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Hybrid adaptive fuzzy control for uncertain MIMO nonlinear systems with unknown dead-zones[☆]

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ABSTRACT

In this paper, a hybrid adaptive fuzzy control approach is proposed for a class of uncertain multiple-input and multiple-output (MIMO) strict-feedback nonlinear systems with unknown dead-zones. Fuzzy logic systems are utilized to approximate the unknown nonlinear functions, and a serial-parallel estimation model is established. Based on the adaptive backstepping dynamic surface control (DSC) technique, and utilizing the bounds of the dead-zone slopes and the prediction errors between the system model and the serial-parallel estimation model, a new robust adaptive fuzzy backstepping controller with the composed parameters adaptive laws is developed. The proposed control method can not only overcome the problem of "explosion of complexity" inherently existing in traditional backstepping design methods, but also improve the control performance. It is proved that all the signals of the closed-loop systems are bounded and the system output can follow the given bounded reference signal. A numerical example and simulation comparisons with the existing control methods are provided to show the effectiveness of the proposed approach.

1. Introduction

In the past decades, approximator-based adaptive control approaches have been developed to deal with uncertain MIMO nonlinear systems with unstructured uncertainties via fuzzy logic systems (FLSs) or neural networks (NNs) approximators (see, for example, [8,11,16,17,23,28,33,49,50]). The basic idea of these works is to use the FLSs or NNs to approximate the unknown nonlinear functions in the systems and implement the design of adaptive fuzzy or NN controller by using Lyapunov stability theory. Generally, the adaptive fuzzy or NN control approaches show good performances. However, these approaches can only be applied to a specific class of nonlinear systems. The key limitation is that the unknown nonlinearities appear on the same equation as the control input in a state space representation. Such restrictions in the location of the uncertain nonlinear functions are usually referred to as the matching conditions. If a physical system is subjected to some unknown nonlinear functions that do not satisfy the matching condition, the adaptive fuzzy control approaches mentioned above cannot be implemented.

With the development of the adaptive and robust backstepping designs in nonlinear systems [15], many fuzzy or NN adaptive control schemes have been reported that combine the backstepping technique with the adaptive technique for uncertain MIMO nonlinear systems [2,3,9,10,36]. Two adaptive neural and fuzzy control schemes have been proposed for two classes of uncertain

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MIMO nonlinear systems in block-triangular forms in [2,10], respectively. Based on the results [2,10], a fuzzy almost disturbance decoupling control scheme has been proposed for a class of uncertain MIMO nonlinear systems in [3], and the developed control scheme has been applied to control a two continuous stirred tank reactor process. Based on the Lyapunov–Krasovskii functional theory, two adaptive neural and fuzzy control schemes have been proposed for two classes of uncertain MIMO nonlinear systems in block-triangular forms with unknown state delays in [4,9]. To solve the immeasurable state problem, a fuzzy adaptive backstepping output feedback control approach has been investigated in [36] for a class of uncertain MIMO nonlinear systems by designing a state observer [18,31,47].

However, due to the employment of the backstepping technique, these methods in [2,3,9,10,36] inevitably suffer from another problem of "explosion of complexity", which is caused by repeated differentiations of some nonlinear functions, i.e., the virtual controllers designed at each step within the conventional backstepping technique. As a result, the complexity of a controller drastically grows as the order of the system increases. To overcome the problem of the "explosion of complexity", an adaptive NN backstepping control approach was first proposed by Wang and Huang [37] for a class of SISO uncertain nonlinear systems based on the so called dynamic surface control technique. Since then, several adaptive fuzzy and NN backstepping DSC control schemes have been developed for uncertain MIMO nonlinear systems in [20,35], where the result in [20] is a state feedback control for a class of uncertain MIMO nonlinear systems, and [35] provides an output feedback control for a class of uncertain MIMO nonlinear systems with immeasurable states. It should be mentioned that the aforementioned control approaches in [2–4, 8–11,15–17,20,23,28,33,35–37,49,50] all assume that the considered nonlinear systems do not contain the dead zone inputs [6,43]. In practice, dead zone is one of the most important nonsmooth nonlinear inputs which exists in many industrial control systems. A robust adaptive NN control has been investigated for a class of uncertain MIMO nonlinear systems with unknown control coefficient matrices and input nonlinearities in [5]. Based on the principle of sliding mode control and the use of Nussbaum-type functions, two adaptive NN tracking control approaches have been investigated for a class of uncertain MIMO nonlinear systems with unknown dead zones in [51,52], but the controlled systems in [51,52] are required to satisfy the matching condition. An adaptive fuzzy output feedback control method has been proposed in [34] for a class of uncertain MIMO nonlinear systems with unknown dead zones and without the direct measurement of the states.

Though the adaptive fuzzy or NN control design gained much progress, the original intention of employing the fuzzy system/NN for approximating the system uncertainty is missing. Intuitively, the more precise approximation of the nonlinear function is obtained, the better performance is achieved. However, most efforts have been directed towards achieving the stability and tracking performance. Little attention has been paid to the accuracy of the identified intelligent models and to the transparency and interpretability. By designing a serial-parallel estimation model and by using the modeling error, a hybrid adaptive fuzzy identification and control was proposed in [12], which can achieve a faster and better tracking performance. However, the nth-order derivative of the plant output is required to be known in [12], which is quite impractical. Some similar control design methods using prediction error with a slightly different serial-parallel estimation model [41] can be found in [1,24]. It should be pointed out that the systems studied in [1,12,24,41] are restricted to the canonical form (satisfying the matching condition). The great feature of this model is that the derivative information can be directly derived from the states. Recently, the authors in [21,48] proposed novel composite fuzzy and neural dynamic surface control methods for a class of uncertain nonlinear strict-feedback systems without satisfying the matching condition. The proposed control methods use the prediction error between system states and serial-parallel estimation model to construct the composite laws for the fuzzy or NN weights updating, and can achieve a better tracking performance than the previous methods [37]. However, the results in [21,48] are only suitable for a class of single-input single-output systems, and require that the virtual control gains and actual control gain are "1". In addition, the unknown dead zone problem has not been considered in [21,48]. To the author's best knowledge, by far, no hybrid control results are available for MIMO nonlinear systems with dead zones and without satisfying the matching condition.

Motivated by the above observations, in this paper, a hybrid adaptive fuzzy output tracking control method is proposed for a class of uncertain MIMO nonlinear systems with unknown dead zones. Fuzzy logic systems are used to approximate the unknown nonlinear functions, and a serial-parallel estimation model is established with which the prediction errors can be obtained. Based on the adaptive backstepping dynamic surface control technique and the prediction error between the system model and the serial-parallel estimation model, a new fuzzy controller with the hybrid parameters adaptive laws is developed. It is proved that all the signals of the closed-loop systems are bounded and the system output can follow the given bounded reference signal. The main contributions of this paper can be summarized as follows:

(1) By designing a serial-parallel estimation model, the prediction error between the system model and the serial-parallel estimation model has been incorporated into the control design scheme, and the proposed control scheme can achieve good control and tracking performances.
(2) By utilizing the information of the bounds of the dead-zone slopes and treating the time-varying inputs coefficients as a system uncertainty, an adaptive robust compensator term is designed, and the unknown dead zones are refrained.
(3) By using the new DSC technique, the proposed fuzzy adaptive control approach can overcome the problem of "explosion of complexity"; therefore the computational burden of the control algorithm can be obviously reduced. In addition, the DSC technique design in this paper uses two kinds of first-order filters instead of a first-order filter in [20,35,37]. Consequently, the restrictive assumption on the bounds of the derivative of the virtual control functions being known can be removed.