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Research article

Improved prescribed performance control for air-breathing hypersonic vehicles with unknown deadzone input nonlinearity

Yingyang Wang*, Jianbo Hu

Equipment Management and Unmanned Aerial Vehicle Engineering College, Air Force Engineering University, Xi'an, 710051, China

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ABSTRACT

An improved prescribed performance controller is proposed for the longitudinal model of an air-breathing hypersonic vehicle (AHV) subject to uncertain dynamics and input nonlinearity. Different from the traditional non-affine model requiring non-affine functions to be differentiable, this paper utilizes a semi-decomposed non-affine model with non-affine functions being locally semi-bounded and possibly in-differentiable. A new error transformation combined with novel prescribed performance functions is proposed to bypass complex deductions caused by conventional error constraint approaches and circumvent high frequency chattering in control inputs. On the basis of backstepping technique, the improved prescribed performance controller with low structural and computational complexity is designed. The methodology guarantees the altitude and velocity tracking error within transient and steady state performance envelopes and presents excellent robustness against uncertain dynamics and deadzone input nonlinearity. Simulation results demonstrate the efficacy of the proposed method.

1. Introduction

The remarkable commercial and military values of air-breathing hypersonic vehicles render them a research hotspot. Many control schemes have been proposed to solve the control problem of air-breathing hypersonic vehicles based on models proposed by Keshmiri [1] and Bolender [2,3]. However, strong couplings, large model uncertainties and complex nonlinearities pose huge challenges to realize a stable control. Initially, an assumption that the AHV model can be described by a linear uncertain model in a specific fight condition has been utilized to simplify the control problem and construct a robust controller [4,5]. Without using the linearization hypothesis, controllers are usually constructed based on the affine nonlinear model of an AHV by utilizing affine nonlinear control schemes, such as feedback linearization [6], LQR control [7], back-stepping control [8–10], adaptive control [11–13], sliding model control [14,15] and switching control [16,17]. Additionally, as it is hard to acquire an exact mathematical AHV model because of the existence of unmodeled dynamics and external disturbances, such approximating structures as neural system [18,19] and fuzzy system [20,21] have been utilized to approximate unknown terms and construct the controller.

Undoubtedly, the above studies have made great contributions to AHV research. However, the non-affine characteristic of AHV model has not been analyzed in the above-mentioned results. In fact, AHV model is a non-affine nonlinear system for complex relationships among aerodynamic coefficient, angle of attack, dynamic pressure and elevator angular deflection [1–3].

Researches on non-affine systems have attracted an increasing attention and many remarkable results have been reported during the past decades. Most notably, mean value theorem has been widely utilized to build a transformational model under the condition that non-affine functions are differentiable and then traditional control schemes such as adaptive neural network control [22–25], adaptive fuzzy control [26–29], fault-tolerant control [30], sliding model control [31] and prescribed performance control (PPC) [32] can be constructed. However, the bounds and signs of the derivatives of nonlinear functions for all the variables are difficult to be known in practical application.

In fact, some non-affine control and PPC methods for AHV have been proposed recently. Regarding the non-affine control, control input nonlinearities for hypersonic vehicles have been discussed [33,34], which are mainly focused on dead-zone or saturation. Particularly, Wang Y et al. have conducted exploratory research for complicated input nonlinearities and put forward an adaptive fuzzy non-affine control scheme for the longitudinal short-period model of a generic hypersonic vehicle [35]. Regarding the PPC methods, a combined backstepping and adaptive neural prescribed performance controller is constructed and has realized efficient control performance [36–38]. However, the aforementioned results [33–38] have all utilized approximating structures, i.e., neural networks, fuzzy systems, etc., and they are only locally valid within the compact set where the capabilities

* Corresponding author.
E-mail address: wangyingyang@outlook.com (Y. Wang).

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of the approximators hold.

As a result, the application of the above schemes [35–38] are limited due to the restrictive condition that non-affine functions are smooth and the partial derivatives exist, which motivates us to devote further study to overcome this limitation of PPC technique for an AHV. Moreover, due to the abrupt change of traditional performance function at the transient or the abrupt change of the reference signal at the steady state, there might exist chattering in control inputs [36–41]. Therefore, we need to develop flexible performance functions to balance the control input requirements and performance specifications in real time. The improved scheme is supposed to avoid the chattering and saturation of the actuator especially when the vehicle is maneuvering, which has a practical significance.

