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Adaptive neural control of MIMO nonlinear state time-varying delay systems with unknown dead-zones and gain signs ☆

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Abstract

In this paper, adaptive neural control is proposed for a class of uncertain multi-input multi-output (MIMO) nonlinear state time-varying delay systems in a triangular control structure with unknown nonlinear dead-zones and gain signs. The design is based on the principle of sliding mode control and the use of Nussbaum-type functions in solving the problem of the completely unknown control directions. The unknown time-varying delays are compensated for using appropriate Lyapunov–Krasovskii functionals in the design. The approach removes the assumption of linear functions outside the deadband as an added contribution. By utilizing the integral Lyapunov function and introducing an adaptive compensation term for the upper bound of the residual and optimal approximation error as well as the dead-zone disturbance, the closed-loop control system is proved to be semi-globally uniformly ultimately bounded. Simulation results demonstrate the effectiveness of the approach.

Keywords: Adaptive control; Neural networks; Sliding mode control; Dead-zone; Nonlinear time-varying delay systems

1. Introduction

In the past decade, adaptive control system design of nonlinear systems using universal function approximators has received a great deal of attention (Ge, Hang, Lee, & Zhang, 2001; Lee & Tomizuka, 2000; Sanner & Slotine, 1992; Su & Stepanenko, 1994; Yesildirek & Lewis, 1995). Typically, these methods use either neural networks (NNs) or fuzzy logic systems to parametrize the unknown nonlinearities (Sanner & Slotine, 1992; Su & Stepanenko, 1994; Yesildirek & Lewis, 1995). Direct adaptive tracking control was proposed for a class of continuous-time nonlinear systems using radial basis function NNs (Sanner & Slotine, 1992). Using a families of novel integral Lyapunov functions for avoiding the possible controller singularity problem without using projection, adaptive neural controls have been investigated for a class of nonlinear systems in nonlinear parametrization (Ge, Hang, & Zhang, 1999b) and in a Brunovsky form (Zhang, Ge, & Hang, 2000), and for a class of MIMO nonlinear systems with a triangular structure in the control inputs (Ge, Zhang, & Hang, 2000). Decentralized indirect adaptive fuzzy control was proposed for a class of nonlinear systems with unknown constant control gains and unknown function control gains (Zhang, 2001).

When there is no a priori knowledge about the signs of control gains, adaptive control of such systems becomes much more difficult. The first solution was given for a class of first-order linear systems (Nussbaum, 1983), where the Nussbaum-type gain was originally proposed. When the high-frequency control gains and their signs are unknown, gains of Nussbaum-type (Nussbaum, 1983) have been effectively used in control design in solving the difficulty of unknown control directions for higher order systems (Ye & Jiang, 1998), and nonlinear systems with unknown time-delays (Ge, Hong, & Lee, 2004), among others.

Dead-zone is one of the most important non-smooth nonlinearities in many industrial processes, which can severely limit

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system performance, and its study has been drawing much interest in the control community for a long time (Cho & Bai, 1998; Selmic & Lewis, 2000; Tao & Kokotovic, 1994, 1995; Taware & Tao, 2003; Wang, Hong, & Su, 2003, 2004). To handle systems with unknown dead-zones, adaptive dead-zone inverses were proposed (Cho & Bai, 1998; Tao & Kokotovic, 1994, 1995). Continuous and discrete adaptive dead-zone inverses were built for linear systems with unmeasurable dead-zone outputs (Tao & Kokotovic, 1994, 1995). Asymptotical adaptive cancelation of unknown dead-zone is achieved analytically (Cho & Bai, 1998) under the condition that the output of the dead-zone is measurable. A compensation scheme was presented for general nonlinear actuator dead-zones of unknown width (Selmic & Lewis, 2000). Given a matching condition to the reference model, adaptive control with adaptive dead-zone inverse has been investigated (Wang et al., 2003). For a dead-zone with equal slopes, robust adaptive control was developed for a class of nonlinear systems (Wang et al., 2004) without constructing the inverse of the dead-zone. In the work (Shyu, Liu, & Hsu, 2005), decentralized variable structure control was proposed for a class of uncertain large-scale systems with state time-delay and dead-zone input. However, the parameters u_{i-}, u_{i+} of the dead-zones (Shyu et al., 2005) and gain signs need to be known, and the disturbances satisfy the matching condition. Adaptive output feedback control using backstepping and smooth inverse function of the dead-zone was proposed for a class of SISO nonlinear systems with unknown dead-zone (Zhou, Wen, & Zhang, 2006). However, the problem of over-parametrization still exists.

