ISA Transactions 70 (2017) 419–431

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research article

Memoryless disturbance-observer-based adaptive tracking of uncertain pure-feedback nonlinear time-delay systems with unmatched disturbances

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ARTICLE INFO

Article history:
Received 24 February 2017
Received in revised form
14 July 2017
Accepted 14 July 2017
Available online 27 July 2017

Keywords:
Nonlinear disturbance observer (NDO)
Adaptive tracking
Unknown time-varying delays
Memoryless
Unmatched external disturbances

ABSTRACT

This paper presents a delay-independent nonlinear disturbance observer (NDO) design methodology for adaptive tracking of uncertain pure-feedback nonlinear systems in the presence of unknown time delays and unmatched external disturbances. Compared with all existing NDO-based control results for uncertain lower-triangular nonlinear systems where unknown time delays have been not considered, the main contribution of this paper is to develop a delay-independent design strategy to construct an NDO-based adaptive tracking scheme in the presence of unknown time-delayed nonlinearities and non-affine nonlinearities *unmatched* in the control input. The proposed delay-independent scheme is constructed by employing the appropriate Lyapunov-Krasovskii functionals and the same function approximators for the NDO and the controller. It is shown that all the signals of the closed-loop system are semi-globally uniformly ultimately bounded and the tracking error converges to an adjustable neighborhood of the origin.

1. Introduction

It is well known that the disturbance observer is a kind of more straightforward and efficient disturbance suppression method to achieve the satisfactory closed-loop control performance in the presence of time-varying external disturbances [1–5]. During recent years, the disturbance-observer-based control methods have been actively presented for several nonlinear systems with time-varying external disturbances [3–17]. These methods have been combined with the function approximation technique to design the nonlinear disturbance observers (NDO) for compensating time-varying external disturbances in the presence of unknown nonlinearities matched in the control input. In [18–20], the function approximators such as neural networks or fuzzy logic systems have been employed to estimate unknown nonlinearities in the NDO and the controller. In addition, the NDO-based control approaches were applied to practical systems such as robotic systems [21,22]. However, systems with nonlinearities matched in the control input were only considered in [18–22]. To consider the unmatched nonlinearities, the approximation-based NDO approaches for tracking control have recently presented for uncertain strict-feedback [23–26] and pure-feedback nonlinear systems [27,28] with time-varying external disturbances. Furthermore, two inertia systems were considered in [29] to design the approximation-based NDO and tracker where fuzzy logic systems were used for constructing the approximation-based NDO. In [30], the fault estimation and tolerant control method using the disturbance observer was presented for fuzzy systems with local nonlinear models. Although these approaches have been successfully developed for a variety of uncertain lower-triangular nonlinear systems, the aforementioned research results have not yet been extended into uncertain lower-triangular nonlinear systems with unknown and unmatched time delays. The main difficulty in dealing with the approximation-based NDO design problem in the presence of unknown time delays is to develop a delay-independent design methodology for the approximation-based NDO design in the recursive and systematic control design procedure. In other words, both the NDO and the tracking controller should be designed without the information of time delays.

On the other hand, the control problem of time-delay systems has attracted considerable attention from the control community because time delays generally degrade the system performance and even result in instability in various practical applications such as chemical processes, biological systems, nuclear reactors, and virtual laboratories, and so on [31–33]. In particular, the recursive and systematic control design methods using backstepping [34] and dynamic surface design [35] have been actively developed for nonlinear time-delay systems in lower-triangular form [36,37]. These results have been extended into approximation-based control results for nonlinear time-delay systems with completely unknown and unmatched nonlinearities in strict-feedback form (see [38–47] and references therein) and in pure-feedback form (see [48–50] and references therein). Despite these progresses,

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http://dx.doi.org/10.1016/j.isatra.2017.07.017
0019-0578/

there have still been no research results available for the NDO-based tracking problem of uncertain lower-triangular nonlinear time-delay systems. Moreover, it is worth pointing out that solving the approximation-based NDO design problem for tracking control in the absence of the exact information of delays is more challenging.

