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Cascade observer design for a class of nonlinear uncertain systems: Application to bioreactor

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Abstract: The present work proposes a state observer with a cascade structure for a class of nonlinear systems in the presence of uncertainties in the state equations and an arbitrarily long delay in the output. The first system in the cascade allows to estimate the delayed state while each of the remaining systems is a predictor. Each predictor estimates the state of the preceding one with a prediction horizon equal to a fraction of the time delay in such a way that the state of the last predictor is an estimate of the system actual state. The design of the observer is achieved by assuming a set of conditions under which the ultimate boundedness of the estimation error is established. It is in particular shown that in the absence of uncertainties, the observation error converges exponentially to zero. In the presence of uncertainties, the asymptotic observation error remains in a ball which radius depends on the delay magnitude and can be decreased by appropriately choosing the cascade length and the observer design parameters. The performance of the proposed observer and its main properties are highlighted through a typical bioreactor model.

Key words : delayed output, uncertain system, cascade observer, high gain observer.

1. INTRODUCTION

During the last two decades, an intensive research activity has been devoted to investigate the stability, control and state estimation for systems with time delays. A particular attention has been paid to the case of linear systems (See for instance Hou et al. [2002], Gu et al. [2003], Kharitonov and Hinrichsen [2004], Mondie and Kharitonov [2005] and references therein) whereas only few results have been established in the nonlinear case (see for instance Mazenc and Niculescu [2001], Trinh et al. [2004]). Moreover, in most works dealing with state estimation for delay systems, the output is assumed to be delay-free. In many real-time applications, some state variables may not be available instantaneously and corresponding measurements are systematically tainted with delay. One can cite the example of bioreactors where most of the component measurements are obtained with a more or less important time delay since they result from time consuming laboratory analyses. Another typical example is that of network connected systems where some output data are transmitted through low-rate communication systems. This generally introduces non negligible time-delays that have to be account for in order to ensure the viability of the control and monitoring system.

The problem of observer design with output delay has been comprehensively examined in Kristic [2009] for linear systems. For nonlinear systems, a cascade observer has been initially proposed in Germani et al. [2002] and the underlying design has been reconsidered in Kazantzis and Wright [2005] for output constant delays and in Farza et al. [2015], Cacace et al. [2014] for output time-varying delays. The cascade observer is constituted by a chain of subsystems where each subsystem predicts the state of the preceding one in the chain on a fraction of the original delay in such a way that the state of the last subsystem provides an estimate of the system actual state. A brief description of the main properties of the cascade observers proposed in Kazantzis and Wright [2005], Farza et al. [2015] is given in Farza et al. [2015]. It should be emphasized that in all the aforementioned works, the considered classes of systems do not involve uncertainties. Hence, one the main motivations of this work is to extend the cascade observer design to a class of systems which accounts for some particular uncertainties. We shall then show that the proposed cascade observer can be used for the estimation of the actual component concentrations as well as the actual reaction rates time-variations in bioreactors from the delayed measurements of some component concentrations. It should be emphasized that such estimates are provided without the use of any mathematical model for the reaction rates.

Indeed, in the present work, one shall propose a cascade observer for a class of MIMO nonlinear uncertain systems which are observable for any input and where the output is available with a delay. The observer is constituted by $m+1$ cascaded subsystems where the dimension of each subsystem is equal to that of the system. The head of the cascade (the first subsystem) is a high gain observer and provides an estimate of the delayed state from the delayed

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output. The m remaining subsystems are predictors and are such that each one predicts the state of the preceding subsystem with a prediction horizon equal to $\frac{\tau}{m}$ in such a way that the state of the last subsystem is an estimate of the system actual state.

This paper is organized as follows. In the next section the class of considered systems is introduced and some requisite preliminaries related to the observer design in the free delay output case are briefly presented. In section 3, the main steps of the observer design are detailed and its main properties are emphasized. In section 4, the use of the proposed observer for the estimation of the actual component concentrations and the actual reaction rates time variations from the measurements of delayed component concentrations is illustrated through a typical bioreactor. Finally, some concluding remarks are given in section 5.

