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Robust tracking control for uncertain MIMO nonlinear systems with input saturation using RWNNDO

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A B S T R A C T

In this paper, the robust tracking control scheme is proposed for a class of uncertain multi-input and multi-output (MIMO) nonlinear systems with input saturation and unknown external disturbance based on the recurrent wavelet neural network disturbance observer (RWNNDO) and the backstepping technique. And then, the developed robust tracking control scheme is applied to an unmanned aerial vehicle (UAV) system. To handle the input saturation, a hyperbolic tangent function and a Nussbaum function are employed, and the dynamic surface method is applied to solve the problem of "explosion of complexity" in backstepping control. It is proved that the proposed control scheme can guarantee that all signals of the closed-loop system are bounded through the Lyapunov analysis. Simulation results are presented to demonstrate the effectiveness of the proposed control scheme for uncertain MIMO nonlinear systems.

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1. Introduction

Owing to the feature of lower cost, higher maneuverability and no casualty, etc., UAV has attracted the increasing interest in the world during the past several decades, and thus has been used in both military and civilian areas [1–3]. However, the robust flight control design of UAV is complex due to the existence of parameter uncertainty, strong nonlinearity, high coupling and unknown external disturbance. In general, the flight control design of UAV can be treated as the robust control design of uncertain multi-input and multi-output (MIMO) nonlinear systems. Hence, various attempts have been made in developing robust control schemes for uncertain MIMO nonlinear systems with application to UAV in the control area [4–6]. The nonlinear disturbance observer [7–10] has been proven to be an effective tool to handle the parameter uncertainty and the unwanted unknown external disturbance in the nonlinear control design. Recently, combining with neural networks or fuzzy logic systems, the efficient nonlinear disturbance observers have been developed [11–13]. In [9,10], a neural network disturbance observer and a fuzzy disturbance observer were studied respectively, and they were successfully applied to the robust control design of air vehicles. At the same time, neural networks or fuzzy logic systems as universal approximators have been extensively used in the robust control design of uncertain nonlinear systems [14–17] and the accordingly efficient control schemes have been developed [18–20]. In [21], the reliable fuzzy control was proposed for active suspension systems with actuator delay and fault. Adaptive sliding-mode control was developed for nonlinear active suspension vehicle systems using the T–S fuzzy approach in [22]. In [23], an observer-based adaptive fuzzy backstepping output feedback control was proposed for uncertain MIMO pure-feedback nonlinear systems. The neural-network-based near-optimal control was presented for a class of discrete-time affine nonlinear systems with control constraints in [24]. In [25], the observer-based adaptive neural network control was developed for nonlinear stochastic systems with time delay.

However, the adopted neural networks are usually feedforward neural networks (FNNs) which belong to static mapping networks. When FNNs are employed to deal with dynamic problems, they require a sufficiently large number of neurons to represent the dynamic responses and weight updating does not utilize the internal information of the neural networks [26]. Recurrent neural networks (RNNs) have capabilities of dynamic response and information storing through the internal feedback loops employed [27] and hence are more appropriate than FNNs for dynamic systems. Wavelet neural networks (WNNs) use wavelet functions that are capable of decomposition in the hidden layers. It has been proven that WNNs can approximate any continuous function over

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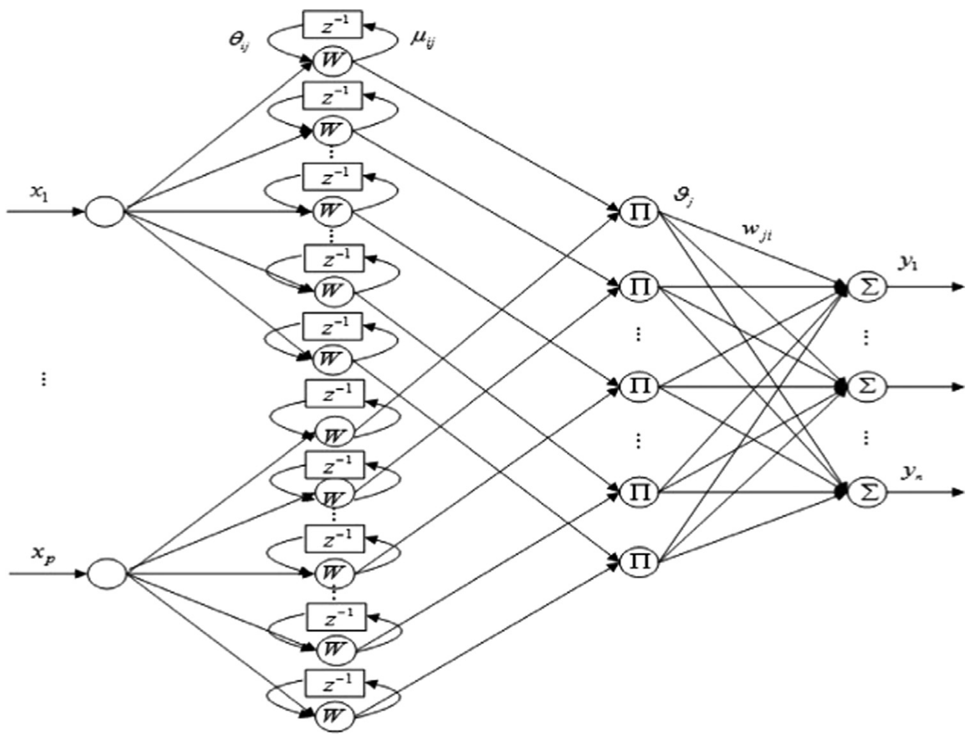

