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Intelligent nonsingular terminal sliding-mode control via perturbed fuzzy neural network

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ABSTRACT

In this paper, an intelligent nonsingular terminal sliding-mode control (INTSMC) system, which is composed of a terminal neural controller and a robust compensator, is proposed for an unknown nonlinear system. The terminal neural controller including a perturbed fuzzy neural network (PFNN) is the main controller and the robust compensator is designed to eliminate the effect of the approximation error introduced by the PFNN upon the system stability. The PFNN is used to approximate an unknown nonlinear term of the system dynamics and perturbed asymmetric membership functions are used to handle rule uncertainties when it is hard to exactly determine the grade of membership functions. In additional, Lyapunov stability theory is used to discuss the parameter learning and system stability of the INTSMC system. Finally, the proposed INTSMC system is applied to an inverted pendulum and a voice coil motor actuator. The simulation and experimental results show that the proposed INTSMC system can achieve favorable tracking performance and is robust against parameter variations in the plant.

1. Introduction

In the last 40 years, the sliding-mode control (SMC) system has been successfully applied to handle several practical control problems in face of system uncertainties and time-varying disturbances (Nayeripour et al., 2011; Zhang et al., 2014). It is known that the chattering problem is one of the most critical handicaps for applying the SMC system to real applications. A solution to this problem is the high-order SMC system (Gennaro et al., 2014; Na et al., 2013). The actual control signal was obtained after integrating the discontinuous derivative control law; however, the main problem of the high-order SMC is the increasing information demand. Meanwhile, Yang et al. (2014) proposed a continuous dynamic SMC system to drive the states to the dynamic sliding surface. Though the level of the chattering phenomenon can be reduced; however, the design procedure is overly complex.

Motivated by the previous discussions, the most commonly used sliding surface is a hyperplane-based sliding surface. The SMC system using the hyperplane-based sliding surface cannot guarantee the convergence in finite time. To attack this problem, a terminal sliding-mode control (TSMC) is presented by introducing a nonlinear item into the sliding mode which offers some superior properties such as fast and better control precision (Chen et al., 2012; Li et al., 2013; Tan et al., 2010; Yu et al., 2005). The states of the TSMC system can guarantee converging to the origin in finite time. Though the TSMC provides fast convergence and high precision control, there are two disadvantages in the TSMC system. One is the singularity point problem and the other is the requirement of system dynamics. To resolve the singularity problem, a nonsingular terminal sliding-mode control (NTSMC) system was proposed (Feng et al., 2013; Komurcugil, 2013; Yang et al., 2013). Though favorable control performance can be achieved by both of TSMC and NTSMC systems, not only the chattering phenomenon cannot be avoided but also these schemes required detailed system models.

Some researchers focus on intelligent NTSMC (INTSMC) approaches to attack the requirement of the system dynamics (Chen and Lin, 2011; Lin, 2006; Lin et al., 2012). Lin (2006) used a fuzzy wavelet network to accurately approximate the unknown dynamics of robotic systems. Though the tracking performance can be guaranteed by Lyapunov stability theory, a conservative switching control law was constructed to cause damage to actuators. The chattering problem is one of the most critical handicaps for applying the INTSMC system to real applications. Chen and Lin (2011) proposed a recurrent Hermite neural network uncertainty estimator to improve the control performance and increase the robustness of the control system. However, the algorithm supposed that the approximation error is constant but this is not true due to the approximated function is a function of

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the states. Lin et al. (2012) developed an interval type-2 recurrent fuzzy neural network to approximate a lumped uncertainty. However, the type-reduction operation of the interval type-2 recurrent fuzzy neural network results in heavy computational loading. It is unsuitable for real-time control applications.

