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Fuzzy adaptive observer backstepping control for MIMO nonlinear systems☆

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Abstract

In this paper, a fuzzy adaptive backstepping output feedback control approach is developed for a class of multi-input and multi-output (MIMO) nonlinear systems with unmeasured states. Using fuzzy logic systems to approximate the unknown nonlinear functions, a fuzzy adaptive observer is designed for state estimation as well as system identification. Combining with the backstepping design techniques, a fuzzy adaptive output feedback control is constructed recursively. It is proved that the proposed fuzzy adaptive control approach can guarantee the semi-global uniform ultimate boundedness for all the signals and the tracking error to a small neighborhood of the origin. Simulation studies illustrate the effectiveness of the proposed approach.

Keywords: MIMO nonlinear systems; Fuzzy control; Adaptive control; Backstepping design; State observer; Stability

1. Introduction

In practice, most plants are nonlinear and contain uncertainties. During the past years, many people have devoted a lot of effort to both theoretical research and implementation techniques to handle nonlinear control problems. In [17], a genetic algorithms-based fuzzy modeling approach was proposed to generate TSK models. A simple and effective fuzzy-rule-based model of complex systems from input–output data was developed in [15]. Fuzzy control methodology has emerged in recent years as a promising way to deal with the control problems of nonlinear systems containing highly uncertain nonlinear functions. It has been shown that fuzzy logic systems (FLS) can be used to approximate any nonlinear function over a convex compact region [24]. Based on this observation, Stable direct and indirect adaptive fuzzy control schemes were first developed to control uncertain nonlinear systems by Lyapunov function method [25]. Afterwards, several stable adaptive fuzzy control schemes have been introduced, respectively, for SISO nonlinear systems [1,5,13,19–22,26]. The corresponding research results have been extended to multi-input and multi-output (MIMO) nonlinear systems [6–8,14,16,29]. The basic idea of these works is to use the fuzzy logic systems to approximate the unknown nonlinear functions in the systems and implement the design of adaptive fuzzy

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controller by using Lyapunov stability theory. All the results mentioned above are obtained with such the restriction that the nonlinear systems must be of the feedback linearization construction, which means that the unknown nonlinear functions need to satisfy the matching conditions. If in the practical systems the matching conditions cannot be satisfied, these adaptive fuzzy control approaches cannot be applied.

Backstepping, which is based on the nonlinear stabilization technique of "adding an integrator" introduced in [12], and was first used in nonlinear adaptive control in [10], leads to the discovery of a structural strict feedback condition under which the systematic construction of robust control Lyapunov function is always possible. Up to now, backstepping-based adaptive control technique, which is mainly used to deal with the robust control of the nonlinear systems with parametric uncertainties and the nonlinear functions assumed to be known, has become one of the most popular design methods for a large class of nonlinear systems [4,18,32].

With the development of adaptive and robust backstepping designs in nonlinear systems, many fuzzy adaptive control schemes have been developed for unknown nonlinear systems not satisfying the matching conditions. Stable fuzzy adaptive backstepping controller design schemes were proposed for unknown nonlinear SISO systems [23,25,30,31,33]. Some further results on fuzzy adaptive backstepping control approaches were reported by [2,3] for a class of MIMO nonlinear systems with triangular structure in control input. The advantage of adaptive fuzzy control based on backstepping methodology includes that both the parameters and the nonlinear functions can be unknown and the uncertainties in systems need not satisfy the matching conditions. However, the existing fuzzy adaptive backstepping controllers are all based on the assumption that the states of the systems are measured directly, there are few results on the fuzzy adaptive output feedback backstepping controllers. Recently, Refs. [9,23] have developed fuzzy adaptive output feedback backstepping control approaches for the uncertain nonlinear SISO systems. The fuzzy adaptive output feedback controller in [9] is designed on the variable structure and backstepping design technique. It takes the unknown function as the external disturbances, and designs a sliding mode controller. In order to overcome the "hard" high gain phenomenon, B-spline-type membership functions are introduced into the controller to form "soft" adaptive fuzzy output controller. Ref. [23] utilizes fuzzy logic systems to approximate the unknown functions in the systems, and a fuzzy adaptive state observer is formed. Based on the backstepping technique, a stable fuzzy adaptive output feedback controller approach is developed. To the best author's knowledge, however, to date, there are no results on adaptive fuzzy output feedback backstepping controllers for MIMO nonlinear systems with unmatched nonlinear functions, which is very important in both theory and real world applications.

The motivation of this paper is to develop an adaptive fuzzy output feedback control approach for a class of uncertain MIMO nonlinear systems. In such problems, the system does not satisfy the matching condition and the state vector is not directly measured. Using fuzzy logic systems to approximate the unknown nonlinear functions, the fuzzy adaptive state observer is first designed for state estimations as well as system identifications. Using the state observer and based on the backstepping design method, a fuzzy adaptive output feedback controller is constructed. It is proved that the proposed design scheme can achieve semi-global uniform ultimate boundedness of all the signals in the closed-loop systems, and the tracking errors converge to a small neighborhood of the origin.

2. Systems descriptions and control problems

Consider a class of MIMO nonlinear systems described by the differential equations as [2,3]

$$
\begin{aligned}
\dot{x}_{i1} &= x_{i2} + f_{i1}(\underline{x}_{n_1}, u_1, \underline{x}_{n_2}, u_2, \ldots, \underline{x}_{n_{i-1}}, u_{i-1}, x_{i1})\\
\dot{x}_{i2} &= x_{i3} + f_{i2}(\underline{x}_{n_1}, u_1, \underline{x}_{n_2}, u_2, \ldots, \underline{x}_{n_{i-1}}, u_{i-1}, x_{i1}, x_{i2})\\
&\vdots\\
\dot{x}_{in_i-1} &= x_{in_i} + f_{in_i-1}(\underline{x}_{n_1}, u_1, \underline{x}_{n_2}, u_2, \ldots, \underline{x}_{n_{i-1}}, u_{i-1}, x_{i1}, \ldots, x_{in_i-1})\\
\dot{x}_{in_i} &= u_i + f_{in_i}(\underline{x}_{n_1}, u_1, \underline{x}_{n_2}, u_2, \ldots, \underline{x}_{n_{i-1}}, u_{i-1}, x_{i1}, \ldots, x_{in_i})\\
y_i &= x_{i1}\\
i &= 1, 2, \ldots, m;\ \ n_1 + \cdots + n_m = n,
\end{aligned}
\tag{1}
$$