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Adaptive fuzzy control for a class of unknown nonlinear dynamical systems ☆

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Abstract

In this study, we investigate an adaptive fuzzy controller design for a class of nonlinear multi-input multi-output (MIMO) systems in interconnected form. The systems considered comprise n subsystems and an unknown interconnection term is included in every equation for each subsystem. The interconnection term is a function of all the states from the first to the $(n-1)$th subsystems. Moreover, the effects of dead-zone models are considered in each subsystem of the systems. These properties of the systems cause the difficulties and add further complexity to the design. In order to overcome these difficulties, we use the following methods: (1) the fuzzy logic systems are employed to approximate the appropriate unknown functions of the systems, (2) a novel backstepping design procedure is constructively designed, and (3) compensative adaptation laws are provided to compensate for the effects of the dead-zone inputs. We show that all the signals in the closed-loop system are bounded and that the outputs converge to a compact set by using the Lyapunov analysis theorem. Simulated examples are presented that validate the effectiveness of the approach.

Keywords: Adaptive fuzzy control; Fuzzy logic systems; Nonlinear system; Uncertainty

1. Introduction

The emergence of uncertainties is inevitable in many practical systems, thus, it is very important to control the systems that possess uncertainties. Fuzzy logic systems (FLSs), neural networks (NNs) or fuzzy neural networks (FNNs), which have excellent function approximation abilities, are very effective methods for coping with the uncertainties. Recently, due to the demands of practical applications, adaptive control using intelligent control for uncertain nonlinear systems has progressed greatly. Adaptive control schemes using intelligent methods were proposed in [1–3] for unknown nonlinear single-input single-output (SISO) systems to guarantee the stability of the closed-loop system. Several adaptive tracking design approaches have been studied for different classes of uncertain nonlinear MIMO

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systems [4,5] and large-scale [6,7] systems based on the fuzzy approximators. Three adaptive control approaches using intelligent methods were described in [8–13] for real nonlinear systems. These approaches were obtained for systems with the matching condition, i.e., the unknown terms appeared only in the last equation for SISO systems and the subsystems of MIMO systems.

To achieve this, some elegant adaptive intelligent feedback designs were proposed in [14–20] for nonlinear strict feedback SISO systems with unknown nonlinear functions. In [21], output feedback adaptive NN controls were investigated for two classes of nonlinear discrete-time SISO systems with unknown control directions. In order to control more complex systems, many approaches have been developed for nonlinear interconnected [22–24] or large-scale [25,26] MIMO systems with unknown functions based on intelligent methods. Almost disturbance decoupling of MIMO nonlinear systems was studied in [27]. In [28], based on the backstepping technique, a fuzzy almost disturbance decoupling control scheme was obtained for a class of MIMO nonlinear systems with completely unknown nonlinearities.

However, the algorithms mentioned above ignore the effects of the input nonlinearities, such as the dead-zone inputs. These input nonlinearities are found frequently in various engineering systems, such as mechanical connections and electric servomotors. An adaptive neural controller was proposed in [29] for nonlinear SISO systems with a dead-zone and multiple time delays. An adaptive fuzzy backstepping control approach was considered in [30] for nonlinear strict-feedback SISO systems with unknown functions, unknown dead zones, and immeasurable states. In [31], an adaptive fuzzy robust output feedback method was developed for nonlinear SISO systems with unknown dead-zones based on a small-gain approach. A decentralized adaptive control method was proposed in [32] to address output tracking for interconnected time-delay subsystems where the input of each loop was preceded by an unknown dead-zone. In [33], adaptive tracking control was designed for a class of uncertain MIMO nonlinear systems with non-symmetric input constraints. In [32,33], a linearly parameterized condition had to be satisfied. Two adaptive control methods were proposed in [34,35] for a continuous stirred tank reactor process with dead-zone inputs based on the NN approximation. An adaptive control algorithm was studied in [36] for uncertain nonlinear MIMO systems with non-symmetric input nonlinearities of saturation and dead zone by using the NN. Based on FLSs, various adaptive fuzzy controllers were obtained in [37–40] for several different classes of nonlinear MIMO systems with the dead-zone inputs. However, the major structural limitations imposed on the systems in [32–40] were as follows: (1) a matching condition was required, i.e., the nonlinear functions were included in the last equation of each subsystem [32,34–37]; (2) the systems did not consider the interconnection terms [32,33], or there are the interconnection terms but they appear only in the last equation of each subsystem [37–40], and they were limited to be a function of the system outputs [40]. The present study aims to control the nonlinear systems without these limitations.

The stability and control issues of uncertain nonlinear interconnected MIMO systems are addressed in the present study. It is very important to control this class of systems because a large number of real systems can be expressed as or transformed into MIMO systems in an interconnected form. Specifically, their control problem becomes more challenging when the dead-zone input is considered to be a crucial component of these systems. The main benefits of this paper are explained in the following

(1) The linearly parameterized condition cannot satisfy the practical requirement because unknown nonlinear functions emerge in practice. Thus, we remove the linearly parameterized condition employed in [32,33] and we consider a class of more complex nonlinear systems with unknown nonlinear functions. The main characteristics are: (i) the systems are composed of n interconnected subsystems and the interconnection term appears in every equation of each subsystem, in contrast to the systems in [32–39]; and (ii) in contrast to the results described in [40], the interconnection term is an unknown nonlinear function of the system outputs, as well as an unknown nonlinear function of all the states from the first to the $(n-1)$th subsystems.

(2) The control of this class of systems is a difficult and complex task due to the existence of dead-zone inputs and the couplings that exists between the subsystems. Thus, different forms Lyapunov functions and systemic design procedures are constructed to address the difficulties of constructing the controllers and adaptation laws.

(3) Moreover, these properties of the interconnection terms produce a novel backstepping design procedure and appropriate unknown nonlinear functions are selected, which are approximated by using FLSs. Adaptive compensation operators are employed to conquer the effects of the dead-zone.