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Decentralized control of a class of large-scale nonlinear systems using neural networks☆

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Abstract

This paper designs a decentralized neural network (NN) controller for a class of nonlinear large-scale systems, in which strong interconnections are involved. NNs are used to handle unknown functions. The proposed scheme is proved guaranteeing the boundedness of the closed-loop subsystems using only local feedback signals.
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1. Introduction

In the past decades, there has been an increased interest in the development theories for large-scale systems. Earlier versions were focused on control of large-scale linear systems. However, most physical systems are inherently nonlinear. Research on decentralized control for nonlinear systems was carried out by Fu (1992), Jain and Khorrami (1997), Tang, Tomizuka, Guerrero, and Montemayor (2000), and Jiang (2000). These previous works consider subsystems which are linear in a set of unknown parameters, or consider interconnections which are bounded by high-order polynomials. In the work of Krishmanurthy and Khorrami (2001), the restriction on the subsystems and interconnections was removed. However, the nonlinear functions and interconnections bounds are required to be known. Neural networks (NNs) have been considered as general tools for modeling nonlinear functions. For decentralized control, Spooner & Passino (1999) and Nardi, Hovakimyan, and Calise (2001) proposed NN control to approximate unknown functions, but at the price of assuming the first-order polynomials. In Huang, Tan, and Lee (2003), the nonlinear bounded interconnections can be accommodated based on NN control. However, the interconnection term depending on the filtered errors is a restrictive condition. The purpose of this paper is to present the solution to the problem of designing a decentralized adaptive NN controller for a class of nonlinear large-scale systems. The strong nonlinear interconnections depending on states are considered, which remove the restriction in Huang et al. (2003). Thus, the current interconnection includes many types of interconnections considered in the existing literature as special cases, for example, the interconnections bounded by first-order polynomials (Nardi et al., 2001; Spooner & Passino (1999)), high-order polynomials (Shi and Singh, 1992; Tang et al., 2000), and known nonlinear bounds (Krishmanurthy and Khorrami, 2001).

2. Preliminaries

Consider a large-scale nonlinear system comprised of n subsystems:

$$\left.\begin{aligned} \dot{x}_{i,1} &= x_{i,2} \\ &\vdots \\ \dot{x}_{i,n_i} &= b_i(\mathbf{x}_i, t)u_i + \Delta_i(\mathbf{x}_1, \ldots, \mathbf{x}_N, t) \\ y_i &= x_{i,1} \end{aligned}\right\} \quad (1)$$

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with $\mathbf{x}_i = [x_{i,1}, x_{i,2}, \ldots, x_{i,n_i}]^{\mathrm{T}}$, $1 \leqslant i \leqslant N$. The present system extends the result of Huang et al. (2003) to the case of the time-varying system (1).

Assumption 2.1. The plant can be defined by (1) with input gain bounded by $0 < b_{0_i} \leqslant |b_i(\mathbf{x}_i, t)| \leqslant b_{1i}$. The input gain rate of change is bounded by $|\dot{b}_i(\mathbf{x}_i, t)| \leqslant B_i(\mathbf{x}_i)$, where $B_i(\mathbf{x}_i)$ is a continuous function.

The tracking error is $e_i = x_{i,1} - y_{di}$ and the filtered error $s_i(t)$ is given by

$$s_i(t) = k_{i,1}e_i(t) + k_{i,2}\dot{e}_i(t) + \cdots + k_{i,n_i-1}e_i^{(n_i-2)} + e_i^{(n_i-1)} = \Lambda_i^{\mathrm{T}}\mathbf{e}_i, \tag{2}$$

where $\Lambda_i = [k_{i,1}, \ldots, 1]^{\mathrm{T}}$, $\mathbf{e}_i = [e_i, \ldots, e_i^{(n_i-1)}]^{\mathrm{T}}$, and the coefficients are chosen such that $k_{i,1} + \cdots + s^{n_i-1}$ is Hurwitz. Let $v_i = y_{di} + k_{i,1}\dot{e}_i(t) + k_{i,2}\ddot{e}_i(t) + \cdots + k_{i,n_i-1}e_i^{(n_i-1)}$. The time derivative of s_i may be written as

$$\dot{s}_i = b_i(\mathbf{x}_i, t)u_i + v_i + \bar{\Delta}_i(y_{di}, y_{di}^{(n_i)}, \mathbf{x}_1, \ldots, \mathbf{x}_N, t), \tag{3}$$

where $\bar{\Delta}_i = -y_{di} - y_{di}^{(n_i)} + \Delta_i(\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N, t)$.