Fig. 1. The structure of recurrent wavelet neural network.

a compact set to any arbitrary accuracy and have fast learning ability [28]. To further improve the disturbance estimate performance, the recurrent wavelet neural networks (RWNNs) [29–31] combining RNNs with wavelets are employed to design the corresponding disturbance observer which is called recurrent wavelet neural network disturbance observer (RWNNDO) in this paper.

On the other hand, the saturation nonlinearity is a common problem for actuators in a wide range of practical systems. The existence of input saturation can degrade the system control performance, even leads to the system instability if it is ignored in the control design [32,33]. Furthermore, control design under consideration of input saturation is a challenging problem for any uncertain MIMO nonlinear system. Several schemes of control design for nonlinear systems with input saturation have been studied in recent years. In [34], neural networks were employed to approximate the input–output difference of actuators, so that a compensator was designed to overcome the input saturation. In [35,36], a robust adaptive control was proposed based on the backstepping technique, using the special property of a hyperbolic tangent function and a Nussbaum function to deal with the input saturation. In [37,38], by regarding the input saturation as a kind of constraints for the optimization function, a predictive control scheme was studied. However, the rudder saturation in the robust control design for UAV with unknown time-varying external disturbance has rarely been considered so far. In this paper, the robust control scheme will be developed based on the RWNNDO and the backstepping technique for the uncertain MIMO nonlinear system and it is applied to the attitude control of UAV.

For a class of cascade nonlinear systems, the backstepping control is an effective technique, which utilizes the Lyapunov analysis to design the controller [39–42]. In [39–41], an adaptive tracking control framework for a class of MIMO nonlinear systems was studied based on radial basis function neural networks (RBFNNs) and the adaptive control scheme was further developed by taking into account of time-varying delays and unknown backlash-like hysteresis in [42]. However, with increasing relative order of the nonlinear system, the number of terms in virtual control laws exponentially increases in the backstepping technique, leading to the problem of calculated expansion. The dynamic surface control (DSC) [43–46] was proposed to solve the explosion of complexity in the backstepping method, which employed an integrating filter in each step for the designed virtual control law to pass through it. This avoids the need of computing the derivatives of virtual control laws and hence simplifies the design process.

Motivated by above discussion and analysis, the robust tracking control scheme is developed for the uncertain MIMO nonlinear system in the presence of the parameter uncertainty, unknown external disturbance and input saturation based on the backstepping technique. The RWNNDO is proposed to approximate the unknown compounded disturbance. The method studied in [35] is extended for uncertain MIMO nonlinear systems, that is, a hyperbolic tangent function and a Nussbaum function are employed to handle the input saturation. Take the advantage of the dynamic surface technique to deal with the explosion of complexity in the backstepping control. The stability of the closed-loop system based on the proposed robust control scheme is rigorously analyzed through the Lyapunov method. The organization of the paper is as follows. Section 2 describes the problem and Section 3 presents the design of RWNNDO. The robust tracking control is investigated for the MIMO nonlinear system by considering the parameter uncertainty, unknown external disturbance and input saturation in Section 4. In Section 5, simulation results are given to illustrate the effectiveness of the proposed robust control scheme, followed by concluding remarks in Section 6.

2. Problem statement

Consider a class of uncertain MIMO nonlinear systems with input saturation which is described by

$$\dot{x}_i = F_i(\overline{x}_i) + G_i(\overline{x}_i)x_{i+1} + \overline{D}_i(\overline{x}_i, t), \quad i = 1, \ldots, k-1$$

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