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Sampled-data adaptive prescribed performance control of a class of nonlinear systems

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ABSTRACT

This paper investigates the sampled-data adaptive control problem for a class of nonlinear systems with prescribed performance. The radial basis function neural networks are employed to approximate the unknown function in controller design procedure. The sampled-data controller and adaptive laws are designed by backstepping design technique, and an explicit formula for the allowable sampling period is derived. The proposed controller can guarantee that all the signals in the closed-loop system are semi-globally uniformly ultimately bounded, and the system output satisfies the prescribed performance. Finally, two examples are given to illustrate the effectiveness of the proposed approach.

1. Introduction

Since the control of systems is usually realized by a digital computer, the sampled-data control technique has been widely used in practical engineering. The sampled-data control system consists of continuous-time plants and discrete-time controllers. Due to the advantages of cost savings and implementation simplicity, it is of great importance to the study on the sampled-data control problem. In recent years, scholars have done many researches on sample-data control system [1–19]. The distributed sampled-data control problem of a group of mobile robots connected via distance-induced proximity networks was considered in [1]. By T–S fuzzy model, a direct discrete-time design methodology of a robust sampled-data fuzzy controller for a class of nonlinear system with parametric uncertainties was represented in [2]. In [3], the guaranteed cost control problem of a class of parabolic PDE systems was investigated via finite dimensional sampled-data fuzzy control approach. A fuzzy guaranteed cost sampled-data control scheme was proposed for a class of nonlinear coupled ODE-PDE systems. The sampled-data fuzzy control of nonlinear systems in strict feedback form with disturbances and random missing input data was considered in [5]. The sampled-data synchronization control scheme was proposed for complex dynamical networks with time-varying coupling delay in [6]. The stability analysis of nonlinear sampled-data systems which were affine in the input was investigated in [7]. The problem of robust finite-time sampled-data control of linear systems subject to random occurring delays and its application to Four-Tank system was studied in [8]. The sampled-data consensus problem for a class of nonlinear multi-agent systems subject to cyber attacks was discussed in [9]. Some output feedback sampled-data control schemes were proposed in [10–15]. The problem of sampled-data output feedback control was investigated for a class of uncertain nonlinear systems in [10]. A global output feedback stabilization control method for a class of feedforward nonlinear systems via linear sampled-data control was presented in [11]. In [12], a systematic design scheme was developed to construct a linear sampled-data output feedback controller that semi-globally asymptotically could stabilize a class of uncertain systems with both higher-order and linear growth nonlinearities. Using a sampled-data output feedback controller, the problem of global output feedback stabilization for a class of nonlinear systems in the presence of uncertain measurement and control gains was solved in [13]. Global practical tracking via sampled-data output feedback control scheme was proposed for a class of uncertain nonlinear systems, and a new sampled-data compensator was constructed to design the sampled-data controller in [14]. In [15], a global sampled-data output-feedback stabilization control method was presented for a class of SNSs whose nonlinear terms may not satisfy Lipschitz conditions. The problem of finite-time sampled-data control for switching T–S fuzzy systems was discussed in [16]. A stochastic sampled-data stabilization

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control method was proposed for neural-network based control systems with an optimal guaranteed cost in [17]. A robust sampled-data controller for a class of nonlinear parametric uncertain systems with constraints on the output imposed by time-domain performances was presented in [18]. The problem of state estimation of Takagi–Sugeno fuzzy delayed neural networks with Markovian jumping parameters via sampled-data control was studied in [19]. Some results have been also achieved in the study of the adaptive sampled-data control. Wu and Ding proposed a sampled-data adaptive control scheme for a class of nonlinear systems in [20]. The problem of stable sampled-data adaptive control of robot arms was studied by using neural networks in [21].

