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Adaptive prescribed performance control of output feedback systems including input unmodeled dynamics

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ABSTRACT

In this paper, an adaptive prescribed performance tracking control scheme is investigated for a class of output feedback nonlinear systems with input unmodeled dynamics based on dynamic surface control method. A transformation with respect to tracking error is introduced to implement prescribed performance tracking control. A novel description based on Lyapunov function for unmodeled dynamics is presented to deal with state unmodeled dynamics. The negative impact of nonlinear input unmodeled dynamics is offset by using a normalization signal. With the aid of Nussbaum function, the unknown control gain sign is effectively handled in the controller design. By the theoretical analysis, not only the signals in the closed-loop system are proved to be semi-globally uniformly ultimately bounded, but also the transient tracking performance can be guaranteed. Two simulation examples are provided to show the effectiveness of the proposed approach.

1. Introduction

Dynamic surface control (DSC) was firstly proposed for a class of nonlinear systems in [1]. Compared with backstepping method, DSC does not need repeated derivative to virtual control, and does not need to assume the approximation error to be bounded before the system stability being proved. These two kinds of improvements greatly simplify the original design deduction and effectively avoid the circular argument in backstepping. In the past decades, DSC has been widely applied to adaptive controller design for nonlinear systems. In [2], a neural adaptive dynamic surface control scheme was proposed for nonlinear systems in strict feedback form. In [3], robust adaptive control was designed for a class of uncertain pure-feedback nonlinear systems with unknown dead zone. In [4,5], using the states of K-filters to estimate unmeasured system states, two adaptive fuzzy output feedback control schemes were investigated for a class of uncertain nonlinear systems.

Since unmodeled dynamics widely exists in practical control systems and may have some negative impact on the stability of the system, it has attracted many scholars' attention. Two methods for handling unmodeled dynamics were presented in [6,7]. One is using dynamic signal to restrict unmodeled dynamics, which is based on the assumption that the unmodeled dynamics is exponentially input-state practically stable. Another is utilizing Lyapunov function to describe unmodeled dynamics, which is based on the assumption that the unmodeled dynamics is global exponential stability. By introducing dynamic signal, robust adaptive fuzzy control was proposed for a class of nonlinear systems with unmodeled dynamics in [8]. Model predictive control was realized for a class of discrete nonlinear systems with the linear residual error of unmodeled dynamics being modeled through learning machine supervised learning in [9]. Using the method in [7], a neural adaptive tracking control scheme was proposed for a class of pure-feedback nonlinear systems with unmodeled dynamics and unknown gain signs in [10]. To handle the unmodeled dynamics in output feedback nonlinear systems, a novel Lyapunov function based description about unmodeled dynamics was given in [11], and using DSC, adaptive output feedback control was investigated for a class of uncertain nonlinear systems. In [12], using recurrent wavelet neural networks, adaptive backstepping control scheme was developed for a class of nonlinear systems with an unknown external disturbance being considered. In [13–16], with backstepping-sliding-mode control or optimization methods, adaptive control was investigated for power systems or multi-agent dynamic systems.

Input unmodeled dynamics is used to generalize modeling error and extra disturbance in actuator. The main instabi-

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lity mechanism brought to the control system by linear input unmodeled dynamics was revealed in [17,18], and combining backstepping method with dynamic nonlinear damping design, global asymptotic stability problems were solved for a class of systems in strict feedback and output feedback form with stable linear input unmodeled dynamics. Based on the assumption that the considered nonlinear input unmodeled dynamics is of stable zero dynamics, a normalization signal was employed in control law to counteract the impact of input unmodeled dynamics on systems in [19], however, input control gain was assumed to be known. Under the assumption that the input unmodeled dynamics possesses minimum phase and relative degree zero, output feedback control was developed by designing a dynamic compensator for a class of nonlinear systems with input unmodeled dynamics in [20]. In [21], using a special small gain theorem to prove the local stability, a nested saturation controller was designed and the global convergence stability was studied for a class of nonlinear systems with input unmodeled dynamics in strict feed forward form. Utilizing K-filters or MT-filters, two decentralized output feedback adaptive control schemes were investigated for uncertain systems with input and output dynamic interactions based on backstepping method in [22,23]. In the above literature, almost the design methods used are not dynamic surface control.