Motivated by the aforementioned observations, this paper presents a memoryless approximation-based NDO design methodology for the adaptive tracking scheme of uncertain pure-feedback nonlinear systems with unknown time delays and external disturbances. The non-affine nonlinearities and time-varying external disturbances are assumed to be unknown and unmatched in the control input. A new delay-independent NDO-based adaptive tracking scheme is designed by choosing appropriate Lyapunov-Krasovskii functionals where the same function approximators are employed for the NDO and the controller in order to estimate unknown nonlinearities derived in the recursive control design procedure. Then, we show that all the signals of the closed-loop system are semi-globally uniformly ultimately bounded and the tracking error converges to an adjustable neighborhood of the origin in the Lyapunov sense.

The main contributions of this paper are twofold.

(C1) In contrast to the existing approximation-based NDO approaches for uncertain nonlinear systems [23–30], this paper considers unknown time delays in nonlinearities and proposes a delay-independent design methodology for the approximation-based NDO scheme in the tracking control framework of uncertain pure-feedback nonlinear time-delay systems. Furthermore, by employing the same function approximators in the NDO and the controller, the computational burden caused by using the function approximators can be reduced in the control scheme; and.

(C2) A recursive memoryless design methodology is developed for dealing with unknown non-affine nonlinearities, time-delayed nonlinearities, and external disturbances *unmatched* in the control input, simultaneously. To the best of our knowledge, this research is the first trial in the field of the approximation-based NDO and tracker design.

This paper is organized as follows. The problem statement is given in Section 2. In Section 3, a delay-independent design methodology for the NDO-based adaptive tracking of uncertain pure-feedback nonlinear time-delay systems with unmatched external disturbances is presented. The stability of the proposed tracking scheme is analyzed in Section 4. Simulation results are discussed in Section 5. Finally, Section 6 gives some conclusions.

2. Problem formulation

Consider a class of uncertain pure-feedback nonlinear time-delay systems with unmatched disturbances described by

$$\begin{aligned} \dot{x}_i(t) &= f_i(\bar{x}_i(t), x_{i+1}(t)) + h_i(\bar{x}_{i,\tau(t)}) + d_i(t), \\ \dot{x}_n(t) &= f_n(\bar{x}_n(t), u(t)) + h_n(\bar{x}_{n,\tau(t)}) + d_n(t), \\ y(t) &= x_1(t), \\ x(t) &= \varphi(t), \quad -\bar{\tau} \le t \le 0, \end{aligned} \tag{1}$$

where $i = 1, \ldots, n-1$, $\bar{x}_i = [x_1, \ldots, x_i]^\top \in \mathbb{R}^i$, $i = 1, \ldots, n$, are state variables, $u \in \mathbb{R}$ and $y \in \mathbb{R}$ are a control input and a system output, respectively, $d_i \in \mathbb{R}$, $i = 1, dots, n$, are unknown external disturbances, $f_i(\cdot): \mathbb{R}^{i+1} \mapsto \mathbb{R}$, $i = 1, \ldots, n$, are unknown C^1 non-affine nonlinear functions, $h_i(\cdot): \mathbb{R}^n \mapsto \mathbb{R}$ with $h_i(0) = 0$ are unknown C^1 nonlinear time-delay functions, $\varphi(t)$ is the initial state vector function, $\bar{x}_{i,\tau(t)} = [x_1(t-\tau_1(t)), \ldots, x_i(t-\tau_i(t))]^\top$ is the delayed state vector; $\tau_i(t)$ are unknown time-varying delays which satisfy $0 < \tau_i(t) \le \bar{\tau}_i < \infty$ and $\dot{\tau}_i(t) \le \bar{\tau}_{i,d} < 1$ with unknown constants $\bar{\tau}_i > 0$, $\bar{\tau}_{i,d} > 0$, and $\bar{\tau} = \max_{i=1,\ldots,n}\{\bar{\tau}_i\}$.

Problem 1. Consider system (1). Our problem is to design a memoryless NDO-based adaptive tracking law u for system (1) in the presence of unknown and unmatched non-affine nonlinearities, time-varying delays and external disturbances so that the system output $y(t)$ follows a given desired signal $y_d(t)$ while all signals of the closed-loop system remain bounded.

Assumption 1. The desired signal $y_d(t)$ and its derivatives $\dot{y}_d(t)$ and $\ddot{y}_d(t)$ are available and bounded.