Assumption 2.2. The trajectory vector $x_{di} = [y_{di}, \dot{y}_{di}, \ldots, y_{di}^{(n_i-1)}]^{\mathrm{T}}$ with $i = 1, 2, \ldots, N$ are continuous, bounded and available, and $x_{di} \in \Omega_{di}$.

Assumption 2.3. The interconnections Δ_i are bounded by polynomial-type nonlinearities in $\mathbf{x}_l$, $1 \leqslant l \leqslant N$, i.e.,

$$|\Delta_i(\mathbf{x}_1, \ldots, \mathbf{x}_N, t)| \leqslant \sum_{j=1}^{N} [\zeta_{ij}^0 + \zeta_{ij}(\mathbf{x}_j)], \tag{4}$$

where ζ_{ij}^0 are unknown constants, and $\zeta_{ij}(\mathbf{x}_j)$ are unknown smooth functions.

Remark 2.1. We consider the dependence of the bounded interconnection functions on the states only, not on the filtered errors as in Huang et al. (2003).

Consider a three-layer NN (Lewis, Yesildirek, & Liu, 1996; Zhang, Ge, & Hang, 1999):

$$f(z) = W^{*\mathrm{T}}\Phi(C^{*\mathrm{T}}\bar{z}), \quad z \in \Omega_z, \tag{5}$$

where $W^* = [w_0^*, \ldots, w_m^*]^{\mathrm{T}}$ is called the weight of the first-to-second layer, $C^* = [c_0^*, \ldots, c_{m+1}^*]^{\mathrm{T}}$ is called the weight of the second-to-third layer, $\Phi = [\phi_0, \ldots, \phi_m]^{\mathrm{T}}$ is called the activation function, and $\bar{z} = [z^{\mathrm{T}}, 1]^{\mathrm{T}}$ is the extended input vector. The control design of each subsystem uses a neural network, i.e., $W_i^{*\mathrm{T}}\Phi_i(C_i^{*\mathrm{T}}\bar{z}_i)$, where i represents the ith subsystem. Let $\hat{W}_i, \hat{C}_i$ be estimates of the ideal W_i and C_i. Define $\tilde{W}_i = W_i^* - \hat{W}_i$ and $\tilde{C}_i = C_i^* - \hat{C}_i$. Then, applying the same treatment of Lewis et al. (1996) and Zhang et al. (1999)

$$\begin{aligned} &W_i^{*\mathrm{T}}\Phi_i(C_i^{*\mathrm{T}}\bar{z}_i) - \hat{W}_i^{\mathrm{T}}\Phi_i(\hat{C}_i\bar{z}_i) \\ &\quad = \tilde{W}_i^{\mathrm{T}}[\Phi_i(\hat{C}_i^{\mathrm{T}}\bar{z}_i) - \Phi_i'(\hat{C}_i^{\mathrm{T}}\bar{z}_i)\hat{C}_i^{\mathrm{T}}\bar{z}_i] \\ &\quad\quad + \hat{W}_i^{\mathrm{T}}\Phi_i'(\hat{C}_i^{\mathrm{T}}\bar{z}_i)\tilde{C}_i^{\mathrm{T}}\bar{z}_i + d_{ui}, \end{aligned} \tag{6}$$

where $d_{ui} = \tilde{W}_i^{\mathrm{T}}\Phi_i'(\hat{C}_i^{\mathrm{T}}\bar{z}_i)C_i^{*\mathrm{T}}\bar{z}_i + W_i^{*\mathrm{T}}O(\tilde{C}_i^{\mathrm{T}}\bar{z}_i)^2$ and

