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Adaptive fuzzy tracking control for a class of uncertain nonaffine nonlinear systems with dead-zone inputs

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Abstract

This paper considers the problem of adaptive fuzzy tracking control for a class of uncertain nonaffine nonlinear systems with mismatched external disturbances, parameter uncertainties, and nonsymmetric dead-zone inputs. Without the help of the dead-zone inverse function and by incorporating the implicit function theorem, both the adaptive state feedback tracking controller and the adaptive output feedback tracking controller based on high gain observer are designed by utilizing fuzzy logic systems (FLS) to approximate the appropriate nonlinear control input functions. A compounded disturbance is defined in terms of the external disturbance, parameter uncertainty, nonsymmetric dead-zone input, and approximation error of FLS. Under the condition that the upper bound of the compounded disturbance is unknown, novel adaptive laws are introduced to estimate and tune the unknown controller parameters on-line. Furthermore, on the basis of Lyapunov stability analysis, it is also proved that the presented control methods can guarantee that all the closed-loop system error signals are uniformly ultimately bounded. Finally, two simulation examples are provided to demonstrate efficiency of the proposed adaptive fuzzy tracking control approaches.

Keywords: Nonaffine nonlinear system; Adaptive tracking control; Fuzzy logic systems (FLS); High gain observer; Dead-zone input

1. Introduction

Adaptive tracking control problem of nonlinear systems with parameter uncertainties is the subject of intensive investigation and attracts an ever increasing interest over the past few decades. Much effort has been devoted to this kind of control problem. Especially, a number of results on robust adaptive control [1–8], T–S fuzzy tracking method [9], sliding mode approaches [10–13], backstepping techniques [14–19] and so on have been obtained. As is well known, neural networks (NNs) and fuzzy logic systems (FLS) treated as very powerful tools have been used to control and design nonlinear systems in views of their universal approximation properties and adaption abilities. In

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the past years, the issues of using NNs and FLS to approximate unknown nonlinearities have been well investigated (see, for example, [20–25], and the references therein).

It is worth mentioning that a number of existing works were focused on the affine nonlinear systems, that is, the actuator inputs lying in the system dynamic equation present in terms of linear expressions. However, for the nonaffine nonlinear systems, the control inputs appear in a nonlinear fashion can represent more practical processes, such as mechanical systems, aircraft systems, Duffing oscillator and chemical reactions processes [26]. In this case, the control design problem for the nonlinear system with the nonlinear fashion of control input is difficult and complicated, and a few of successful control methods for nonaffine nonlinear systems have been applied to the references [27–34]. Adaptive sliding mode control approach [35] and adaptive control based on high-order sliding mode observer [36] were extended to the nonaffine nonlinear systems. Subsequently, under the partial persistent excitation (PE) condition and with an appropriate state transformation, [37] studied the problem of adaptive neural network learning control scheme of a class of nonaffine nonlinear systems. Nevertheless, the main limitation in [37] and most of existing results are that the states of the systems are assumed to be available. It is also well known that the output feedback control is more useful in practical application because of its low cost. More specially, for the nonlinear systems [34], [38] and [39] with unmeasurable states, the estimated states from the corresponding gain observers were used to construct the adaptive output feedback control scheme, where the high gain is designed to ensure the closed-loop system stability. In [40], direct adaptive NNs control approaches were investigated for uncertain nonaffine nonlinear systems by constructing the high gain observer and the disturbance observer.

For the practical engineering systems, a number of nonlinear constraints including dead-zone, hysteresis and backlash commonly occur in actuators, such as hydraulic servovalves, piezoelectric translators, mechanical connections, electric servomotors and other areas. As an important nonsmooth nonlinearity, dead-zone exists in a wide of range of industrial and mechanics processes, which often severely affects system stability and performance. More recently, [41] proposed adaptive NN dynamic surface control method via state feedback for uncertain nonaffine nonlinear systems with unknown dead-zone nonlinearities. Adaptive fuzzy output feedback control approaches have been investigated in [42] and [43] for single-input and single-output (SISO) and multi-input and multi-output (MIMO) nonlinear systems with unknown dead-zone inputs, respectively. In [44], an adaptive control scheme with positive integrable time-varying function was presented to compensate for the dead-zone nonlinearity. However, the controlled systems in [42–44] are concerned with the nonlinear systems in affine form, not concerned with the ones in nonaffine form. In [45], an adaptive fuzzy output tracking control method is considered for a class of uncertain nonaffine nonlinear systems with nonsymmetric dead-zone inputs, but the presented approach is outlined in a framework of disturbance-free.

On the other hand, it is noticed that the nonlinear systems considered in [28,33,34,40,41,44,45] are confined to satisfy matching conditions, i.e., the unknown parameter uncertainties and external disturbances must present to the same equation as the control input channel. Nevertheless, the uncertainties and disturbances existing in many practical systems [46–48] may be not subject to the matching condition. The reason is that the parameter variations and external disturbances always impose on the states directly rather than only influence through the control input channels. Because of this, the methods presented in these works are not feasible for more the general nonaffine nonlinear systems with mismatched parameter uncertainties and external disturbances.

Motivated by the above discussions, in the presented work, we will further study the adaptive fuzzy tracking control for a class of uncertain nonaffine nonlinear systems in the presence of mismatched external disturbances, unknown parameter uncertainties, and nonsymmetric dead-zone inputs. Compared with the existing work, there are four main contributions as follows:

1) First of all, it should be noted that the system considered in this paper is a more extended uncertain nonaffine nonlinear system than the ones given in the references [28,33,34,40,44,45], and that the mismatched external disturbances, unknown parameter uncertainties, FLS approximation errors, and nonsymmetric dead-zone inputs are treated as a compounded disturbance.
2) In [40], based on the idea of disturbance observer, the bounds of the derivatives of the compounded disturbance are assumed to be known, that is, a priori knowledge of the dynamic system is required to determine these bounds, which will be difficult to acquire in practical designs and applications. In this paper, under a weaker condition that only the upper bounds of the compounded disturbance is unknown, novel adaptive laws are introduced to estimate and tune the unknown controller parameters on-line.