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Observer-based adaptive fuzzy controller for nonlinear systems with unknown control directions and input saturation

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Abstract

This paper addresses design of an observer-based adaptive fuzzy controller for a class of single-input–single-output (SISO) nonlinear systems with unknown dynamics subject to input nonlinearity and unknown direction. The proposed controller is singularity free. A high-gain observer is designed to estimate the unmeasured states, and the Lipschitz condition for proving boundedness of the estimated states is relaxed. The Nussbaum function is used to handle the unknown virtual control directions and the backstepping technique has been applied for controller design. It is proved that all closed loop signals are semi-globally uniformly ultimately bounded (SGUUB) and the output tracking error converges to a small neighborhood of the origin by choosing the design parameters appropriately. Numerical example illustrates effectiveness of the proposed method even for the system with a change in control direction.

Keywords: Adaptive fuzzy control; High-gain observer; Input saturation; Unknown direction; Singularity free

1. Introduction

Most of processes frequently have nonlinear behaviors. During last decades, control design of nonlinear systems has received a great deal of attention. As a significant issue, controller design of these systems is restricted by the lack of an accurate dynamical model. More recently fuzzy logic systems (FLS) or neural networks (NN) have been extensively used to model the unknown dynamics of the process due to their universal approximation properties. Adaptive fuzzy control for uncertain SISO nonlinear strict-feedback systems is developed in [1–4]. Adaptive fuzzy or neural control for multi-input–multi-output (MIMO) strict-feedback systems is proposed in [5–12].

In many practical nonlinear systems, some of the states are often unmeasured. To tackle this problem, state observer has been used. In [11,13,14], Luenberger-like observer for fuzzy adaptive output feedback control of nonlinear systems with unmeasured states was developed. In [15–17], the adaptive backstepping control technique for a class of nonlinear SISO systems based on K-filters has been proposed. Another approach for estimating the unmeasured states is using

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the fuzzy high-gain observer. This type of observer has been combined with output feedback control strategy to control SISO strict-feedback nonlinear systems [18–20]. The main constraint in observer design is the realization of the Lipschitz inequality. In [21], it has been shown that in design of adaptive Luenberger-like observer for nonlinear systems, if fuzzy logic or neural network is being used, stability would be independent of the Lipschitz condition.

In addition most of control systems have limitations on their inputs, such as input saturation, backlash, or dead zone. Among these nonlinear elements, controller design is strongly influenced by the input saturation, because of having intense effect on performance and stability of the control system [22]. Control of systems with input saturation constraints have been considered in [23–26]. In [23], a novel adaptive controller for a class of nonlinear systems in the presence of input saturation and external disturbances is proposed by introducing an augmented state. In [27], an auxiliary system which has the same order as the nonlinear system, has been considered to compensate the effect of saturation. If first order axillary system is used, similar results will be obtained [22].

In [28–30], an adaptive neural network is combined with a backstepping controller to design a singularity-free adaptive controller for strict feedback nonlinear systems. In the backstepping control strategy when the virtual control coefficients g_i, $i = 1, \dots, n$ are unknown and control signals $\alpha_i = (\nu_i - \hat{f}_i)/\hat{g}_i$ are considered, where $\hat{f}_i$, $\hat{g}_i$ are estimates of f_i, g_i and signal ν_i is the new control to be designed, difficulties arise when $\hat{g}_i$ convergences to zero, resulting in singular controller action [30]. One of the most common proposed solution, also mentioned in the above reference, is use of the integral Lyapunov function.

When the system input directions are unknown, the adaptive fuzzy controller design based on output feedback will be faced with a new challenge. Because in this case, the virtual control directions are difficult to be detected. The popular method for solving this problem is using the Nussbaum function [31–34]. For example, the Nussbaum function for adaptive dynamic surface control with unknown control direction has been used in [26]. Psillakis has proposed an adaptive control scheme for nonlinear systems with unknown dynamics and control directions. By introducing a novel hysteretic deadzone modification with resetting, boundedness of all closed-loop signals has been proved [35]. In [36] also the Nussbuam gain method has been used to handle the unknown control direction problem.

Some of the above mentioned restrictions are considered by other researchers. For example in [23], an adaptive controller for uncertain nonlinear system in the presence of input saturation and external disturbances has been designed. In another work [26], an adaptive neural network controller is designed for a class of uncertain nonlinear strict-feedback systems with unknown control direction in the presence of input saturation. In both of these works, it has been assumed that all state measurements are available which is not true for many practical applications.

In another work [37], an observer-based adaptive fuzzy controller for nonlinear systems with unknown control directions has been designed. In this work, input saturation or nonlinearity is not taken into account while such a limitation exists in most of practical applications.

To the best of author's knowledge there is no published work that considers simultaneously all of the aforementioned restrictions, i.e. unmeasured states, input saturation, control singularity problem and unknown control directions for a class of uncertain nonlinear systems.

In the present work, the fuzzy logic system has been used to estimate the system unknown dynamics. Since for control implementation system states are required, a fuzzy adaptive high-gain observer has been designed. The unknown control direction problem has been handled by using a Nussbaum function. To tackle input nonlinearity problem, the input saturation function has been estimated by a smooth function.

As mentioned above, the control signal $\alpha_i = (\nu_i - \hat{f}_i)/\hat{g}_i$ becomes infinite when $\hat{g}_i$ convergences to zero, resulting in a singular controller action. To avoid controller singularity, several approaches have been proposed in the literature namely; the projection algorithm, the integral Lyapunov function method, and the direct adaptive fuzzy controller technique.

In the projection algorithm approach, the estimated parameters are kept inside a feasible set in order to prevent singularity problem. Although projection algorithm is a standard technique in adaptive controller design, it usually requires a priori knowledge for the feasible parameter set and no systematic procedure is available for constructing such a set for a general plant. Using the integral Lyapunov function method is also complicated, because choosing the appropriate function is a difficult task. In the direct adaptive fuzzy controller design, information about control direction is required which is not available for systems with unknown control direction. In the present work, a new approach for handling the singularity problem has been proposed which will be discussed in the related section.