2. PROBLEM FORMULATION AND PRELIMINARIES

Consider the class of multivariable nonlinear systems that are diffeomorphic to the following bloc triangular form:

$$\begin{cases} \dot{x}(t) = Ax(t) + \varphi(u(t), x(t)) + B\varepsilon(t) \\ y_\tau(t) = Cx(t-\tau) = x^1(t-\tau) \end{cases} \tag{1}$$

with

$$x = \begin{pmatrix} x^1 \\ \vdots \\ x^{q-1} \\ x^q \end{pmatrix} \in \mathbb{R}^n, \quad \varphi(u,x) = \begin{pmatrix} \varphi^1(u,x^1) \\ \varphi^2(u,x^1,x^2) \\ \vdots \\ \varphi^{q-1}(u,x^1,\ldots,x^{q-1}) \\ \varphi^q(u,x) \end{pmatrix}$$

$$A = \begin{pmatrix} 0_{(q-1)p,p} & I_{(q-1)p} \\ 0_{p,p} & 0_{p,(q-1)p} \end{pmatrix}, \; B = \begin{pmatrix} 0_p & 0_p & \ldots & I_p \end{pmatrix}^T,$$

$$C = \begin{pmatrix} I_p & 0_p & \ldots & 0_p \end{pmatrix} \tag{2}$$

where $x^i \in \mathbb{R}^p$ for $i \in [1,\ q]$ are the state variables blocks, $u(t) \in U$ a compact subset of $\mathbb{R}^m$ denotes the system input and $y_\tau \in \mathbb{R}^p$ denotes the delayed output of the system, $\tau > 0$ is the measurement delay, $\varepsilon : \mathbb{R}^+ \mapsto \mathbb{R}^p$ is an unknown function describing the system uncertainties and may depend on the state, the input and uncertain parameters.

As it is mentioned in the introduction, our main objective is to design a cascade observer providing an estimation of the full state of system (1) by using the delayed output measurements. Such a design will be carried out under the following assumptions:

A1. The state $x(t)$ is bounded i.e. there exists a compact set $\Omega \in \mathbb{R}^n$ such that $\forall t \geq 0,\ x(t) \in \Omega$.

A2. The function φ is Lipschitz with respect to x uniformly in u, i.e.

$$\forall \rho > 0;\ \exists L_\varphi > 0;\ \forall u\ s.t.\ \|u\| \leq \rho; \forall (x,\bar{x}) \in \Omega \times \Omega : \\ \|\varphi^i(u,x) - \varphi^i(u,\bar{x})\| \leq L_\varphi \|x - \bar{x}\| \tag{3}$$

A3. The unknown function ε is essentially bounded, i.e.

$$\exists \delta_\varepsilon > 0\ ;\ \sup_{t \geq 0} Ess\| \varepsilon(t)\| \leq \delta_\varepsilon \tag{4}$$

There are two remarks that are worth to be pointed out. Firstly, the class of systems described by (1) may seem very restrictive since it assumes a non prime dimension ($n = pq$) and the state blocks x^k have the same dimension p. This is not the case since it is shown in Hammouri and Farza [2003] that in the uncertainties-free case, system (1) is a normal form which characterizes a class of uniformly observable nonlinear systems that can be put under this form via an injective map (see e.g. Hammouri and Farza [2003], Farza et al. [2004] for more details). Secondly, since the system state trajectory lies in a bounded set Ω, one can extend the nonlinearities $\varphi(u,x)$ in such a way that this extension becomes globally Lipschitz on the entire state space $\mathbb{R}^n$. The observer synthesis will then be based on the resulting extended system which coincides with the original system on the domain of interest i.e. Ω. One can refer to Shim et al. [2001], Andrieu and Praly [2006] and references therein for more details on how to carry globally Lipschitz prolongations in the state observation context.

In the free delay case ($y_\tau(t) = y(t)$), a high gain observer has been proposed for system (1). The equation of the proposed observer can be written as follows Farza et al. [2004]:

$$\dot{\hat{x}}(t) = A\hat{x}(t) + \varphi(u(t),\hat{x}(t)) - \theta\Delta_\theta^{-1}K(C\hat{x}(t) - y(t)) \tag{5}$$

where K is a constant vector and is chosen such that the matrix $A - KC$ is Hurwitz, $\theta \geq 1$ is a design parameter and Δ_θ is the following diagonal matrix

$$\Delta_\theta = diag\left(1, \frac{1}{\theta}, \ldots, \frac{1}{\theta^{q-1}}\right) \tag{6}$$

It has been shown that the observation error is bounded as follows:

$$\|\hat{x}(t) - x(t)\| \leq \mu(\theta)e^{-\lambda(\theta)t}\|\hat{x}(0) - x(0)\| + \frac{M}{\theta}\delta_\varepsilon \tag{7}$$

where $\theta > 0$ is the observer design parameter, $M > 0$ is a positive constant that does not depends on θ, $\mu(\theta)$ is polynomial in θ with $\lim_{\theta \to +\infty} \lambda(\theta) = +\infty$ and finally δ_ε is the bound of the uncertainty as given by (4) in Assumption **A3**.

It should be emphasized that in the absence of uncertainties i.e. $\delta_\varepsilon = 0$, the observation error converges exponentially to zero. In the case where the uncertainties are bounded the observation error is ultimately bounded and the underlying ultimate bound can be made as small as desired by choosing values sufficiently high for the observer design parameter θ.

The main outlines of the cascade observer design shall be detailed in the subsequent sections.

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