To the best of the authors' knowledge, designing a controller for the longitudinal model of an AHV with non-affine functions being possibly in-differentiable is still an open issue within the PPC framework. Motivated by the above discussions, this paper presents an improved prescribed performance controller for non-affine longitudinal model of flexible air-breathing hypersonic vehicles subject to uncertain dynamics and input nonlinearity. The special contributions of this paper are presented as follows:

(1) We utilize a semi-decomposed non-affine model for an AHV and remove the restrictive assumptions about the partial derivatives of non-affine functions. Therefore, non-affine nonlinear functions are no longer required to be differentiable.
(2) Compared with most of available studies on AHV, only a semi-bounded condition for non-affine functions rather than an exact control gain function is required in this paper, such that the controller designed based on the transformational model presents excellent robustness against uncertain dynamics and deadzone input nonlinearity.
(3) A new constraint variable is defined to construct control laws that ensure the altitude and velocity tracking performance specifications. The new error transformation avoids the non-differentiable problem and complex deductions caused by conventional error constraint approaches.
(4) Novel performance function can change automatically and flexibly to prevent the overrun and chattering of control inputs especially when the reference signal changes drastically.

The rest of this paper is structured as follows. In Section 2, AHV model description and control objective are provided. The conception of the novel prescribed performance is described in Section 3. Section 4 presents the prescribed performance controllers for velocity subsystem and altitude subsystem. The simulation studies that verify the theoretical findings are given in Section 5. Finally, conclusions are provided in Section 6.

2. AHV model

The longitudinal dynamic model of an AHV utilized in this paper is developed by Bolender and Doman [2]. The equations of motion are described as follows [3]:

$$\begin{cases} \dot{V} = \frac{T\cos(\theta-\gamma)-D}{m} - g\sin\gamma \\ \dot{h} = V\sin\gamma \\ \dot{\gamma} = \frac{L+T\sin(\theta-\gamma)}{mV} - \frac{g}{V}\cos\gamma \\ \dot{\theta} = Q \\ \dot{Q} = \frac{M+\tilde{\psi}_1\ddot{\eta}_1+\tilde{\psi}_2\ddot{\eta}_2}{I_{yy}} \\ k_1\ddot{\eta}_1 = -2\zeta_1\omega_1\dot{\eta}_1 - \omega_1^2\eta_1 + N_1 - \tilde{\psi}_1\frac{M}{I_{yy}} - \frac{\tilde{\psi}_1\tilde{\psi}_2\ddot{\eta}_2}{I_{yy}} \\ k_2\ddot{\eta}_2 = -2\zeta_2\omega_2\dot{\eta}_2 - \omega_2^2\eta_2 + N_2 - \tilde{\psi}_2\frac{M}{I_{yy}} - \frac{\tilde{\psi}_2\tilde{\psi}_1\ddot{\eta}_1}{I_{yy}} \end{cases} \quad (1)$$

where T, D, L, M and N_i $(i = 1, 2)$ are defined as [3]:

$$\begin{aligned} &T \approx C_T^{\alpha^3}\alpha^3 + C_T^{\alpha^2}\alpha^2 + C_T^{\alpha}\alpha + C_T^0 \\ &D \approx \bar{q}S\left(C_D^{\alpha^2}\alpha^2 + C_D^{\alpha}\alpha + C_D^{\delta_e^2}\delta_e^2 + C_D^{\delta_e}\delta_e + C_D^0\right) \\ &L \approx \bar{q}S\left(C_L^{\alpha}\alpha + C_L^{\delta_e}\delta_e + C_L^0\right) \\ &M \approx z_T T + \bar{q}S\bar{c}\left(C_{M,\alpha}^{\alpha^2}\alpha^2 + C_{M,\alpha}^{\alpha}\alpha + C_{M,\alpha}^0 + c_e\delta_e\right) \\ &N_1 \approx N_1^{\alpha^2}\alpha^2 + N_1^{\alpha}\alpha + N_1^0 \\ &N_2 \approx N_2^{\alpha^2}\alpha^2 + N_2^{\alpha}\alpha + N_2^{\delta_e}\delta_e + N_2^0 \\ &\bar{q} = \tfrac{1}{2}\bar{\rho}V^2, \quad \bar{\rho} = \bar{\rho}_0\exp\left(\frac{h_0-h}{h_s}\right) \end{aligned}$$

