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Design of a unified adaptive fuzzy observer for uncertain nonlinear systems

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A B S T R A C T

This paper presents *an adaptive fuzzy observer* for a class of uncertain nonlinear systems. More precisely, we propose a unified approach for designing such an observer with some design flexibility so that it can be easily adaptable and employed either as a high-gain or a sliding mode observer by selecting its gain appropriately. Additionally, we derive a suitable parameter adaptation law so that the proposed observer is robust with respect to ubiquitous fuzzy approximation errors and external disturbances. We also show that the observation error is ultimately bounded using a Lyapunov approach without having recourse to the usual strictly positive real (SPR) condition or a suitable observation error filtering. The effectiveness of the proposed observers is illustrated through two simulation case studies taken from the adaptive fuzzy control literature.

1. Introduction

In most practical situations, one is rarely if ever in the presence of a system whereby all the states variables of the system are fully measured or accessible. This particular fact has been the main motivation and driving force behind the development of the observation theory for dynamical systems for the purpose of process control and fault diagnosis. In effect, over the years there has been a considerable development in various observer design methodologies using different approaches (see list of references herein). Among these, the design of adaptive observers is quite challenging since they allow to estimate not only the state variables but the unknown system parameters as well [14] and this in the presence of modelling uncertainties.

The first nonlinear adaptive observer was proposed in [2] for single-input single-output (SISO) nonlinear systems that can be transformed into an uncertain observable canonical form. The multiple-input single-output (MISO) case has been investigated in [22,23] for nonlinear systems that are linear with respect to the unknown parameters. Additionally, these systems are transformable, by using a suitable change of coordinates, into a special canonical form whereby the nonlinearities are functions of the output only. An adaptive observer with an arbitrary fast exponential convergence has been proposed in [24] for the class of MISO systems mentioned above. The multiple-input multiple-output (MIMO) case has been treated in [5,27] for a particular class of Lipschitz nonlinear systems that are linear in the unknown parameters owing to an appropriate dissipative or strictly positive real (SPR) condition. In [12], an adaptive observer has been presented for a class

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of time-delay systems whereby the underlying observation algorithm is designed independently of the time-delay variations, thanks to an adequate SPR condition on the observation error dynamics along with a matching condition involving the system nonlinearities.

Adaptive observers as well as adaptive controllers (see e.g. [17,6,25,26,34,44] and [18,20–21,26,30–32,35,36,38,41–43]) for nonlinear systems incorporating universal approximators, namely fuzzy systems (FS) and neural networks (NN) have also received considerable attention over the past few decades. These universal approximators [4,11,36,37] make it possible to relax the aforementioned structural constraints such as the linearity in the unknown parameters, the Lipschitz condition on the nonlinearity involved or the prior knowledge of the nonlinearities and the output feedback form. In [17], an adaptive observer has been proposed for SISO nonlinear systems based on the universal approximation theorem along with a suitable SPR condition on the observation error dynamics. An appropriate filtering of the observation error dynamics is used to deal with the SPR requirement. This filtering inevitably increases the order of the observer dynamics. In [29], a fuzzy adaptive observer has been developed for a class of time-delayed chaotic systems. Sufficient conditions guaranteeing robust observation performances have been established.

A set of adaptive fuzzy or neural observers has been developed for a class of uncertain nonlinear systems in [6,25,26,34] without resorting to the SPR condition. In [25,26], the output observation error is filtered and the state variables of the filter employed are used to design the underlying adaptation law as well as the robust compensator. The filter is mainly used to deal with the fuzzy approximation error as well as external disturbances. It is important to note that there is a kind of redundancy in these contributions due to the use of a specific estimator consisting of a chain of integrators to estimate the filter states. An adaptive observer has been developed in [6] using an appropriate filtering of the regressor vector for stability purposes. It is mostly based on the nonlinear model estimation method for automated fault diagnosis proposed in [33]. Neural adaptive observers for a large class of unknown nonlinear systems have been designed in [34] with mild assumptions without resorting to the usual SPR condition.

In this paper, we propose a unified adaptive fuzzy observer design framework for a class of uncertain nonlinear systems based on the high gain observer concept. The proposed observer presents some design flexibility in the sense that one can either obtain a high-gain observer or a sliding mode observer, depending on the choice of the output error corrective term of the latter. Also, unlike previous adaptive fuzzy or neural observers, the corrective term is nonlinear with respect to the output observation error. The main feature of the proposed observer is that, firstly, the SPR condition is no longer required and secondly, a PI parameter adaptation is used to provide a suitable robustness with respect to fuzzy approximation errors and external disturbances.

An outline of the paper is as follows: In the next section, the class of systems considered and notations employed throughout the paper are given. In Section 3, an adaptive fuzzy system is used to approximate the unknown nonlinearity involved in the system is presented. In Section 4, the adaptive fuzzy observer is derived under some given assumptions together with the underlying adaptation law. The convergence analysis of the observer is also carried out. Section 5 is devoted to simulation case studies dealing with a mass–spring–damper system and a half-car active suspension system. Finally, some conclusions are given.

2. Notation and the class of systems considered

Throughout the paper, R denotes the set of real numbers, R^n the set of real n-vectors and $R^{n\times m}$ the set of real $m \times n$ matrices. The Euclidian norm of a vector $\underline{x} \in R^n$ is denoted by $\|\underline{x}\|$, i.e. $\|\underline{x}\| = \sqrt{x_1^2 + \cdots + x_n^2}$, and the induced norm of a matrix $A \in R^{n\times m}$, is denoted by $\|A\|_2$. More precisely, $\|A\|_2 = \sqrt{\lambda_{\max}(A^T A)} = \sigma_{\max}(A)$, $\lambda_{\max}(\cdot)$ and $\lambda_{\min}(\cdot)$ are largest and smallest eigenvalues of the matrix A and $\sigma_{\max}(A)$ is the maximum singular value. The absolute value is denoted by $|\cdot|$.

We consider the class of nth order nonlinear dynamical systems of the form

$$y^{(n)} = f(y, \dot{y}, \ldots, y^{(n-1)}, u) + d(t) \tag{1}$$

or equivalently of the form

$$\begin{aligned} \dot{\underline{x}} &= A\underline{x} + B[f(\underline{x}, u) + d(t)] \\ y &= C\underline{x} \end{aligned} \tag{2}$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}, \quad C^T = \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} \tag{3}$$

$u \in \Omega_u \subset R$ is the input, $y \in R$ is the output, f is an unknown but continuous function, d is the external bounded disturbances, i.e. $|d(t)| \leqslant D$ and $\underline{x} = [y, \dot{y}, \ldots, y^{(n-1)}]^T = [x_1, x_2, \ldots, x_n]^T \in \Omega_{\underline{x}} \subset R^n$ is the unknown state vector.