Disturbance observer-based robust missile autopilot design with full-state constraints via adaptive dynamic programming

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Abstract

This paper aims to develop a robust optimal control method for longitudinal dynamics of missile systems with full-state constraints suffering from mismatched disturbances by using adaptive dynamic programming (ADP) technique. First, the constrained states are mapped by smooth functions, thus, the considered systems become nonlinear systems without state constraints subject to unknown approximation error. In order to estimate the unknown disturbances, a nonlinear disturbance observer (NDO) is designed. Based on the output of disturbance observer, an integral sliding mode controller (ISMC) is derived to counteract the effects of disturbances and unknown approximation error, thus ensuring the stability of nonlinear systems. Subsequently, the ADP technique is utilized to learn an adaptive optimal controller for the nominal systems, in which a critic network is constructed with a novel weight update law. By utilizing the Lyapunov’s method, the stability of the closed-loop system and the convergence of the estimation weight for critic network are guaranteed. Finally, the feasibility and effectiveness of the proposed controller are demonstrated by using longitudinal dynamics of a missile.

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1. Introduction

Aerospace systems such as aircraft, spacecraft and missiles usually possess some common features, such as nonlinearity, uncertainties, time-varying and saturation. Their performance

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is highly dependent on the capabilities of guidance, navigation and control systems [1]. To achieve improved performance in such aerospace systems, several nonlinear control methods have been developed and tried on aircraft, spacecraft and missiles, which include adaptive control [2,3], dynamic inversion control [4], backstepping control [5], sliding mode control [6–8], optimal control [9], and so on. In [2], the adaptive dynamic inversion technique was utilized to design a state-feedback controller for air-breathing hypersonic vehicle system. Considering the actuator failures, in [3], an adaptive failure compensation controller was developed for a nonlinear aircraft dynamic model. Alam and Celikovsky [4] studied the control problem of 3-DOF longitudinal dynamics for a fixed-wing aircraft by utilizing the nonlinear dynamic inversion technique, where three differential flight controllers were designed to account for all significant nonlinearities. For guidance problem, He et al. [5] developed an adaptive backstepping guidance law for maneuvering target interception with impact angle constraints and input saturation. In order to compensate the uncertainties and disturbances, the sliding mode strategies were developed for matched and mismatched disturbances [8]. Furthermore, an adaptive higher order sliding mode control scheme was proposed to mitigate the chattering effects by regulating the design parameters [6, 7]. Although the mentioned control methods have effectively improved the system performance from different aspects, the optimality of controller is not taken into consideration. Optimal control strategy can not only stabilize the control systems, but also guarantee the optimal performance of the closed-loop systems, which is a preferable choice for the engineers. Unfortunately, the optimal control problem for nonlinear systems is a challenging task in control engineering. To obtain the solution of optimal control, the Hamilton–Jacobi–Bellman (HJB) equation has to be solved. Nevertheless, the HJB equation is actually a nonlinear partial differential equation, which is extremely difficult or impossible to solve by analytical methods.

To cope with this issue, adaptive dynamic programming (ADP) algorithms were proposed by Werbos [10], in which the functional approximation structure was constructed to estimate the cost function and solve dynamic programming problem forward-in-time. It is considered to be an effective technique to find the solution of HJB equation. Thereafter, the ADP techniques have received a great deal of attention. Various ADP-related works have been made [11–26]. In recent years, robust optimal control via ADP technique has attracted considerable interest for nonlinear systems. Jiang and Jiang [27–29] developed a robust ADP algorithm for a class of uncertain nonlinear systems, which would be the first time to investigate the robust ADP problems. Assuming the uncertainties were bounded by a known state-dependent function, Wang et al. [19,30] and Liu et al. [14] presented robust control strategies for uncertain nonlinear systems by redefining the infinite horizon cost function. Combining the zero-sum differential game theory and ADP technique, the nonlinear $H_\infty$ control problem was considered to compensate the disturbances in [31–33]. Sun et al. [34] proposed a robust differential game strategy that has been verified in the uncertain interceptor-target engagement successfully. However, it should be noted that the $H_\infty$ control is a worst case-based design and has been criticized as being ‘overconservative’ [35,36].

On the other hand, disturbances including external disturbances, unmodeled dynamics and parameter perturbations, widely exist in aerospace engineering, which severely degrade control performance of systems. To guarantee system stability and achieve a satisfactory performance when disturbances are encountered, disturbance attenuation is of great importance in control system design. To tackle this problem, several elegant methods have been developed. In addition to $H_\infty$ control, sliding mode control (SMC) [7,8,37,38] and disturbance-observer-based control (DOB) [35,39–43] have also been widely developed. In [7], an adaptive higher order
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