외란 관측기를 이용한 비선형 시스템의 강인 적응제어

Robust Adaptive Control for Nonlinear Systems Using Nonlinear Disturbance Observer

황영호*, 한병조*, 김홍필**, 양해원*
Young-Ho Hwang*, Byung-Jo Han*, Hong-Pil Kim**, Hai-Won Yang*

Abstract - A controller is proposed for the robust adaptive backstepping control of a class of uncertain nonlinear systems using nonlinear disturbance observer (NDO). The NDO is applied to estimate the time-varying lumped disturbance in each step, but a disturbance observer error does not converge to zero since the derivative of lumped disturbance is not zero. Then the fuzzy neural network (FNN) is presented to estimate the disturbance observer error such that the outputs of the system are proved to converge to a small neighborhood of the desired trajectory. The proposed control scheme guarantees that all the signals in the closed-loop are semiglobally uniformly ultimately bounded on the basis of the Lyapunov theorem. Simulation results are presented to illustrate the effectiveness and the applicability of the approaches proposed.

Key Words : Robust adaptive control, backstepping, fuzzy neural networks, nonlinear disturbance observer.

1. INTRODUCTION

The backstepping is one of the most important results, which provides a powerful design tool, for nonlinear (and linear) system in the pure feedback and strict feedback forms [1]. In [2], [3] gain functions are assumed to be unknown and a backstepping design is proposed that incorporates adaptive neural network techniques.

This paper presents NDO for a class of time-varying nonlinear systems with unknown lumped disturbances. Then the fuzzy neural network (FNN) is presented to estimate the disturbance observer error such that the outputs of the system are proved to converge to a small neighborhood of the desired trajectory.

With the proposed robust adaptive backstepping control scheme, semiglobal uniform ultimate boundedness of all the signals in the closed-loop are guaranteed, and the output of the system is proven to converge to a small neighborhood of the desired trajectory. The control performance of the closed-loop system is guaranteed by suitably choosing the design parameters

2. PROBLEM FORMULATION

The model of many practical nonlinear systems can be expressed in or transformed into a special state-space form

$$\dot{x}_i = f_i(\overline{x}_i) + g_i(\overline{x}_i)x_{i+1} + L_i(\overline{x}_{i+1}, t), 1 \le i \le n-1$$
$$\dot{x}_n = f_n(\overline{x}_n) + g_n(\overline{x}_n)u + L_n(\overline{x}_n, u, t), \; n \ge 2$$
$$y = x_1 \tag{1}$$

where $\overline{x}_i = [x_1, \dots, x_i]^T \in R^i, i = 1, \dots, n,$ denote the state vector, $u \in R$ is the control, $y \in R$ is the output, $f_i(\overline{x}_i), g_i(\overline{x}_i)$ are a known function and $\Delta f_i(\overline{x}_i), \Delta g_i(\overline{x}_i)$ are an unknown nonlinear function, $d_i(t)$ is an unknown external disturbance.

$L_i(\overline{x}_{i+1},\ t) = \Delta f_i(\overline{x}_i) + \Delta g_i(\overline{x}_i)x_{i+1} + d_i(t) \quad 0 \le i \le n-1$

and $L_n(\overline{x}_n,\ u,\ t) = \Delta f_n(\overline{x}_n) + \Delta g_n(\overline{x}_n)u + d_n(t)$ represent a time-varying lumped disturbance.

Assumption : The signs of $g_i(\cdot)$ are known, and there exist constants $g_{i1} \ge g_{i0} > 0$ such that $g_{i1} \ge \left| g_i(\cdot) \right| \ge g_{i0}, \ \forall \overline{x}_n \in \Omega \subset R^n$.

3. NONLINEAR DISTURBANCE OBSERVER DESIGN

We consider a class of time-varying nonlinear first order systems with lumped disturbance.

$$\dot{\xi} = \overline{f}(\xi) + \overline{g}(\xi)u + \overline{d}(t) \tag{2}$$

where the scalar variable ξ is the output,

저자 소개
* 황영호 : 한양대학교 전자전기제어계측학과 박사과정
* 한병조 : 한양대학교 전자전기제어계측학과 석사과정
** 김홍필 : 경일대학교 컴퓨터제어·전기공학과 교수
* 양해원 : 한양대학교 전자컴퓨터공학부 교수

$\bar{f}(\xi)=\bar{f}_n(\xi)+\Delta\bar{f}(\xi)$, and $\bar{g}(\xi)=\bar{g}_n(\xi)+\Delta\bar{g}(\xi)$ in which $\bar{f}_n(\xi)$, $\bar{g}_n(\xi)$ are a known function and $\Delta\bar{f}(\xi)$, $\Delta\bar{g}(\xi)$ are an unknown function, u is a control input and $\bar{d}(t)$ is an unknown disturbance.

