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# Fuzzy dynamic surface control for uncertain nonlinear systems under input saturation via truncated adaptation approach ☆

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**Abstract**

In this paper, a fuzzy control scheme is presented for uncertain nonlinear systems with input saturation and external disturbance using truncated adaptation and dynamic surface control technique. Fuzzy logic systems are used in the online approximating of uncertain system dynamics, and adaptation laws used to online adjust weights of fuzzy logic system are designed. Auxiliary system is constructed and used to truncate the adaptation laws of fuzzy logic system and disturbance attenuator to prevent aggressive action when input saturation happens. Dynamic surface control technique is incorporated into traditional backstepping design to circumvent the problem of "explosion of complexity" caused by differentiating the so-called virtual controllers during the recursive procedures. It is proved that the proposed controller guarantees the uniformly ultimately boundedness of all signals in the closed-loop system. The steady tracking error and transient tracking error can be adjusted to arbitrarily small by choosing proper design parameters in spite of uncertain dynamics, external disturbance and input saturation. Numerical simulations are presented to demonstrate the effectiveness of the proposed controller.


*Keywords:* Adaptive fuzzy control; Input saturation; Uncertain nonlinear system; Dynamic surface control; Truncated adaptation

## 1. Introduction

Control design for nonlinear systems has been greatly advanced from both theoretical interests and practical applications in recent years, since plants to be controlled in practical engineering are generally nonlinear caused by the complex coupling relationship among state variables and time-varying properties. Backstepping synthesis and design, a Lyapunov-based analysis approach, has been widely used in the control of nonlinear systems. Adaptive fuzzy backstepping has been widely reported in existing literature. In [1], a robust adaptive fuzzy backstepping control is developed for nonlinear systems with modeling uncertainties and external disturbances. In [2] and [3], adaptive fuzzy output feedback backstepping control is developed for nonlinear systems with dead zone input. In [4], a direct

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adaptive fuzzy control is designed for a class of perturbed nonlinear systems using the backstepping approach. In [5], a fuzzy adaptive observer backstepping control is developed for MIMO nonlinear systems. In [6], globally stable adaptive backstepping fuzzy control is developed for nonlinear systems with unknown high-frequency gain sign. In [7], adaptive output feedback fuzzy control is designed for nonlinear via backstepping approach. Generally speaking, the adaptive fuzzy backstepping approach is capable of providing a systematic design methodology to control a large class of nonlinear systems in the following main steps: i), construct fuzzy logic system to online approximate uncertain dynamics, ii), design proper adaptation laws to tune the weights of fuzzy logic system based on Lyapunov stability theorem, iii), extend to high-order nonlinear system recursively using backstepping method.

Although numerous results on adaptive fuzzy backstepping control have been reported in the literature, the approaches designed in aforementioned literature suffer from the problem of "explosion of complexity" caused by the repeated differentiations of the modeled nonlinearities [8]. In [8], the adaptive backstepping control proposed does not require differentiating any model nonlinearities via the addition of $n$ first order low pass filters, which is named after the "dynamic surface control" (DSC), and the uncertainties therein are assumed to be linear in the unknown constants. In [9], a DSC is designed for non-Lipschitz systems. Further in [10], neural networks are introduced to approximate the unknown functions in nonlinear systems. In [11], robust neural adaptive DSC is designed by combining "minimal learning parameter" technique. In [12], adaptive fuzzy output feedback control is designed for uncertain nonlinear systems with unmodeled dynamics using DSC technique. Recent applications of DSC technique can be found in Refs. [13–16]. In spite of the theoretical progress and practical application of DSC technique, input saturation, a physical consideration in practical engineering, needed to be considered in the control design in an explicit form. Input saturation implies that the actual input to the system is constrained because the serving actuator cannot afford unlimited control signal, which appears in many practical engineering, such as spacecraft control [17], mobile robot [18], robot manipulator [19], and so on. Without considering the effect of input saturation, systematic performance degradation, even closed-loop instability, may appear in adaptive control system because adaptation laws will act aggressively to seek the desired systematic performance [20,21]. In this sense, it is of great significance and challenge to develop control scheme for nonlinear systems with input saturation from both practical and theoretical points of view.

There are several interesting control schemes that attempted adaptive controllers for nonlinear systems with input saturation. A concept named augmented error signal (AES) is proposed in [22] to absorb the effect caused by input saturation, the AES is generated by auxiliary system with $\Delta u$ being the input, $\Delta u := v - u$, where $v$ and $u$ represent the constrained control and designed control, respectively. The AES-based adaptive control allows the adaptation laws go on even with input saturation is in effect, which has been demonstrated to be effective in adaptive flight control [23], adaptive launch vehicle control [24], and so on. Inspired by the AES-based adaptive control, an online-approximation based adaptive control is designed in [20] to prevent the learning capacities and closed-loop stability from being destroyed, and it is pointed out that the design methodology can be extended to the control of high-order nonlinear systems using recursive design of backstepping approach. Therefore, in [25], AES-based adaptive has been incorporated into backstepping design for nonlinear chaotic systems, where fuzzy neural networks are used as online approximator of unknown dynamics, an auxiliary system that has the same order of the controlled plant is used to compensate the effect of the input saturation inspired by the main idea of AES-based adaptive method. In [26], robust adaptive backstepping control is developed for uncertain nonlinear systems with input saturation and external disturbance, where Nussbaum function is used to compensate the nonlinear dynamics caused by input saturation. In [27], adaptive fuzzy output feedback control is designed for nonlinear systems with input saturation. In [28], adaptive fuzzy output feedback control is developed for output constrained nonlinear systems with input saturation. In spite of the fruitful methods reported, there is an accordant space which can be improved in above-mentioned methods that deal with input saturation, that is, the problem of "explosion of complexity" exists in these works. An alternative method to avoid this problem is to use fuzzy logic system or neural networks approximate the combination of unknown systematic dynamics and differentiations of virtual controllers, as can be seen in [29] and [30]. However, this method augments the computational amount of calculation because the information of desired trajectory and its up-to $n$th derivatives must be contained in the input of fuzzy logic system or neural networks.

Motivated by the foregoing observations, this paper concerns the adaptive fuzzy dynamic surface control for a class of uncertain nonlinear systems in the presence of input saturation and external disturbance. Partially inspired by the AES method proposed in [22], truncated adaptation technique is developed by utilizing an auxiliary system, which truncates the adaptation laws of fuzzy logic system and disturbance attenuators, and thus prevents the adaptation ca-