In recent years, the systems with prescribed performance have been paid much attention to. The systems are required to satisfy steady performance and transient performance simultaneously. It means that at the meantime of guaranteeing the tracking error converging to predefined arbitrary small residual set, the convergence rate is no less than a pre-set value, and maximum overshoot and undershoot are exhibited to be less than some sufficiently small preassigned constants. Commonly, the prescribed performance is regarded as the constraints to tracking error, and the key idea for studying constrained nonlinear system is constructing an error transformation to transform the constrained system into an equivalent unconstrained one. This idea was first proposed and applied to design adaptive controller in [24,25]. Based on backstepping and fuzzy approximation technique, improved adaptive control was proposed for a strict feedback dynamic nonlinear system with prescribed performance in [26]. By introducing a new state transformation, a prescribed performance output feedback controller was designed for interconnected time-delay systems in [27]. Utilizing an output error transformation, a switching adaptive control scheme was proposed to achieve preset performance in [28]. By constructing a continuous dynamic switching type controller, the prescribed performance bounds of the systems output and the boundedness of all other closed-loop signals were guaranteed in [29]. Prescribed performance control was further developed towards realizing tracking control for flexible joint robots with unknown time-varying elasticity, robot-motor dynamics and prescribed performance attributes on the link position error in [30]. Owing to a performance function and an output error transformation, a backstepping controller was designed for a class of strict feedback nonlinear systems with prescribed performance in [31]. On the basis of [31], an error transformation, which eliminates the limitation of initial error being known, was presented, and the prescribed performance control problem was discussed for similar systems with unknown control gains in [32]. Based on DSC and the given prescribed performance bounds, fuzzy adaptive decentralized control was proposed for a class of output feedback nonlinear large-scale systems with unknown time-varying delays and unstructured uncertainties in [33]. Adaptive control was designed for a continuously differentiable friction model with guaranteed transient and steady-state performance in [34]. By using the dynamical signal and changing supply function to handle unmodeled dynamics and combining backstepping with predefined performance technique, a robust fuzzy output feedback control scheme was constructed for a class of uncertain nonlinear systems in [35]. In [36], based on DSC design and changing supply function, new adaptive fuzzy output feedback prescribed constraint control was developed for a class of uncertain nonlinear systems with unmodeled dynamics and strict-feedback form. In most of the above literature, the effects of unmodeled dynamics on system performance were not considered in the controller design, and the main method adopted in controller design was backstepping technique in [26,27,31,32,35]. Only the regulation problem of the system was concerned with for prescribed performance control in [27,33,35,36].

Inspired by [19,25], adaptive output feedback tracking control is developed for a class of uncertain nonlinear systems with state and input unmodeled dynamics as well as prescribed performance based on dynamic surface control. The main contributions in this paper are summarized as follows:

(i) To achieve prescribed tracking performance, a conversion function about prescribed performance function and tracking error are added into the first dynamic surface. Through this transformation, a prescribed performance tracking control problem is changed into a normal tracking control problem. Therefore, combining K-filters with dynamic surface control, both steady-state and transient prescribed performance of the system can be preserved.
(ii) We consider the output feedback nonlinear systems with nonlinear unmodeled dynamics in the input. Under the Assumptions similar to [19], a normalization signal $\overline{m}(t)$ is designed and appended to the virtual controller, which can effectively counteract the instability influence of input unmodeled dynamics. Compared with [19], related hypothesis are broaden in this paper. For example, nonlinear functions and constants of input unmodeled dynamic subsystem do not need to be known in this paper, however, $\overline{c}_{\Delta}$, the sign of d_{Δ} and input gain sign were all known in [19].
(iii) In general theoretical analysis of dynamic surface control method, the hyper-radius determined by the defined compact set is equal to the initial value of the total Lyapunov function, which easily leads to the boundedness of black-box functions. However, in this paper, due to the method for handling the unmodeled dynamics, the above equal relationship does not exist, so the first task of the theoretical analysis is to establish the mathematical relationship between hypersphere radius and initial value of the Lyapunov function. With the task completed, this work extends the existing stability analysis method under dynamic surface control. Based on this improved method, all the signals in the closed-loop system are proved to be semi-globally uniformly ultimately bounded.

This paper is organized as follows. In Section 2, the problem description and basic assumptions are presented. In Section 3, K-filters are designed based on neural networks. Prescribed tracking performance is analyzed in Section 4. Adaptive neural tracking control is developed based on dynamic surface control and Nussbaum functions. The closed-loop system stability is analyzed through constructing appropriate Lyapunov function in Section 5. Two simulation examples are used to demonstrate the effectiveness of the approach in Section 6. Section 7 contains the conclusions.