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Dynamic learning from adaptive neural control with predefined performance for a class of nonlinear systems

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ABSTRACT

In this paper, a neural learning mechanism is presented for a class of single-input–single-output (SISO) uncertain nonlinear systems, which can achieve knowledge acquisition, storage and reuse of the unknown system dynamics as well as the predefined tracking error behavior bound. Using the novel transformed function, the constrained tracking control problem of the original nonlinear system is transformed into the stabilization problem of an augmented system. By combining a filter tracking error with the universal approximation capabilities of radial basis function (RBF) neural networks (NNs), a stable adaptive neural control (ANC) scheme is proposed to guarantee the ultimate boundedness of all the signals in the closed-loop system and the prescribed transient and steady tracking control performance. In the steady control process, a partial persistent excitation (PE) condition of RBF NNs is satisfied during tracking control to recurrent reference orbits. Consequently, it is shown that the proposed ANC scheme can acquire and store knowledge of the unknown system dynamics. The stored knowledge is reused to develop neural learning control, so that the improved control performance with the faster tracking convergence rate and the less computational burden is achieved, while guaranteeing the prescribed transient and steady tracking performance when the initial condition satisfies the prescribed performance bound. Simulation studies are performed to demonstrate and verify the effectiveness of the proposed scheme.

1. Introduction

In the past decades, adaptive control has attracted much attention in both control theory and industrial applications [8,14,16,17,22,28,29,47]. Recently, adaptive control has been a mature research area in the control community. In the early stage of adaptive control, nonlinearities are usually assumed to have the prior knowledge of the bound or can be linearly parameterized [17,22,28,29]. The real systems may rarely satisfy such an assumption due to the existence of modeling errors. Neural networks and fuzzy logic systems, as the universal approximators, have been found to be particularly suitable for handling systems with uncertain nonlinearities [25,27,46]. By combining the universal approximators and adaptive control techniques, a lot of research results and successful applications have been reported [6,9,11,23,26,34–36,39,41–43,45] to guarantee the stability and tracking performance of various classes of nonlinear systems. The approximated-based adaptive

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control method was further extended to solve the tracking control problem for a class of nonlinear systems with only system output being measurable [12,31–33]. Traditionally, the tracking performance is confined to guarantee that the tracking error converges to a small residual set, whose size depends on design parameters and some unknown bounded terms. However, the practical engineering often requires the proposed control scheme to satisfy certain prespecified transient and steady-state tracking performance (such as overshoot, convergence rate and convergence accuracy). Prespecified performance issues are extremely challenging and difficult to be achieved, even in the case of known linearities and nonlinearities [21,44]. More recently, the problem was solved for a class of feedback linearizable nonlinear systems using adaptive control with prescribed performance [3,4]. The proposed method was further applied to solve the robot force/position tracking control problem [5].

Another important issue associated with approximated-based adaptive control is the learning ability. The learning ability is one of the fundamental attributes of the autonomous control system [2,10], which is closely related to the issue of parameter convergence in the areas of system identification and adaptive control [1,22]. However, the traditional approximation-based adaptive control focuses on the system stability through online adjustment of controller parameters which are not required to converge to their optimal values. As a result, in the steady control process, the optimal parameter values cannot be stored, so that the parameter estimates have to be re-adapted even for repeating exactly the same control task, which causes unnecessary waste of energy and time. In this sense, the learning ability of the traditional approximation-based adaptive control is very limited [2]. As indicated in [10,38], approximation-based adaptive control including ANC, initially motivated by learning abilities of human beings, should at least possess the abilities of "learning by doing" and "doing with the learned knowledge". However, how to gain knowledge about a dynamic closed-loop control process is an extremely challenging problem. Further, how to store the learned knowledge in the steady control process and how to exploit the stored knowledge for the improved control performance are important problems in the control community.

Fortunately, based on the previous works on system identification and adaptive control [1,22], it is shown that, to achieve accurate parameter convergence, the persistent excitation (PE) condition is normally required to be satisfied. However, it is very difficult to establish the PE condition in dynamical nonlinear systems. Recently, the difficulty has been overcome in [38] by the following two steps: (1) adaptive neural control is developed to achieve tracking convergence of the second-order Brunovsky system states to the recurrent reference orbits, so that the internal system states become recurrent signals and (2) combining the obtained tracking convergence with the associated properties of localized RBF networks (such as the linear-in-parameter form, the function approximation ability, the spatially localized structure), a partial PE condition of the regression subvector constructed out of the RBFs along the recurrent tracking orbit is subsequently satisfied. With the partial PE condition satisfied, authors in [38] proved, for the neurons centered close to the tracking orbit, their neural weights will exponentially converge to optimal values, and be stored as past experience for reusing to the similar or same control task. The proposed method in [38] is called as "deterministic learning", and further extended to high-order nonlinear systems by combining a state transformation [19,40]. Some applications, such as oscillation faults diagnosis [37], ocean surface ship [7], have been presented using the deterministic learning algorithm. So far, the deterministic learning algorithm provides an efficient solution to the problem of learning in dynamic environment, but the problem of designing an adaptive neural control scheme, which is able to make the tracking error converge to a predefined arbitrarily small residual set with the prespecified convergence rate and overshoot and achieve storage and reuse of the optimal neural weight values for achieving the improved control performance of the same or similar control task, still remains challenging.

In this paper, we propose a novel neural learning mechanism for a class of SISO nonlinear systems with unknown nonlinearities, which is capable of guaranteeing the prescribed transient and steady tracking control performance, and achieving knowledge acquisition, storage and reuse of the unknown system dynamics. To achieve the constrained tracking error, a novel transformed function is constructed to transform the constrained tracking control problem into the unconstrained stabilization control problem. Subsequently, a filtered tracking error is introduced to simplify the adaptive neural controller design, and the RBF NN is used to approximate the unknown system dynamics. And then, a stable adaptive neural controller is proposed to guarantee the prescribed tracking control performance. Under the steady control process, the internal system states become recurrent signals based on the recurrent reference orbits, and the partial PE condition of RBF NNs is subsequently satisfied. By combining a state transformation, an accurate neural approximation of the unknown system dynamics is achieved along recurrent reference orbits. The learned knowledge on unknown system dynamics is stored in the constant RBF NNs. Subsequently, the neural learning controller that effectively exploits the learned knowledge without re-adapting to the controller parameters is proposed to achieve the improved control performance for the same or similar control task, while guarantee the prescribed performance.

The rest of the paper is organized as follows. Section 2 gives the problem formulation and preliminaries. In Section 3, adaptive neural control is proposed to guarantee the stability of the closed-loop system and the prescribed transient and steady tracking control performance. The designed adaptive neural controller with predefined control performance is shown to be capable of achieving the knowledge acquisition, expression and storage of unknown system dynamics in the steady control process, and the stored knowledge can be reused to achieve the improved control performance in Section 4. In Section 5, simulation studies are performed to show the effectiveness of the proposed method. The conclusions are included in Section 6.