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Neural networks-based command filtering control of nonlinear systems with uncertain disturbance

Jinpeng Yu*, Bing Chen, Haisheng Yu, Chong Lin, Lin Zhao

The College of Automation and Electrical Engineering, Qingdao University, Qingdao 266071 PR China

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This paper is concerned with neural networks-approximation based command filtering backstepping control for uncertain strict-feedback nonlinear systems with unknown disturbances. The "explosion of complexity" problem arising from the virtual controllers' derivatives is resolved by utilizing the command filtering technique, and the shortcoming existing in dynamic surface method is properly overcome via an introduced error compensation mechanism (ECM). Moreover, the nonlinear functions of the underlying system are well approximated by exploiting neural networks-based framework. The developed strategy may cover two features with comparison of current achievements: 1) The filtering error can be eliminated in the light of the designed compensating signals; 2) The requirement of adaptive parameters is reduced to only one, which may enhance the control performance for realistic project implementation. At last, an application example in position tracking control of surface permanent magnet synchronous motor (SPMSM) is carried out to further verify the effectiveness and advantages of the theoretical result.

1. Introduction

As is well-known, in view of the excellent ability of asymptotic tracking and global stability for strict-feedback nonlinear systems [11], adaptive backstepping control method has been widely applied to controller design in nonlinear systems [15,16,22]. Nevertheless, it is commonly recognised that there may be two problems restricting wide utilization of the classical backstepping: one is that "certain functions may not be nonlinear" [5,34,35], another is the "explosion of complexity" (EOC) issue [2,6,14,26,29,38,40,42]. On the other hand, with the increasing emergence of approximation theory, e.g., fuzzy logic system (FLS) [1,3,4,10,21,23–25,27,28,30,31,45] or neural networks (NNs) [12,13,33,39,41,43,46,47,50] approximators, adaptive control methods have been updated constantly for the analysis and synthesis of uncertain nonlinear systems. It should be mentioned that, the first issue existing in the adaptive backstepping has been successfully tackled by the adaptive fuzzy or NNs control strategy, which may be regarded as one of the systematic methodologies for the approximation of nonlinear functions. Then, the second one, i.e., EOC, may not be fully settled via the aforementioned control approach [36].

In recent years, it is noted that dynamic surface control (DSC) [18,32,44] has been put forward to solve the EOC problem [19,20,37]. But the issue of errors arising from the filter is not concerned by the NNs controllers and the DSC approach, which may affect the system performance to some degree. In this way, the command filtered backstepping method was proposed for the EOC in [8], after which a command filter-based backstepping was properly generalized to the adaptive case

* Corresponding author.
E-mail address: yjp1109@hotmail.com (J. Yu).

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in [7]. Furthermore, upon the premise of the command filters, the EOC problem can be eliminated well with the outputs [9,48,49] and it is also known that the input signals of the filters may be seen as virtual control functions in the backstepping design. However, it is worth mentioning that the complex case has not been fully probed from the above discussion yet.

In view of the foregoing observations, neural networks-approximation based command filtering backstepping control is introduced for nonlinear single-input-single-output (SISO) systems with unknown disturbances. It is shown that semiglobal uniform ultimate boundedness (SUUB) of the closed-loop system can be ensured by the proposed method, and output of the system can be adjusted within a small neighborhood of the reference signal. Compared with the current results, the main advantage of the obtained result can be threefold: 1) The two knotty problems in the classical backstepping can be solved via the neural networks and command filtering based adaptive backstepping control, and the online calculational complexity can also be alleviated for the design in a certain degree; 2) The introduction of the error compensation mechanism (ECM) is provided to further offset the shortcoming of the DSC; 3) The associated adaptive parameters are reduced to only one for the controller design, which may alleviate the computational burden and enhance the control performance in realistic project implementation. At last, an application example in position tracking control of surface permanent magnet synchronous motor (SPMSM) is followed to illustrate the effectiveness and novelty of the proposed methods.