Though the INTSMC system can achieve favorable control performance, the approximation error introduced by the used neural networks may cause instability of the control system. Thus, an extra compensator, such as the switching compensator (Mon and Lin, 2012) and the supervisory compensator (Chen and Hsu, 2010), should be used. These compensators result in the chattering phenomena so as to cause damage to actuators or plants. Zhao et al. (2011) proposed a low-pass filtering for chattering reduction; however, a trade-off problem between chattering phenomenon and control accuracy arises. A L_2 compensator was proposed (Hsu, 2012; Lee and Li, 2012). The control input may lead to a large control signal as the specified attenuation level was chosen small. A smooth compensator was proposed to achieve the uniformly ultimately bound stability of the control system without occurring chattering phenomena (Kim and Calise, 2007; Lin and Li, 2013; Na et al., 2013). When the approximator error is large, the smooth compensator cannot improve the convergent speed of tracking error due to its control gain is fix.

It is known that the type-1 fuzzy sets are unable to directly handle the rule uncertainties. To attack this problem, several studies on the theory of type-2 fuzzy systems have been conducted (Castillo and Melin, 2012; Lou and Dong, 2012; Mendel, 2001). Type-2 fuzzy systems make it possible to model and minimize the effects of uncertainties that cannot be directly modeled by type-1 fuzzy systems. Though interval type-2 fuzzy systems are useful in handling uncertainties, the problem of how to design interval type-2 fuzzy systems remains an unsolved problem. To address this problem, several interval type-2 fuzzy neural networks (T2FNNs) were proposed based on gradient-descent-learning algorithms (Abiyev and Kaynak, 2010; Chang and Chan, 2014; Kayacan et al., 2012, 2015). The interval T2FNNs use a typical type reduction operation, namely the Karnik–Mendel iterative procedure, to find the extended output. The type reduction operation is complex and time consuming, especially for hardware implementation. A simplified type reduction operation was proposed to reduce the hardware implementation cost (Juang and Chen, 2013, 2014; Juang and Juang, 2013) proposed.

Contributions of this paper are twofold. First, a perturbed fuzzy neural network (PFNN) using a perturbed asymmetric membership function is proposed. The perturbed functions possess the ability of handling rule uncertainties with a simplified computation complexity. Unlike interval T2FNN, the PFNN does not require the time-consuming type reduction operation. The proposed online parameter learning ability makes it feasible for online approximating an unknown nonlinear term of the system dynamics. Second, an intelligent nonsingular terminal sliding-mode control (INTSMC) system is proposed for an unknown nonlinear system. The design contains two parts. One is the design of terminal neural controller and the other is the design of robust compensator upon the system stability. The robust compensator which is based on the choice of an exponential term that adapts to the variation of the system states is proposed. Thus, the control chattering occurred in TSMC and NTSMC can be alleviated. Further, the proposed INTSMC system is applied to an inverted pendulum and a voice coil motor (VCM) actuator to verify its effectiveness.

2. Problem formulation

Consider an nth order nonlinear system as

$$x^{(n)} = f(\mathbf{x}) + g(\mathbf{x})u \tag{1}$$

where $\mathbf{x} = [x, \dot{x}, \ldots, x^{(n-1)}]^T$ is the state vector, $f(\mathbf{x})$ and $g(\mathbf{x})$ are the system dynamics, and u is the control input. Without losing generality, it is assumed that $g(\mathbf{x}) > 0$ for all time. The control objective is to find a control law so that the state vector $\mathbf{x}$ can track a command vector $\mathbf{x}_c = [x_c, \dot{x}_c, \ldots, x_c^{(n-1)}]^T$ closely. To achieve this control objective, define a tracking error vector as

$$\mathbf{e} = \mathbf{x} - \mathbf{x}_c = [e, \dot{e}, \ldots, e^{(n-1)}]^T \tag{2}$$

where $e = x - x_c$. Substituting (1) into (2) yields

$$e^{(n)} = u + z(\mathbf{x}) \tag{3}$$

where the nonlinear term $z(\mathbf{x})$ is defined as $z(\mathbf{x}) = -x_c^{(n)} + \left(1 - \frac{1}{g(\mathbf{x})}\right)x^{(n)} + \frac{f(\mathbf{x})}{g(\mathbf{x})}$. If the system uncertainties occur, i.e., parameters of the system deviate from its nominal values, the error dynamic equation can be modified as

$$e^{(n)} = u + z_n(\mathbf{x}) + \Delta z(\mathbf{x}) \tag{4}$$

where $z_n(\mathbf{x})$ is the nominal behavior of nonlinear term $z(\mathbf{x})$ and $\Delta z(\mathbf{x})$ denotes the system uncertainties. It is assumed to be bounded by $|\Delta z(\mathbf{x})| \le Z$ where Z is a positive constant.

