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Adaptive robust backstepping attitude control for a multi-rotor unmanned aerial vehicle with time-varying output constraints

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ABSTRACT

Output constraints and uncertainties are the main factors that degrade the control performance of the multi-rotor unmanned aerial vehicle (MUAV). In this paper, an adaptive neural network backstepping dynamic surface control algorithm based on asymmetric time-varying Barrier Lyapunov Function is proposed for the attitude system of a novel MUAV under asymmetric time-varying output constraints, model uncertainties and external disturbances. The asymmetric time-varying Barrier Lyapunov Function, which will grow infinite when its arguments approach some limit, is introduced to keep the output under time-varying asymmetric constraints. Considering the derivation problem of the virtual control function in backstepping, the dynamic surface control is applied to simplify the algorithm. The adaptive neural network is used to approximate the dynamic model of the attitude system, and the minimal learning parameters are employed at the same time to reduce online computation burden. In order to balance out the external disturbance and further reduce the approximate error of the adaptive neural network, a robust term is designed to compensate the above negative impacts. The proposed algorithm guarantees that all the signals of the closed-loop system bounded by Lyapunov theory. Finally, some contrast simulation experiments are given to illustrate the effectiveness and superiority of the control scheme.

1. Introduction

Multi-rotor unmanned aerial vehicles (MUAVs) have many attractive properties such as vertical take-off and landing (VTOL), hovering, high agility and maneuverability. Based on the above advantages, MUAVs have a broad application prospect in various fields, for example, search and rescue missions, surveillance, inspection, mapping, and aerial cinematography [1]. Attitude control plays an important role in realizing stable operation, hovering and accurate trajectory tracking tasks of the MUAV. However, keeping the attitude system stable is a challenge task because the MUAV suffers from time-varying output constraints and different kinds of perturbations during flight missions. The high maneuvering flight and strong disturbances make it easy for the MUAV to reach the time-varying constrained boundary. The practical meanings of considering asymmetric time-varying output constraints for MUAV attitude system come from three aspects: firstly, missions often need the MUAV to fly in narrow or restricted area, hence physical environment confines attitude angles changing. In addition, the environment or the boundary is varied. Setting asymmetric time-varying output constraints can assure successful execution of the flight missions. Secondly, taking into account asymmetric time-varying output constraints administers to get a prescribed transient and steady-state performance in finite time, which is very difficult work in common control schemes without depending on trial and error. It also facilitates to optimize the dynamic property of the attitude system. For example, when transporting liquid materials, large attitude changes will cause liquid sloshing. Considering asymmetric time-varying output constraints helps maintain a high degree of attitude stabilization. Thirdly, introducing asymmetric time-varying output constraints guarantees safe flight. Physical characteristics of the MUAV determine the instability of the system when its attitude angles become too large. The asymmetric time-varying output constraints ensure the attitude angles stay in safe area and also facilitate obstacle avoidance. But the asymmetric time-varying output constraints bring great difficulties in controller design and stability proof of the attitude system. On the other hand, the MUAV will confront with external disturbances when executing flight missions, such as air drag and random wind. The external disturbances make the UAV easier cross the output

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constrained boundary. Negative factors including asymmetric time-varying output constraints, external disturbances, together with model uncertainties will degrade the control performance or even make the system unstable if being ignored. There is an urgent need to take into account all negative factors above when designing flight controllers to ensure the stability and tracking accuracy of the UAV attitude system. Lots of literatures pay attention to disturbance rejection control of the MUAV and gain some achievements, like fuzzy gain-scheduling sliding mode control [2], integral backstepping sliding mode control [3], adaptive robust control [4,5], disturbance observer-based control [6], adaptive backstepping control [7]. While there is no literature concerning with the asymmetric time-varying output constrained problem of the MUAV attitude system so far. So this paper is going to accomplish the accurate attitude tracking tasks of the MUAV in the presence of asymmetric time-varying output constraints, external perturbations and model uncertainties. A state feedback controller is designed for attitude system to keep the angles under time-varying constrained sets, and counteract all negative factors to obtain good tracking performance.

