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Observer-based fuzzy adaptive control for multi-input multi-output nonlinear systems with a nonsymmetric control gain matrix and unknown control direction

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Abstract

In this study, we present an observer-based fuzzy adaptive control scheme for a class of uncertain multi-input multi-output nonlinear systems with a nonsymmetric control gain matrix, unknown control direction, and unmeasured states. In this scheme, fuzzy systems are used to approximate the unknown nonlinear functions and an adaptive fuzzy state observer is designed to estimate the unmeasured states. The parameter adaptive laws are designed by fuzzy basis functions rather than by its filtering and a robust control term is used to compensate for the lumped errors. The proposed method solves the problem of the nonsymmetric control gain matrix and it requires no a priori knowledge of the control direction for the states that are unmeasured. We prove that all of the signals in the resulting closed-loop systems are bounded and that the tracking errors converge asymptotically to zero. Two simulation examples are used to demonstrate the effectiveness of the proposed scheme.

Keywords: Fuzzy adaptive control; MIMO nonlinear system; Nussbaum gain; State observer

1. Introduction

In control engineering, most practical systems are multi-input multi-output (MIMO) systems. In these systems, the control problem is highly complex due to the coupling between inputs and outputs. It becomes even more difficult to deal with these systems if they are nonlinear and uncertain. Because of these difficulties, relatively few results are available for a general class of MIMO systems compared with single-input single-output (SISO) systems.

Thanks to the universal approximation property [1,2], several adaptive fuzzy control schemes have been developed for MIMO nonlinear systems in the past two decades [3–23]. To handle approximation errors and external

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disturbances, the fuzzy adaptive controller was augmented by a robust compensator in some of the proposed schemes [3,4,7,9,10,12,15]. Furthermore, to obtain a robust compensator and to facilitate performance analyses of these systems, some of the aforementioned results were obtained under the restrictive assumption that the control direction was known a priori. For example, in [9,10,12,15,16], it was assumed that the control gain matrix was positive definite, while a restriction was made for the smallest singular of the gain matrix in [11]. There are particular cases where the control direction can be known a priori [24], but the assumption regarding the control direction does not appear to be realistic in a general case [25]. If there is no a priori knowledge of the control direction, the adaptive fuzzy control of these systems becomes much more difficult. The pioneering research in this area involved the development of a class of first order linear systems [26], where the Nussbaum-type gain was originally proposed, and the Nussbaum-type function has been used effectively for solving the unknown control direction problem for MIMO nonlinear systems [13,14,27,28] and for systems in the parameter-strict feedback form [29–31]. However, in [13,14], the restrictive assumption required that the control gain matrix had nonzero leading principal minors. In addition, the control direction was assumed to be positive or negative, and the case with an indefinite direction was not considered. In [27,28], the two main limitations were that the structure of nonlinear systems comprised a lower triangular and that the boundedness of the control gains were required to be known. For systems in the parameter-strict feedback form, the key assumption was that the control gains were constant [29,31] or bounded [30].

Another key assumption of some of the schemes mentioned above is that all of the state variables of the systems are available for measurement. In many control engineering problems, however, the state variables may be partially unavailable or totally unavailable. In these cases, output feedback control schemes must be employed to obtain the desired performance. In the last decade, many adaptive fuzzy output feedback control schemes have been developed for a class of nonlinear systems [32–42]. However, these results can only be applied to a relatively simple class of nonlinear SISO systems. Due to the complexity of MIMO nonlinear systems, most of the schemes developed for SISO systems cannot be extended directly to MIMO systems. In recent years, several observer-based adaptive fuzzy control schemes have been developed for a class of MIMO nonlinear systems [3,4,10,17,19,22,23] and for a class of strict feedback nonlinear systems [18,20,21,23,43]. However, some of the schemes proposed above require strictly positive real (SPR) conditions on the estimation error dynamics so they allow the filtering of the fuzzy basis functions, which makes the dynamic order of the system controller/observer very large [32]. To avoid the filtering of fuzzy basis functions, an observer-based adaptive fuzzy control scheme was developed for a class of uncertain nonlinear systems [40,41]. However, the use of the assumption $u \in L_\infty$ is not acceptable before the stability analysis [44]; in addition, it is necessary to assume that the control direction is known a priori. In [17], fuzzy adaptive output feedback control was developed for a class of uncertain MIMO nonlinear systems with unknown control direction. However, results can only be obtained in cases where the control gain coefficient was an unknown constant and the filtering of fuzzy basis functions was used to design the adaptive laws and control law. The schemes in [18,20,21,23,43] do not require SPR conditions, thus they do not result in the filtering of the fuzzy basis functions. However, it is necessary to assume that the control direction is known a priori. To the best of our knowledge, however, few previous studies have considered the class of MIMO uncertain affine nonlinear systems with a nonsymmetric control gain matrix, unknown control direction, and unmeasured states.

Based on previous results, we developed a fuzzy adaptive output control scheme for a class of MIMO nonlinear systems with nonsymmetric control gain matrix, unknown control direction, and unmeasured states. In the control design, fuzzy systems are used to approximate the unknown nonlinear functions and an adaptive fuzzy state observer is designed to estimate the unmeasured states. A robust control term is used to compensate for the lumped errors. Although the stability analysis is performed using the SPR conditions, the parameter adaptive laws are designed by fuzzy basis functions rather than by its filtering. The main original aspects of the proposed control scheme are as follows: (i) it can solve the problem of a nonsymmetric control gain matrix because a matrix decomposition technique is used in controller design; and (ii) it does not require a priori knowledge of the control direction for MIMO nonlinear system when the states are unmeasured due to the incorporation of Nussbaum gain in the robust control term. The proposed design scheme guarantees that all of the signals in the resulting closed-loop systems are bounded and that the tracking errors converge asymptotically to zero.

The remainder of the paper is organized as follows. In Section 2, we describe the plant dynamics and control objective, and we provide a brief description of fuzzy systems. In Section 3, we explain the proposed adaptive fuzzy output control scheme. In Section 4, simulation results are presented that demonstrate the effectiveness of the method. Finally, our conclusions are given in Section 5.