Equation (5) can be written in a nominal model form as

$$\dot{\xi}=\bar{f}_n(\xi)+\bar{g}_n(\xi)u+\bar{L}(\xi,t) \tag{3}$$

where $\bar{L}(\xi,t)=\Delta\bar{f}(\xi)+\Delta\bar{g}(\xi)u+\bar{d}(t)$ represents a time-varying lumped disturbance.

$$\bar{L}(\xi,t)=\dot{\xi}-\bar{f}_n(\xi)-\bar{g}_n(\xi)u \tag{4}$$

For the formulation of NDO, a new state variable $\bar{z}$ is designed as

$$\bar{z}=\hat{\bar{L}}(\xi,t)-G\xi \tag{5}$$

The NDO is formulated as

$$\begin{cases}\hat{\bar{L}}(\xi,\bar{z})=\bar{z}+G\xi\\ \dot{\bar{z}}=-Gz-G\left(\bar{f}_n(\xi)+\bar{g}_n(\xi)u+G\xi\right)\end{cases} \tag{6}$$

The disturbance observer error can be defined as

$$e_{\bar{L}}=\bar{L}(\xi,t)-\hat{\bar{L}}(\xi,\bar{z}) \tag{7}$$

The equation of disturbance observer error is derived from (3), (6) as

$$\begin{aligned}\dot{e}_{\bar{L}}&=\dot{\bar{L}}(\xi,t)+G\left(z+\bar{f}_n(\xi)+\bar{g}_n(\xi)u+G\xi\right)-G\dot{\xi}\\ &=-Ge_{\bar{L}}+\dot{\bar{L}}(\xi,t)\end{aligned} \tag{8}$$

4. BACKSTEPPING CONTROLLER DESIGN

In this section, we will incorporate the proposed NDO technique into control design scheme for the n th-order system described by (1). Similar to the traditional backstepping design method, the recursive design procedure contains n steps.

Step 1: At the step, we consider the first equation in (1),

$$\dot{x}_1=f_1(x_1)+g_1(x_1)x_2+L_1(\bar{x}_2,t) \tag{9}$$

where $L_1(\bar{x}_2,t)=\hat{L}_1(\bar{x}_2,z_2)+e_{L_1}$, $e_{\bar{L}}$ is disturbance observer error.

At the step, NDO is formulated as

$$\begin{cases}\hat{L}_1(\bar{x}_2,z_1)=z_1+G_1x_1\\ \dot{z}_1=-G_1z-G_1\left(f_1(x_1)+g_1(x_1)x_2+G_1x_1\right)\end{cases} \tag{10}$$

where $G_1>0$ is a disturbance observer gain.

Let $x_{1d}=y_d$ and define $e_1=x_1-x_{1d}$.

Its derivative is

$$\dot{e}_1=f_1(x_1)+g_1(x_1)x_2+\hat{L}_1(\bar{x}_2,z_1)+e_{L_1}-\dot{x}_{1d} \tag{11}$$

The state observer is proposed as

$$\dot{\hat{x}}_1=f_1(x_1)+g_1(x_1)x_2+\hat{L}_1(\bar{x}_2,z_1)+\hat{e}_{L_1}+\eta_1(x_1-\hat{x}_1)$$

The disturbance observer error can be defined as $\tilde{x}_1=x_1-\hat{x}_1$, its derivative is

$$\dot{\tilde{x}}_1=\dot{x}_1-\dot{\hat{x}}_1=-\eta_1\tilde{x}_1-\tilde{W}_1^T\phi_1(e_1,\tilde{x}_1)+\varepsilon_1 \tag{12}$$

By employing a FNN virtual controller can be used as follows:

$$\begin{aligned}x_{2d}=-c_1e_1-\frac{1}{g_1(x_1)}\Big(&f_1(x_1)+\hat{L}_1(\bar{x}_2,z_1)\\ &+\hat{W}_1{}^T\phi_1(e_1,\tilde{x}_1)-\dot{x}_{1d}\Big)\end{aligned} \tag{13}$$

where $\Gamma_1=\Gamma_1^{-1}>0$ is an adaptation gain matrix.