Assumption 2. [51] Let $g_i(\bar{x}_i, x_{i+1}) = \partial f_i(\bar{x}_i, x_{i+1})/\partial x_{i+1}$ where $i = 1, \ldots, n$ and $x_{n+1} = u$. Then, g_i are non-zero, unknown, and their signs are known. Furthermore, there exist constants $\underline{g}_i > 0$ and $\bar{g}_i > 0$ such that $0 < \underline{g}_i \le |g_i| \le \bar{g}_i$ for $(\bar{x}_i, x_{i+1}) \in \Gamma_{i+1}$ where $\Gamma_{i+1} \in \mathbb{R}^{i+1}$ is a compact set. Without losing generality, we assume that the signs of g_i are positive.

Assumption 3. [52] $\dot{g}_i$ is bounded as $|\dot{g}_i| \le \bar{g}_{i,d}$ for $(\bar{x}_i, x_{i+1}) \in \Gamma_{i+1}$ where $i = 1, \ldots, n$ and $\bar{g}_{i,d} > 0$ is an unknown constant.

Assumption 4. [24] The disturbance d_i and its derivative $\dot{d}_i$ are bounded as $|d_i| \le \bar{d}_i$ and $|\dot{d}_i| \le \bar{d}_{i,d}$, respectively, where $\bar{d}_i > 0$ and $\bar{d}_{i,d} > 0$ are unknown constants.

Lemma 1. [53] *For any continuous function* $h(\varrho_1, \ldots, \varrho_n): \mathbb{R}^{m_1} \times \cdots \times \mathbb{R}^{m_n} \to \mathbb{R}$ *satisfying* $h(0, \ldots, 0) = 0$, *where* $\varrho_j \in \mathbb{R}^{m_j}$; $j = 1, 2, \ldots, n$ *and* $m_j > 0$, *there exist positive smooth functions* $\varpi_j(\varrho_j): \mathbb{R}^{m_j} \to \mathbb{R}$, $j = 1, 2, \ldots, n$, *satisfying* $\varpi_j(0) = 0$ *such that* $|h(\varrho_1, \ldots, \varrho_n)| \le \sum_{j=1}^n \varpi_j(\varrho_j)$.

From Lemma 1, the time-delay functions $h_i(\bar{x}_i(t-\tau_i(t)))$ can be expressed as

$$|h_i(\bar{x}_i(t-\tau_i(t)))| \le \sum_{l=1}^{i} \varpi_{i,l}(x_l(t-\tau_l(t))), \tag{2}$$

where $\varpi_{i,l}(x_l)$ are unknown nonlinear functions.

Remark 1. Compared with the existing NDO-based tracking results [23–30] for nonlinear systems without time delays, this paper consider the pure-feedback systems (1) with unknown non-affine nonlinearities and time delays. In addition, the delay-independent NDO-based tracker design problem in the presence of unknown time delays is considered in this paper. Thus, the existing results [23–30] cannot provide a solution on Problem 1.

3. Memoryless NDO-based adaptive tracker design using neural networks

3.1. Radial basis function neural networks

The radial basis function neural network (RBFNN) [54,55] is employed to approximate the continuous nonlinear function $\psi(\nu): \mathbb{R}^q \mapsto \mathbb{R}$ as follows:

$$\psi(\nu) = \hat{W}^\top S(\nu) \tag{3}$$

where ν is the input vector, $\hat{W} = [\hat{w}_1, \ldots, \hat{w}_l]^\top \in \mathbb{R}^l$ with the node number $l > 1$ is the weighting vector, $S(\nu) = [s_1(\nu), \ldots, s_l(\nu)]^\top \in \mathbb{R}^l$; $s_i(\nu)$, $i = 1, \ldots, l$, are Gaussian functions, which have the form

$$s_i(\nu) = \exp\left[\frac{-(\nu - \varrho_i)^\top(\nu - \varrho_i)}{r_i^2}\right], \tag{4}$$

where $\varrho_i = [\varrho_{i,1}, \varrho_{i,2}, \ldots, \varrho_{i,q}]^\top$ is the center of the receptive field and r_i is the width of the Gaussian function. According to the universal