2. Problem description and preliminaries

Consider the following SISO nonlinear systems

$$\dot{x}_i = f_i(\bar{x}_i) + g_i(\bar{x}_i)x_{i+1} + d_i(t) \tag{1}$$

$$\dot{x}_n = f_n(x) + g_n(x)u + d_n(t) \tag{2}$$

where $i = 1, 2, \ldots, n-1$, $x = [x_1, \ldots, x_n]^T \in R^n$ is the state vector with $x(0) = x_0$, $\bar{x}_i = [x_1, \ldots, x_i]$, the first state x_1 is the output and u is the control input. The functions $f_i(.)$ are unknown smooth nonlinear functions. $d_i(.)$ are the unknown bounded time-varying disturbances. For a desired reference input x_d, which will be stated in Assumption 1, the control law and adaptive law will be specified to steer the output signal from any initial conditions to track the reference signal x_d and to guarantee all the signals and states of the system can be bounded.

Assumption 1. The given reference input x_d and its first-order derivative $\dot{x}_d$ are known and smooth, and both are bounded.

Assumption 2. [7]: Let $\Omega_d \subset R^n$ represent an open set that contains the origin, the initial condition $x(0)$ and the trajectory $x_d(t)$. In the systems (1)-(2), for $i = 1, 2, \ldots, n$: 1) $g_i^{(j)}(.)$ and $f_i^{(j)}(.)$ are bounded on $\bar{\Omega}_d$ for $j = 1, 2, \ldots, n-i$, and 2) $g_i(.)$ are smoothly nonlinear functions and there exist known positive scalars η and ρ satisfying $\eta < |g_i(.)| < \rho$. Without loss of generality, assume $g_i(.) > 0$.

Then, according to Assumption 2, the functions f_i and g_i are all Lipschitz on $\bar{\Omega}_d$.

Assumption 3. There exist constants $\bar{d}_i$ such that $d_i(t)$ satisfy $|d_i(t)| \le \bar{d}_i$.

Remark 1. It is noted that, the exact information of $x_d^{(i)}(t)(i = 0, 1, \ldots, n-1)$ is required for the traditional backstepping method, while Assumption 1 only needs the information of $x_d(t)$ and $x_d^{(1)}(t)$ in this paper. It can be obviously seen that the condition is less stringent for Assumption 1, which signifies that the proposed NNs control via command filter backstepping is more suitable for many practical engineerings, for example, the land vehicle driving system with high order derivatives may not be provided. In general, the above assumptions may be applied to the great majority of practical application systems.

3. Design of the command filtered adaptive neural control

In the following, a NNs-based command filtered backstepping control is presented for the nonlinear systems. Let the tracking error variable be

$$z_1 = x_1 - x_d, z_i = x_i - x_{i,c}$$

for $i = 2, 3, \ldots, n$. In addition, virtual controllers α_{i-1} represent control signals of the command filters, and $x_{i,c}$ denote outputs of the command filters. By Lemma 2 in [45], the designed command filters are shown by:

$$\dot{\varphi}_1 = \omega_n \varphi_2 \tag{3}$$

$$\dot{\varphi}_2 = -2\zeta\omega_n\varphi_2 - \omega_n(\varphi_1 - \alpha_i) \tag{4}$$

for $i = 1, 2, \ldots, n-1$. Assume that the initial conditions of each filter are denoted by $\varphi_1(0) = \alpha_i(0)$ and $\varphi_2(0) = 0$. Moreover, the parameters $\omega_n > 0$ and $\zeta \in (0, 1]$ may be found to satisfy $|\varphi_1 - \alpha_i| \le \mu$ for any $\mu > 0$.

Remark 2. In fact, the errors of the filtering arising from the command filters may be larger with the increasement of the order n. This is indeed a difficult task for a small tracking error. Therefore, the ECM in the sequel is introduced to avoid the errors $(x_{i+1,c} - \alpha_i)$ caused by the filtering process herein.