with

$$\begin{aligned} &C_T^{\alpha^3} = \beta_1(h,\bar{q})\Phi + \beta_2(h,\bar{q}) \\ &C_T^{\alpha^2} = \beta_3(h,\bar{q})\Phi + \beta_4(h,\bar{q}) \\ &C_T^{\alpha} = \beta_5(h,\bar{q})\Phi + \beta_6(h,\bar{q}) \\ &C_T^0 = \beta_7(h,\bar{q})\Phi + \beta_8(h,\bar{q}) \end{aligned}$$

Remark 1. There are two control inputs Φ, δ_e, four flexible states η_1, η_2, $\dot{\eta}_1$, $\dot{\eta}_2$, and five rigid-body states V, h, γ, θ, Q in this model. S denotes the reference area, $\bar{c}$ the mean aerodynamic chord and z_T the thrust moment arm. C is the coefficient of the curve-fit approximation. The specific parameter definitions can be found in Ref. [3]. Moreover, rigid-body states V, h, γ, θ, Q are assumed to be available for measurement [10–13,16–21]. Flexible states η_1, η_2, $\dot{\eta}_1$, $\dot{\eta}_2$ are treated as model uncertainties for their difficulties of measurement and will be handled by the controller's robustness.

Electronic circuits, hydraulic servo values and mechanical connections promote the deadzone actuation to be the most common nonlinearity in real control systems. Most papers [36,37] do not consider the actuator dynamics of elevator deflection within the PPC framework. In this paper, the deadzone input nonlinearity $\delta_e = D(\upsilon)$ is an unknown non-affine Lipschitz continuous function. For $\upsilon \geq \underline{\upsilon} \geq 0$ and $\upsilon \leq \bar{\upsilon} \leq 0$, there exist unknown constants $\underline{l}_1$, $\bar{l}_1$, $\underline{g}_1$ and $\bar{g}_1$ such that

$$\begin{cases} D(\upsilon) \geq \underline{g}_1\upsilon + \underline{l}_1, & \upsilon \geq \underline{\upsilon} \\ D(\upsilon) \leq \bar{g}_1\upsilon + \bar{l}_1, & \upsilon \leq \bar{\upsilon} \end{cases} \quad (2)$$

where $\underline{\upsilon}$ and $\bar{\upsilon}$ are unknown constants. For $|\upsilon| > \max\{|\bar{\upsilon}|, \underline{\upsilon}\}$, there exists an unknown positive constant $g_{1,m}$ satisfying $\min\{\underline{g}_1, \bar{g}_1\} \geq g_{1,m}$. Fig. 1 illustrates the deadzone input nonlinearity. It should be noted that the straight lines are only special forms of boundary functions $\underline{g}_1\upsilon + \underline{l}_1$ and $\bar{g}_1\upsilon + \bar{l}_1$.

Remark 2. The above definition of $D(\upsilon)$ represents a fairly general class of asymmetric and nonlinear deadzones. In this respect, the variation of

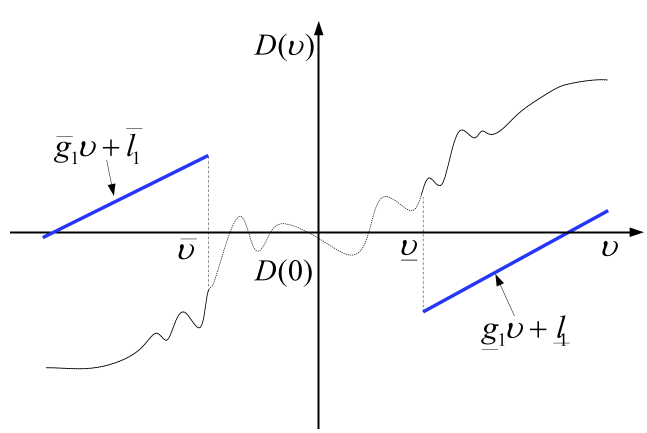

Fig. 1. Illustration of the deadzone input nonlinearity.