Since the prescribed performance control considers the transient performance of the systems and the steady state simultaneously, it has become research hotspot. The concept of prescribed performance control was proposed in [22]. The prescribed performance means that the tracking error should converge to an arbitrarily predefined small residual set, with convergence rate no less than a prespecified value, exhibiting a maximum overshoot less than a sufficiently small prespecified constant. The adaptive output feedback control problems of nonlinear systems with prescribed performance were considered in [23–26]. An adaptive fuzzy decentralized output-feedback control method was proposed for a class of nonlinear large-scale systems in [23]. In [24], the decentralized output feedback adaptive NN tracking control problem for interconnected nonlinear time-delay systems with prescribed performance was discussed. For a class of nonlinear systems with unmeasurable states, prescribed performance tracking error constraint, and output dead zone, an adaptive NN backstepping output feedback tracking control scheme was proposed in [25]. Based on dynamic surface control technique, the adaptive prescribed performance tracking control problem for a class of output feedback nonlinear systems with input unmodeled dynamics was solved in [26]. A fractional-order adaptive fuzzy controller was designed for a class of uncertain fractional-order nonlinear systems with external disturbances and prescribed performance in [27]. The adaptive fuzzy prescribed performance control problem of MIMO nonlinear systems with unknown control direction and unknown dead-zone inputs was discussed in [28]. An alternative adaptive prescribed performance control scheme with prescribed was proposed to address the output tracking of nonlinear systems with a nonlinear dead zone input in [29]. The adaptive prescribed performance motion control of servo mechanisms with friction compensation was studied in [30]. In [31], an adaptive prescribed performance control method was proposed for vehicle active suspensions with unknown nonlinearities. Some adaptive prescribed performance control schemes were proposed for switched nonlinear systems in [32–36]. In [32], the tracking control design problem for a class of switched nonlinear systems with unknown dead zone was investigated. For a class of uncertain nonlinear switched uncertain nonlinear large-scale systems with unknown dead-zones and unmeasured states, an adaptive fuzzy output-feedback decentralized control scheme was proposed in [33]. In [34], an output feedback control method with prescribed performance was presented for SISO switched non-strict-feedback nonlinear systems. The prescribed performance adaptive fuzzy output-feedback control problem for a class of uncertain MIMO switched nonlinear systems with unmeasured states was discussed in [35]. An adaptive prescribed performance control scheme was proposed for a class of switched uncertain nonlinear systems under arbitrary switching signals in [36].

Although the output feedback control for nonlinear systems with guaranteed prescribed performance has been addressed, some challenging questions arise: when the systems contain unmodeled dynamics, can we still achieve stabilization for the nonlinear systems? Moreover, if the input of the nonlinear system is implemented in discrete-time context, how can we design the sampled-data controller? This paper will address these questions. The main contributions are summarized as follows:

(i) The restrictions on the nonlinear functions in some existing literature are relaxed. Meanwhile, both steady state and transient performance of the systems are considered simultaneously by employing the prescribed performance control.
(ii) The adaptive sampled-data control problem for the nonlinear system with unmodeled dynamics is firstly investigated.
(iii) Under the sampled-data controller, the stability of the corresponding closed-loop system is developed and the allowable sampling period is derived.

The remainder of the paper is organized as follows. In Section 2, the system description and the preliminary knowledge are given. The sampled-data adaptive prescribed performance control results are derived in Section 3. Two simulation examples show the effectiveness of the proposed method in Section 4. Finally, this paper is concluded in Section 5.

Notations: R denotes the set of all real numbers; R^n denotes the real n-dimensional space; $R^{m\times n}$ denotes the real $m\times n$ matrix space; $\|\cdot\|$ denotes the Euclidean norm. The argument of the functions will be omitted throughout the paper for simplicity whenever no confusion arises, such as functions V, x_1 and $\hat{x}_1$ to be used hereafter.

2. Problem statement and preliminaries

2.1. System descriptions and assumptions

Consider the following uncertain nonlinear system:

$$\begin{cases} \dot{\xi} = q(\xi, x), \\ \dot{x}_i = x_{i+1} + f_i(x) + \Delta_i(\xi, x), \ \ i = 1, 2, \dots, n-1, \\ \dot{x}_n = u + f_n(x) + \Delta_n(\xi, x), \\ y = x_1, \end{cases} \tag{1}$$

where $y\in R$ is the output of the system; $x = [x_1, \dots, x_n]^T \in R^n$ is the system state; $\xi \in R^{n_0}$ is the unmodeled dynamics; $f_i(x)$ is the unknown smooth function, $f_i(0) = 0$; $\Delta_i(\xi, x)$ is the unknown nonlinear dynamic disturbance, $\Delta_i(0, 0) = 0$; $q(\xi, x)$ is an unknown Lipschitz function. Only the system output y is available, the states $x_2, \dots, x_n$ are unmeasurable. u is the input of the system which takes the following sampled-data controller

$$u(t) = u(t_k), \ \ \forall t \in [t_k, t_{k+1}),$$

where $t_k = kT, \ \ k = 0, 1, 2, \dots,$ and t_{k+1} are the sampling points and T is the sampling period.

Remark 1. Many practical nonlinear systems, such as the mass-spring-damper system and the electromechanical system, can be described as system (1). The sampled-data control provides the advantages of cost savings and implementation simplicity in practice. Therefore, it is of great importance to study the sampled-data control of system (1).

We make the following assumptions.

Assumption 1 [37]**.** There exist unknown nonnegative continuous functions $\phi_{i1}(\cdot)$ and $\phi_{i2}(\cdot)$ for each $i = 1, 2, \dots, n,$ such that

$$|\Delta_i(\xi, x)| \ \leq \phi_{i1}(\|x\|) + \phi_{i2}(\|\xi\|). \tag{2}$$

Remark 2. It should be pointed out that Assumption 1 is a common assumption, the assumption can be found in existing literature such as [43–46].