In this study, a nonsingular terminal sliding surface is designed as (Feng et al., 2013)

$$s_i = s_{i-1} + \frac{1}{\lambda_i}\dot{s}_{i-1}^{\frac{p_i}{q_i}} \quad \text{for} \quad i = 1, 2, \ldots, n-1 \tag{5}$$

where $s_0 = e$, λ_i is designed positive constant and p_i and q_i are positive odd integers which should satisfy the condition $q_i < p_i < 2q_i$. If a controller can guarantee that the system state approaches the nonsingular terminal sliding surface $s_i = 0$ in finite time and confines the state on the sliding surface, $s_{i-1} = 0$ can be achieved as Feng et al. (2013). When the nonsingular terminal sliding surface is reached within limited time t_r, the system dynamic can be determined by the following nonlinear differential equation:

$$\dot{s}_{i-1} = -\lambda_i s_{i-1}^{\frac{q_i}{p_i}} \tag{6}$$

Then, a finite time t_s is taken to travel from $s_{i-1}|_{t=t_r} \ne 0$ to $s_{i-1}|_{t=t_r+t_s} = 0$. So on so forth, finally $s_1 = 0$ and $s_0 = 0$ (that is $e = 0$) will converge to zero within a limited time.

Assuming that the nominal system dynamic $z_n(\mathbf{x})$ is known, there exists an NTSMC system as (Feng et al., 2013)

$$u_{smc} = -z_n(\mathbf{x}) - \sum_{i=1}^{n-1} \lambda_i \frac{q_i}{p_i}\frac{d^{n-i}}{dt^{n-i}} s_{i-2}^{\,2-\frac{p_i}{q_i}} - Z\operatorname{sgn}(s_{n-1}) \tag{7}$$

where $\operatorname{sgn}(\cdot)$ is a sign function. It is obvious that the term $\lambda_i \frac{q_i}{p_i}\frac{d^{n-i}}{dt^{n-i}} s_{i-2}^{\,2-\frac{p_i}{q_i}}$ in (7) will not result in the negative power as lone as the condition $q_i < p_i < 2q_i$ holds for $i = 1, 2, \ldots, n-1$. Differentiating (5) with respect to time and using the control law $u = u_{smc}$, we can obtain that

$$\begin{aligned}\dot{s}_{n-1} &= \dot{s}_{n-2} + \frac{1}{\lambda_{n-1}}\frac{p_{n-1}}{q_{n-1}}\dot{s}_{n-2}^{\frac{p_{n-1}}{q_{n-1}}-1}\dot{s}_{n-2} \\ &= \delta_{n-2}[\Delta z(\mathbf{x}) - Z\operatorname{sgn}(s_{n-1})]\end{aligned} \tag{8}$$

where $\delta_{n-2} = \frac{1}{\lambda_{n-1}}\frac{p_{n-1}}{q_{n-1}}\dot{s}_{n-2}^{\frac{p_{n-1}}{q_{n-1}}-1}$. Since p_{n-1} and q_{n-1} are both positive odd integers and $1 < \frac{p_{n-1}}{q_{n-1}} < 2$, there is $\dot{s}_{n-2}^{\frac{p_{n-1}}{q_{n-1}}-1} > 0$ and $\delta_{n-2} > 0$ for $\dot{s}_{n-2} \ne 0$. To guarantee the stability of the NTSMC system, consider the candidate Lyapunov function in the following form as

$$V_1(t) = \frac{1}{2}s_{n-1}^2 \tag{9}$$

Differentiating (9) with respect to time and using (8) yields

$$\dot{V}_1(t) = s_{n-1}\dot{s}_{n-1}$$