Section 3 shows the main results where the control design and theorem are proposed. In Section 4, simulation examples are proposed. Section 5 is ended by the conclusion.

2. Problem statement and preliminaries

Consider the following nonlinear system with input saturation and unknown control direction

$$\dot{X}_i = F_i(\bar{X}_i) + X_{i+1} + D_i(t),\ \ i = 1, \dots, n-1$$
$$\dot{X}_n = F_n(\bar{X}_n) + bu + D_n(t)$$
$$y = X_1 \tag{1}$$

where $\bar{X}_i = [X_1, X_2, \dots, X_i]^T \in R^i$ with $i = 1, 2, \dots, n$. $X = \bar{X}_n = [X_1, X_2, \dots, X_n]^T \in R^n$ and $y \in R$ are the system states and output, respectively. b is an unknown control coefficient. $F_i(\bar{X}_i)$ is an unknown smooth nonlinear function and $D_i(t)$ is a time-varying disturbance. Note that in this paper, we omit the subscript for simplicity whenever no confusion can arise.

Remark 1. In this paper, the considered nonlinear system (1) can be used to govern many practical plants, for examples, inverted pendulums [17], spring, mass and damper systems [24] and two stirred isothermal tank reactors [25]. It is worth mentioning that the problem of unknown control directions has been studied for decades in the area of adaptive control [28]. In several practical applications, the control directions could not always be known [17]. For instance, ship systems with unknown control direction was studied in [29].

The actual control input u satisfies the saturation function $sat(v)$ described as follows:

$$u = sat(v) = \begin{cases} u_m sign(v), & |v| \geq u_m \\ v, & |v| < u_m \end{cases} \tag{2}$$

where u_m is a known saturation bound and $sign(\cdot)$ is a sign function. An approximation is employed to process the sharp corners of $sat(v)$, then the input saturation is rewritten as

$$u = sat(v) = g(v) + \delta(v) \tag{3}$$

where $g(v) = u_m \tanh(v/u_m)$ and $\delta(v) = sat(v) - g(v)$ with $|\delta(v)| \leq u_m(1 - \tanh(1)) = \delta^*$.

The control objective is to design an adaptive NN output feedback control scheme so that the output tracking error satisfies the desired time-varying tracking performance when the system (1) suffers from the unknown control direction and input saturation.

Define the new state variable $x_i = \frac{X_i}{b}$, the new smooth function $f_i(\bar{x}_i) = \frac{F_i(\bar{X}_i)}{b}$ and the new disturbance $d_i(t) = \frac{D_i(t)}{b}$, then system (1) converts to the following system:

$$\dot{x}_i = f_i(\bar{x}_i) + x_{i+1} + d_i(t),\ \ i = 1, \dots, n-1$$
$$\dot{x}_n = f_n(\bar{x}_n) + u + d_n(t) \tag{4}$$

where $\bar{x}_i = [x_1, x_2, \dots, x_i]^T \in R^i$, $i = 1, 2, \dots, n$.

The following assumptions are presented for system (4).

Assumption 1. The desired trajectory y_r and its derivatives are available and bounded.

Assumption 2. The constant b and its sign are unknown, and there exist positive constants b_l and b_u, such that $b_l \leq |b| \leq b_u$.

Assumption 3. There exists an unknown positive constant $\bar{d}_i$, such that $|d_i(t)| \leq \bar{d}_i$.

Remark 2. According to the transformation $d_i(t) = \frac{D_i(t)}{b}$, Assumption 3 is also tenable for system (1) with b being an unknown constant, i.e. $|D_i(t)| \leq \bar{D}_i$, where $\bar{D}_i$ is an unknown positive constant.

Remark 3. The assumptions proposed above have been widely used in [21,26]. Assumptions 1 and 2 are frequently used to address the control direction unknown problem. Assumption 3 is quite general used to handle the unknown time-varying disturbance term.

In this paper, the radial basis function (RBF) NN [2] is employed to approximate any unknown nonlinear function $\varphi(Z)$ as the following form:

$$\varphi_{nn}(Z) = W^T S(Z) \tag{5}$$

where $Z \in \Omega_Z \subset R^q$ and $W = [w_1, w_2, \dots, w_l]^T \subset R^l$ are the input vector and weight vector, respectively. $S(Z) = [s_1(Z), s_2(Z), \dots, s_l(Z)]^T \subset R^l$ is the regress vector with $s_i(Z)$ commonly chosen as

$$s_i(Z) = \exp\left[\frac{-(Z - \xi_i)^T (Z - \xi_i)}{\eta_i^2}\right],\ \ i = 1, 2, \dots, l \tag{6}$$