Consider the following adaptation law

$$\dot{\hat{W}}_1=\Gamma_1\left\{\phi_1(e_1,\tilde{x}_1)(e_1+\tilde{x}_1)-\sigma_1\hat{W}_1\right\} \tag{14}$$

Step n: This is the final step. In (1) when, consider the following equation

$$\dot{x}_n=f_n(\bar{x}_n)+g_n(\bar{x}_n)u+L_n(\bar{x}_{n+1},t) \tag{15}$$

NDO is formulated as

$$\begin{cases}\hat{L}_n(u,z_n)=z_n+G_nx_n\\ \dot{z}_n=-G_nz_n-G_n\left(f_n(\bar{x}_n)+g_n(\bar{x}_n)u+G_nx_n\right)\end{cases} \tag{16}$$

The state observer is proposed as

$$\dot{\hat{x}}_n=f_n(\bar{x}_n)+g_n(\bar{x}_n)u+\hat{L}_i(u,z_n)+\hat{e}_{L_n}+\eta_n(x_n-\hat{x}_n)$$

The state observer error can be defined as $\tilde{x}_n=x_n-\hat{x}_n$, its derivative is

$$\dot{\tilde{x}}_n=\dot{x}_n-\dot{\hat{x}}_n=-\eta_n\tilde{x}_n-\tilde{W}_n^T\phi_n(e_n,\tilde{x}_n)+\varepsilon_n \tag{17}$$

Choose the control

$$\begin{aligned}u=-e_{n-1}-c_ne_n-\frac{1}{g_n(\bar{x}_n)}\Big(&f_n(\bar{x}_n)+\hat{L}_n(u,z_n)\\ &+\hat{W}_n^T\phi_n(e_n,\tilde{x}_n)-\dot{x}_{nd}\Big)\end{aligned} \tag{18}$$

Consider the following adaptation law

$$\dot{\hat{W}}_n=\Gamma_n\left\{\phi_n(e_n,\tilde{x}_n)(e_n+\tilde{x}_n)-\sigma_n\hat{W}_n\right\} \tag{19}$$

Let $c_n=c_{n0}+c_{n1}$ and $\eta_n=g_n(\bar{x}_n)(\eta_{n0}+\eta_{n1})$

$$\begin{aligned}\dot{V}_n<&-\sum_{k=1}^{n}c_{k0}e_k{}^2-\sum_{k=1}^{n}\eta_{k0}\tilde{x}_k{}^2-\sum_{k=1}^{n}\frac{\sigma_k\|\tilde{W}_k\|^2}{2g_k(\bar{x}_k)}\\ &+\sum_{k=1}^{n}\frac{\sigma_k\|W_k^*\|^2}{2g_k(\bar{x}_k)}+\sum_{k=1}^{n}\frac{\varepsilon_k^{*2}}{4g_k^2(\bar{x}_k)c_{k1}}+\sum_{k=1}^{n}\frac{\varepsilon_k^{*2}}{4g_k^2(\bar{x}_k)\eta_{k1}}\end{aligned} \tag{20}$$

According to [3], equation(20) shows the stability and control performance of the closed-loop adaptive system.

5. SIMULATION

A simple simulation is presented to show the effectiveness of the approach proposed above. The model of the system is given as

$$\dot{x}_1 = f_1(x_1) + \Delta f_1(x_1) + \big(g_1(x_1) + \Delta g_1(x_1)\big)x_2 + d_1(t)$$
$$\dot{x}_2 = f_2(\overline{x}_2) + \Delta f_2(\overline{x}_2) + \big(g_2(\overline{x}_2) + \Delta g_2(\overline{x}_2\big)u + d_2(t)$$
$$y = x_1$$

$$\begin{cases} f_1(x_1) = 0.5x_1, & \Delta f_1(x_1) = 2f_1(x_1) \\ g_1(x_1) = 1 + 0.1x_1^2, & \Delta g_1(x_1) = 2g_1(x_1) \end{cases}$$