$$\begin{aligned} |d_{ui}| \leqslant{}& \|C_i^*\|_F\|\bar{z}_i\hat{W}_i^{\mathrm{T}}\Phi'(\hat{C}_i^{\mathrm{T}}\bar{z}_i)\|_F \\ &+ \|W_i^*\|\|\Phi_i'(\hat{C}_i^{\mathrm{T}}\bar{z}_i)\hat{C}_i^{\mathrm{T}}\bar{z}_i\| + |W_i^*|_1. \end{aligned} \tag{7}$$

3. Decentralized controller design and stability analysis

We propose the adaptive decentralized controller

$$u_i = -K_i s_i - \hat{W}_i^{\mathrm{T}}\Phi_i(\hat{C}_i^{\mathrm{T}}\bar{z}_i) + u_{1i}, \quad z_i = [x_i^{\mathrm{T}}, x_{di}^{\mathrm{T}}]^{\mathrm{T}} \tag{8}$$

with $K_i > \frac{1}{2}$ and

$$\begin{aligned} u_{1i} = & -K_{ci}[\|\bar{z}_i\hat{W}_i^{\mathrm{T}}\Phi_i'(\hat{C}_i^{\mathrm{T}}\bar{z}_i)\|_F^2 \\ & + \|\Phi_i'(\hat{C}_i^{\mathrm{T}}\bar{z}_i)\hat{C}_i^{\mathrm{T}}\bar{z}_i\|^2 + v_i^2]s_i. \end{aligned} \tag{9}$$

The control objective is to guarantee the stability under this decentralized control. The system (3) can be written after applying the controller, as $\dot{s}_i = b_i(\mathbf{x}_i, t)[-K_i s_i + (v_i/b_i(\mathbf{x}_i, t)) - \hat{W}_i^{\mathrm{T}}\Phi_i(\hat{C}_i^{\mathrm{T}}\bar{z}_i) + u_{1i}] + \bar{\Delta}_i$. Thus, we have

$$\begin{aligned} &\frac{\dot{s}_i}{b_i(\mathbf{x}_i, t)} - \frac{\dot{b}_i(\mathbf{x}_i, t)s_i}{2b_i^2(\mathbf{x}_i, t)} \\ &\quad = -K_i s_i + \frac{v_i}{b_i(\mathbf{x}_i, t)} - \hat{W}_i^{\mathrm{T}}\Phi_i(\hat{C}_i^{\mathrm{T}}\bar{z}_i) + u_{1i} \\ &\quad\quad + \frac{\bar{\Delta}_i}{b_i(\mathbf{x}_i, t)} - \frac{\dot{b}_i(\mathbf{x}_i, t)s_i}{2b_i^2(\mathbf{x}_i, t)}. \end{aligned} \tag{10}$$

Consider the following update laws:

$$\dot{\hat{W}}_i = r_i\{[\Phi_i(\hat{C}_i^{\mathrm{T}}\bar{z}_i) - \Phi_i'(\hat{C}_i^{\mathrm{T}}\bar{z}_i)\hat{C}_i^{\mathrm{T}}\bar{z}_i]s_i - r_{wi}\hat{W}_i\}, \tag{11}$$

$$\dot{\hat{C}}_i = r_i[\bar{z}_i\hat{W}_i^{\mathrm{T}}\Phi_i'(\hat{C}_i^{\mathrm{T}}\bar{z}_i)s_i - r_{ci}\hat{C}_i], \tag{12}$$

where r_i, r_{w_i}, r_{c_i} are positive constants.

Theorem 3.1. *For the closed-loop adaptive subsystems consisting of plant* (3) *and decentralized controller* (8), *if the assumptions hold and* $\mathbf{e}_i(0) \in \Omega_0$, *then all the signals in the closed-loop subsystems are bounded and the filtered tracking errors* $s_i(t)$ *is uniformly ultimately bounded* (UUB).

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