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Adaptive fuzzy dynamic surface control of nonlinear systems with input saturation and time-varying output constraints

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A B S T R A C T

This paper deals with the design of adaptive fuzzy dynamic surface control for uncertain strict-feedback nonlinear systems with asymmetric time-varying output constraints in the presence of input saturation. To approximate the unknown nonlinear functions and overcome the problem of *explosion of complexity*, a Fuzzy logic system is combined with the dynamic surface control in the backstepping design technique. To ensure the output constraints satisfaction, an asymmetric time-varying Barrier Lyapunov Function (BLF) is used. Moreover, by applying the minimal learning parameter technique, the number of the online parameters update for each subsystem is reduced to 2. Hence, the semi-globally uniformly ultimately boundedness (SGUUB) of all the closed-loop signals with appropriate tracking error convergence is guaranteed. The effectiveness of the proposed control is demonstrated by two simulation examples.

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1. Introduction

Due to practical applications and theoretical challenges, many significant results in the field of adaptive control of nonlinear systems have been obtained during the past decades. Owing to their universal approximation feature, fuzzy logic systems (FLSs) and Neural Networks (NN) are effective tools for modeling uncertain nonlinear systems. Meanwhile, the adaptive fuzzy backstepping control can provide a symmetric framework for solving control problems. Therefore, various attempts have been made in developing approximation-based adaptive backstepping control schemes for a large class of uncertain nonlinear systems, see [1–5] and references therein. However, a number of papers on adaptive fuzzy backstepping control have focused on SISO nonlinear systems [1–3] and the others have focused on MIMO nonlinear systems [4,5].

Inputs, outputs, and/or state constraints are common in most physical systems. They manifest themselves in the form of the physical stoppages, saturation, hysteresis, dead-zone or even performance and safety specifications. Input saturation constraint as a common input constraint appears in many industrial control systems. Saturation is a potential problem that deteriorates the control system performance, or can even lead to closed-loop system instability. Also, control signal magnitudes are usually limited, hence saturation of the control signal is inevitable in many practical applications. The analysis and control design of systems with input saturation nonlinearity have been studied by many authors [6–11]. In [6], the problem of robust adaptive controller design for a class of uncertain nonlinear systems is addressed in the presence of input saturation and unknown disturbance. To deal with input saturation, a hyperbolic tangent smooth function has been introduced to

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approximate the saturation with a bounded approximation error. However, the control method in [6] is restricted by the linearly parameterized assumption. Refs. [7,8] are the extensions of [6] and use fuzzy logic systems to approximate unknown functions. In [9], a robust controller design for uncertain MIMO nonlinear systems is investigated in the presence of input saturation and unknown disturbance. To approximate the unknown disturbance, the recurrent wavelet Neural Network disturbance observer (RWNNDO) is introduced. Also, the method studied in [6–8] is employed for dealing with input saturation in [9]. In [10], to design an adaptive Neural Network control for uncertain MIMO nonlinear systems, variable structure control (VSC) is combined with the backstepping approach. In [11], a full state and output feedback NN-based impedance controller is investigated. However, none of the aforementioned works considered the system output constraint problem and input saturation, simultaneously.

The other important constraint in many industrial systems is output constraint. Ignoring the constraints on output leads to performance degradation, hazard or system damage. To cope with the output constraints, some important control design methods have been developed including the model predictive control [12], reference governor (RG) [13,14], and the use of set invariance notions [15,16]. The MPC tackles the output constraints problem within a finite-horizon optimization framework [12]. In the RG-based controller design, the reference signal has been modulated by using online optimization algorithms. Therefore, any violation of system constraints can be avoided [13,14]. Recently, the use of Barrier Lyapunov functions (BLFs) has received much attention for dealing with output constraints since such a function grows to infinity whenever its associated states approach certain limits. By keeping bounded the Barrier Lyapunov function, any violation of the output constraints can be prevented. In [17–20], BLFs have been used to tackle the output constraints. In [17], the nonlinear system is in the strict-feedback form and the control gain function is assumed known. In [18], an adaptive neural control is investigated for the output-constrained nonlinear systems in the output feedback form with unknown constant control gain function and it is assumed that only outputs are available for measurement. In [19], a BLF-based adaptive neural controller design is studied for uncertain nonlinear systems in the strict-feedback form and the control gain function is assumed completely unknown. In [20], an adaptive neural-based controller with both full state and output feedback is addressed for a robotic manipulator in the presence of dead-zone nonlinearity and output constraints. Besides the static output constraints, the problem of time-varying output constraints has also been studied in [21,22]. In [21], the problem of the symmetric output constraints is investigated by using a time-varying BLF. Then, [22] extended the results in [21] to the asymmetric case. In [22], the knowledge of control gain function is required. Meanwhile, Refs. [23,24] have focused on the adaptive control design for totally unknown systems with time-varying output constraints. However, in [23,24], a satisfaction of certain conditions has been required by the lower and upper bounds of the output. In [25], a Neural Network-based adaptive controller scheme is proposed for a class of uncertain high-order MIMO nonlinear systems in the presence of asymmetric time-varying output constraints. For dealing with the controller singularity problem, a single Neural Networks has been used to approximate the control gain matrix. However, the control design methods reported in [17–25] cannot deal with input saturations. There are few studies in the adaptive backstepping control design for uncertain nonlinear systems in the strict-feedback form where input and output constraints are simultaneously considered. In [26], the problem of an adaptive fuzzy output feedback control design is addressed for a class of nonlinear systems with input and output constraints. Also, the states are considered immeasurable and only the output of the system is available. In [27], an indirect adaptive fuzzy control for nonlinear systems in the strict-feedback form is investigated in the presence of output constraint and input saturation. In [28], an adaptive fuzzy-based control scheme has been investigated for a class of non-strict-feedback systems with input and output constraints. To overcome the difficulty of the non-strict-feedback structure, a variable separation technique has been employed. All [26–28] assume static output constraints. To the author's best knowledge, no adaptive fuzzy or Neural Network-based controller designs are available for uncertain nonlinear systems with time-varying output constraints in the presence of input saturation.

Due to the repeated differentiation of virtual controls, traditional backstepping scheme suffers from the problem of explosion of complexity. In [29], an adaptive control for a more general class of MIMO nonlinear systems with non-symmetric input constraints is proposed. In [30], the results of the strict-feedback and pure-feedback nonlinear systems are extended to the MIMO uncertain switched non-strict-feedback systems and the restrictive assumptions are eliminated. To overcome the time derivative computation of virtual control laws, in both [29,30], command filters are employed. In [31], RBFNN is used to approximate the derivations of virtual control law, which further leads to heavier calculation burden in each step design. Recently, the Dynamic Surface Control (DSC) method is employed to solve this problem by introducing a first-order low-pass filter. By the combination of the MLP and DSC techniques, a robust adaptive tracking control design was proposed in [32]. In [33], a nonlinear disturbance observer-based adaptive DSC scheme is studied for uncertain nonlinear strict-feedback systems with input saturation. In [34], an adaptive DSC-based decentralized control is addressed for the interconnected pure-feedback systems. In [35], an adaptive DSC based on Nussbaum approach is developed. In [36], backstepping DSC incorporated with BLF is proposed for the output constrained strict-feedback system. In [37,38], instead of the first-order filter in DSC, a modified sliding mode filter and two kinds of first-order filters are applied, respectively. However, DSC should be further investigated for uncertain strict-feedback nonlinear systems in the presence of input saturation, output constraints, and unknown external disturbance.

Motivated by the above discussions, and compared with the existing results, the main advantages of the proposed control method are listed as below.

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