$$\begin{cases} f_2(\overline{x}_2) = x_1 x_2, & \Delta f_2(\overline{x}_2) = 2f_2(\overline{x}_2) \\ g_2(\overline{x}_2) = 2 + \cos x_1, & \Delta g_2(\overline{x}_2) = 2g_2(\overline{x}_2) \end{cases}$$

$$\begin{cases} d_1(t) = 0.2\cos(3t - 5.5), & t \geq 10 \\ d_2(t) = 0.2\cos(3t - 5.5), & t \geq 15 \end{cases}$$

The control objective is to guarantee all the signals in the closed-loop system remain bounded and the output y follows a desired trajectory y_r generated from the following van der Pol oscillator system:

$$\dot{x}_{r1} = x_{r2}$$
$$\dot{x}_{r2} = -x_{r1} + \beta\big(1 - x_{d1}^2\big)x_{r2}$$
$$y_r = x_{d1}$$

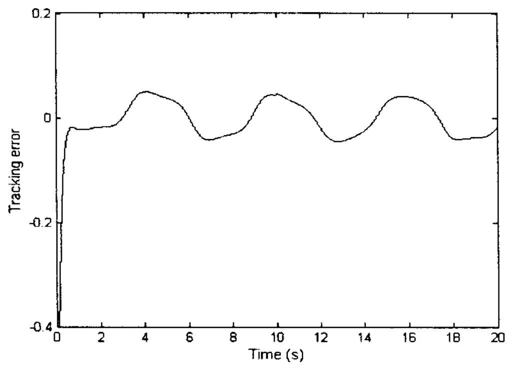

Fig. 1. Output tracking error

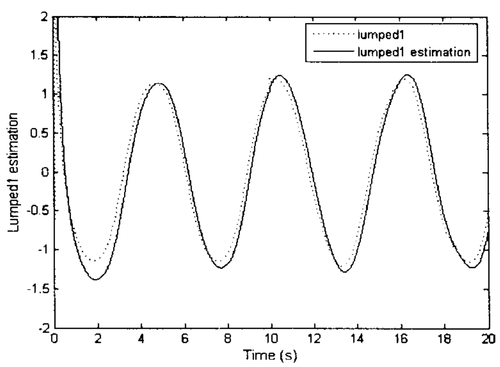

Fig. 2. Lumped 1 and its estimation

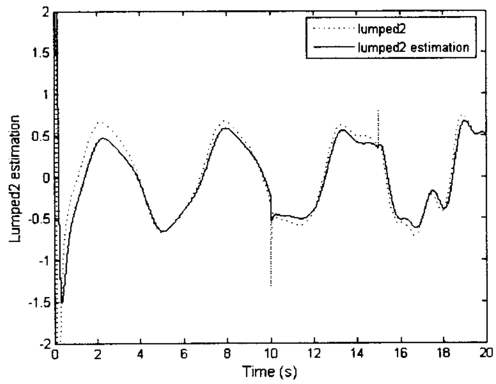

Fig. 3. Lumped 2 and its estimation

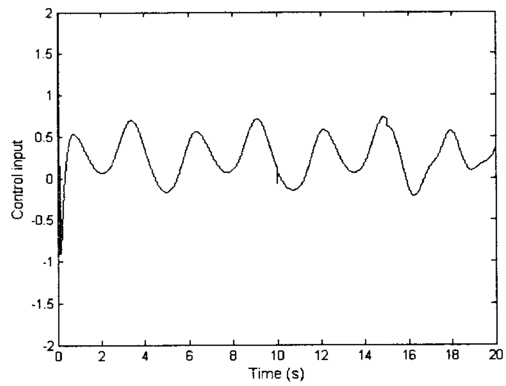

Fig. 4. Control input

The design parameters of the above controller are $c_1 = 10$, $c_2 = 10$ and $\beta = 0.2$.

6. CONCLUSIONS

In this paper, a robust adaptive control scheme is presented of a class of uncertain nonlinear system using NDO. All the signals of the closed-loop system are guaranteed to be semiglobally uniformly ultimately bounded, and the output of the system is proven to converge to a small neighborhood of the desired trajectory.

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