Output constraints are commonly found in control systems in the form of physical stoppage performance. The constraint consideration has been significantly important for control systems because it ensures the avoidance of collision hazards and stability simultaneously. Some significant achievements on constrained control problem have been obtained in recent years, including model predict control [8], use of set invariance [9] and reference governors [10]. Beyond these, the Barrier Lyapunov Function (BLF) was first proposed to handle constraints in [11]. Such a function grows to infinite when its arguments approach some limit, and the constraints are guaranteed not transgressed by ensuring the boundedness of the BLF in the closed-loop. Adaptive backstepping algorithm offers a systematic framework for the design of tracking and regulation strategies, meanwhile it handles the nonlinear system without the requirement of the matching condition [12]. Employing BLF, a backstepping controller was designed for strict-feedback nonlinear system with output constraints in [13], taking both symmetric and asymmetric constant constraints into account. After that, many applications about BLF-based backstepping control approach have been obtained [14–18]. On this basis, Tee extended the BLF to an asymmetric time-varying Barrier Lyapunov Function (ABLF) in [19]. The ABLF is appropriate for handling asymmetric time-varying constrained problem. However, the above backstepping-based control strategies all needed to calculate the derivatives of the virtual control functions repeatedly. The 'explosion of complexity' problem will become more serious for high-order nonlinear system, which is the main drawback of backstepping method.

Dynamic surface control (DSC) was employed to overcome the main drawback of 'explosion of complexity' by introducing a first-order filter to the synthetic input at each step of the backstepping procedure [20]. Backstepping DSC approach greatly reduces the design complexity and computation of the controller, which makes the algorithm easier to physical implementation. Combining with BLF, the BLF-based backstepping DSC method was used to tackle output constrained problem for a class of nonlinear system [21], pure-feedback system [22], and also the engineering anti-skid braking system [23]. However, the above studies ignored the model uncertainties and external perturbations, and these adverse elements will damage the control performance.

Adaptive neural network is one of the main solutions to handle system uncertainties. The distinct universal approximation property for control system, with no requirement for linearly parameterizing unknown nonlinear uncertainties, renders the broad usage of the algorithm in many fields [24,25]. For MUAV systems, approximation components based on neural network were introduced to facilitate the compensation of model uncertainties for the attitude system in [26]. A neural-network-based observer was introduced to estimate the translational velocity and angular velocity of the quadrotor, and an output feedback control law was developed in [27]. A controller made use of radial basis function neural network (RBFNN) to deal with image dynamic uncertainties, and moving target tracking task was achieved in [28]. In [29], the neural network was used to build the dynamic model of a quadrotor with a unique structure. By employing BLF, the adaptive neural network backstepping control approach was able to both meet constraint satisfaction and balance out total uncertainties for nonlinear system [30,31]. Using BLF-based adaptive neural network backstepping control approach, the tracking problem of a direct-current motor with state constraints was investigated in [32]. The regulation of robotic manipulator system with output constraints was studied in [33]. However, only constant constraint was considered in all above studies. The asymmetric time-varying constraint, which is a more complicated and common situation, is not taken into account. The asymmetric time-varying constraint brings greater difficulties in control system. Meanwhile, ensuring the stability of the whole control system with asymmetric time-varying output constraint becomes even harder.

To sum up, none of the above literatures considered all important factors including asymmetric time-varying output constraint, the 'explosion of complexity' drawback of backstepping, model uncertainties and external disturbances at the same time. Motivated by above discussions and analysis, this paper presents the attitude regulation problem of a 12-rotor unmanned aerial vehicle (UAV) in the presence of asymmetric time-varying output constraints and internal/external uncertainties. An adaptive robust backstepping controller in conjunction with ABLF, DSC, adaptive neural network and robust term is developed to guarantee all the closed-loop signals bounded. The ABLF ensures that the asymmetric time-varying output constraints are not transgressed during operation. There is no need to calculate the derivatives of virtual control functions by introducing DSC. The adaptive neural network is applied to approximate dynamic model, and an additional robust term is added into the controller to compensate the external disturbance together with the approximation error caused by adaptive neural network.

The main contributions of this paper are: (1) The paper comprehensively deals with the practical asymmetric time-varying output constrained problem for the 12-rotor UAV attitude system in the presence of model uncertainties and external disturbances, which has never been done before. (2) A novel adaptive robust backstepping controller in conjunction with ABLF, DSC, adaptive neural network and robust term is proposed for the UAV attitude system. The ABLF is introduced to keep the attitude angles staying strictly within the constrained sets. The DSC technique is used to address the derivation problem of the virtual control functions in recursive backstepping. The adaptive neural network is applied to approximate the dynamic model of the attitude system, which is facilitate to compensate the model uncertainties. The robust term can estimate and compensate the external disturbance together with the approximation error. Few literatures have introduced ABLF, adaptive neural network, DSC and robust term together to design a new control algorithm. (3) The semiglobally uniformly ultimately bounded stability of the UAV attitude system is obtained under the proposed novel adaptive robust backstepping control algorithm, and the tracking errors converge to a neighborhood of zero.

The outline of this paper is organized as follows: the problem formulation and preliminaries are given in Section 2. In Section 3, the proposed adaptive robust backstepping controller in conjunction with ABLF, DSC, adaptive neural network and robust term is developed and the stability analysis is discussed. The relative contrast simulation experiments are given in Section 4 to demonstrate