Time-delay is often encountered in various systems, for example, in the turbojet engines, aircraft systems, microwave oscillators, nuclear reactors, rolling mills, chemical processes, and hydraulic systems, etc. (Liu & Su, 1998). The existence of time-delays in a system frequently becomes a source of instability, and may degrade the control performance. Therefore, a number of different approaches have been proposed in order to stabilize such systems with time-delays (Nguang, 2000; Niculescu, 2001; Richard, 2003). Using appropriate *Lyapunov–Krasovskii functionals* to compensate for the uncertainties from unknown time-delays (Hale, 1977), thorough adaptive neural controls were presented for classes of nonlinear systems with unknown time delays and virtual control coefficients as either unknown constants or unknown functions with known or unknown sign (Ge, Hong, & Lee, 2003, 2005; Ge et al., 2004).

In this paper, we consider a class of uncertain MIMO nonlinear state time-varying delay systems with both unknown nonlinear dead-zones and unknown gain signs. To the best of our knowledge, there are few works dealing with such kinds of systems in the literature at present stage. The main contributions of the paper include:

(i) the novel description of a general nonlinear dead-zone model which makes the control system design possible without necessarily constructing a dead-zone inverse using the mean value theorem;
(ii) the removal of the need for known parameter bounds of dead-zones and the linear functions outside the deadband;
(iii) the use of integral Lyapunov function in avoiding the controller singularity problem which may be caused by time-varying gain functions;
(iv) the use of the Nussbaum-type functions and multilayer NNs in solving the problem of both unknown control directions and unknown control gain functions; and
(v) the combination of Lyapunov–Krasovskii functional and Young's inequality in eliminating the unknown time-varying delay $\tau_i(t)$ in the upper bounding function of the Lyapunov functional derivative, which makes NN parametrization with known inputs possible.

This paper is organized as follows. The problem formulation and preliminaries are given in Section 2. In Section 3, adaptive NN control is firstly developed for SISO time-varying delay systems with nonlinear dead-zones by using integral Lyapunov functions, then, it is extended to MIMO systems. Simulation results are performed to demonstrate the effectiveness of the approach in Section 4, followed by conclusion in Section 5.

2. Problem formulation and preliminaries

2.1. Problem formulation

Consider a class of uncertain MIMO nonlinear time-varying delay systems with dead-zones in the following form

Plant:

$$\begin{cases} \dot{x}_{1j} = x_{1,j+1}, \quad j = 1, \ldots, n_1 - 1, \\ \dot{x}_{1n_1} = f_1(x) + f_{1,\tau}(x_1(t - \tau_1(t)), \ldots, \\ \qquad x_m(t - \tau_m(t))) + b_1(x_1)u_1, \\ \dot{x}_{ij} = x_{i,j+1}, \quad j = 1, \ldots, n_i - 1, \\ \dot{x}_{in_i} = f_i(x, u_1, \ldots, u_{i-1}) + f_{i,\tau}(x_1(t - \tau_1(t)), \ldots, \\ \qquad x_m(t - \tau_m(t))) + b_i(x_1, \ldots, x_i)u_i, \\ \qquad i = 2, \ldots, m, \\ x_i(t) = \phi_i(t), \quad t \in [-\tau_{\max}, 0], \; i = 1, \ldots, m, \\ y_1 = x_{11}, \ldots, y_m = x_{m1}. \end{cases} \tag{1}$$

Dead-zone:

$$u_i = D_i(v_i) = \begin{cases} g_{ir}(v_i) & \text{if } v_i \geqslant b_{ir}, \\ 0 & \text{if } b_{il} < v_i < b_{ir}, \\ g_{il}(v_i) & \text{if } v_i \leqslant b_{il}. \end{cases} \tag{2}$$

where $x = [x_1^{\mathrm{T}}, x_2^{\mathrm{T}}, \ldots, x_m^{\mathrm{T}}]^{\mathrm{T}} \in R^n$ is the state vector, $x_i = [x_{i1}, \ldots, x_{in_i}]^{\mathrm{T}}$, $i = 1, \ldots, m$, $n = \sum_{i=1}^{m} n_i$; functions $g_{ir}(v_i), g_{il}(v_i)$ are unknown smooth nonlinear functions; $y_i \in R$ denotes the ith subsystem output; $f_1(x), f_2(x, u_1), \ldots, f_m(x, u_1, \ldots, u_{m-1}), f_{i,\tau}(x_1(t-\tau_1(t)), \ldots, x_m(t - \tau_m(t)))$ are the unknown continuous functions; $b_1(x_1), b_2(\bar{x}_2), \ldots, b_m(\bar{x}_m)$ are the unknown differentiable control gains, $\bar{x}_i = [x_1^{\mathrm{T}}, x_2^{\mathrm{T}}, \ldots, x_i^{\mathrm{T}}]^{\mathrm{T}}$; $\tau_1(t), \ldots, \tau_m(t)$ are unknown time-varying delays, $\phi_1(t), \ldots, \phi_m(t)$ are known continuous initial state vector functions, $\tau_{\max}$ as will be defined later is a known positive constant; $u_i \in R$ is the output of