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# Adaptive backstepping control for air-breathing hypersonic vehicles with input nonlinearities

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ABSTRACT

This paper addresses the control problem of air-breathing hypersonic vehicles subject to input nonlinearities, aerodynamic uncertainties and flexible modes. An adaptive backstepping controller and a dynamic inverse controller are developed for the altitude subsystem and the velocity subsystem, respectively, where the former eliminates the problem of "explosion of terms" inherent in backstepping control. Moreover, a modified smooth inverse of the dead-zone is proposed to compensate for the dead-zone effects and reduce the computational burden. Based on this smooth inverse, an input nonlinear pre-compensator is designed to handle input saturation and dead-zone nonlinearities, which leads to a simpler control design for the altitude subsystem subject to these two input nonlinearities. It is proved that the proposed controllers can guarantee that all closed-loop signals are bounded and the tracking errors converge to an arbitrarily small residual set. Simulation results are carried out to demonstrate the effectiveness of the proposed control scheme.





## 1. Introduction

Air-breathing hypersonic vehicles (AHVs) have received tremendous attention in recent years, since such vehicles have been viewed as the next critical step toward achieving the reliable and cost-efficient access to space and possessing the ability of prompt global strike. The emergence of AHVs benefits a lot from the state-of-the-art technologies, such as ram/scramjet propulsion, high temperature material, thermal protection system, etc. Despite the progress of these advanced technologies, the design of the control schemes for AHVs is still an open problem, owing to the significant flexible effects aroused by their slender geometry and light structure, and the input nonlinearities such as input saturation and dead-zone.

During the past decades, the problem of longitudinal control design for AHVs has been extensively investigated. Schmidt [1,2] proposed a multivariable and classic linear control for the linearized longitudinal model of the vehicles developed by Chavez and Schmidt [3,4]. Later, some similar works have also been presented in [5–7]. However, to guarantee a desirable control performance, these control schemes developed based on a linearized model are always designed by combining the gain scheduling technique, which inevitably requires massive texting and offline analysis. To remedy this, extensive efforts have been devoted to developing control algorithms directly for nonlinear models of AHVs. For instance, in [8], a state-feedback controller was designed by incorporating feedback linearization and disturbance observer-based control. Wu et al. [9] proposed a robust backstepping control approach for a flexible AHV in the presence of aerodynamic uncertainties. Liu et al. [10] presented an output feedback controller by means of the immersion and invariance technique to provide asymptotically stable estimates of the unmeasurable states. However, it is notable that the control schemes in [8–10] do not fully consider the input nonlinearities of input saturation and dead-zone simultaneously.

From a practical viewpoint, the aerodynamic control surfaces of AHVs are always subject to input saturation [11] and dead-zone [12] due to their physical properties. These two inevitable constraints, as dominant input nonlinearities, often limit system performance severely, and may result in undesirable inaccuracy or lead to instability. With this in mind, the control design of AHVs with explicit consideration of these input nonlinearities has attracted a great interest over the past years. Xu et al. [13] proposed fault-tolerant control algorithms for tracking control of AHVs, in which command filters were introduced to deal with input saturation issue. Almost simultaneously, a similar result was presented in [14]. Later, inspired by [15], an auxiliary system was constructed in [16] to systematically account for the non-symmetric input saturation constraint. Recently, Bu et al. [17] developed a novel aux-

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iliary system which was integrated in the adaptive neural control scheme to handle the physical constraint on actuator.

Zhou et al. [18] introduced a mean-value theorem to overcome the obstacle generated from input saturation by combining adaptive backstepping control method. Regarding the dead-zone issue, Xu [19] incorporated the Nussbaum gain into the robust adaptive neural control to account for dead-zone nonlinearity. Despite the recent progress, it is noticed that most of the aforementioned works are focused on either input saturation or dead-zone separately. Actually, these two kinds of input nonlinearities always occur simultaneously, which poses significant challenges for the control design of AHVs. At present, some researches on integrating dead-zone with saturation have been presented in [20–22] for the nonlinear systems, under the assumption that the parameters of dead-zone are known. Yet, this assumption is not always satisfied in practice, thus making these control schemes not applicable to our work. In view of this, it is necessary to further explore new methodologies for the control design of AHVs with dead-zone and saturation nonlinearities. On the other hand, due to the characteristics of the AHVs, the dynamic model is also subject to aerodynamic uncertainties [23,24] and flexible modes [25] in practice, which may lead to control performance degradation. Hence, the development of tracking control schemes that are not only robust against aerodynamic uncertainties and flexible modes, but also able to handle input saturation and dead-zone nonlinearities is an imperative to achieve high precision tracking control of AHVs.

Motivated by the above observation, an adaptive control scheme is proposed for AHVs in the presence of input nonlinearities, aerodynamic uncertainties and flexible modes. Specifically, by viewing aerodynamic uncertainties and flexible modes integrally as lumped disturbances, an adaptive backstepping controller and a dynamic inverse controller are designed for the altitude subsystem and the velocity subsystem, respectively. Then, nonlinear disturbance observers (NDO) separated from the controllers design are constructed for each subsystem to estimate the lumped disturbances. Aiming at the altitude subsystem, dynamic surface control (DSC) technique is introduced to eliminate the problem of "explosion of terms" inherent in traditional backstepping approaches, which greatly reduces the computational burden and simplifies the controller structure. Moreover, a modified smooth inverse structure is proposed to compensate the dead-zone effects. By employing this smooth inverse, only slopes of dead-zone are required to be estimated, thus leading to a reduction of the computational burden. An input nonlinear pre-compensator is constructed to handle input saturation and dead-zone nonlinearities, which significantly simplifies the control design for the altitude subsystem. Based on this pre-compensator, an auxiliary system is designed to address the input saturation issue.

The rest of this paper is organized as follows. Section 2 presents the vehicle model, while Section 3 presents an input nonlinear pre-compensator for the input nonlinearities. The derivation of the control scheme is presented in Section 4. Then, the closed-loop stability analysis is given in Section 5 and followed by Section 6 in which numerical simulations are performed to validate the effectiveness of the proposed control scheme. Finally, this paper is concluded in Section 7.

## 2. Model description

### 2.1. Vehicle model

The flexible model of the longitudinal dynamics of AHVs used in this study is developed by Fiorentini et al. [25], and can be formulated as

$$\begin{cases} \dot{V} = \dfrac{T\cos\alpha - D}{m} - g\sin\gamma \\ \dot{h} = V\sin\gamma \\ \dot{\gamma} = \dfrac{L + T\sin\alpha}{mV} - \dfrac{g\cos\gamma}{V} \\ \dot{\alpha} = Q - \dot{\gamma} \\ \dot{Q} = \dfrac{M}{I_{yy}} \\ \ddot{\eta}_i = -2\xi_i\omega_i\dot{\eta}_i - \omega_i^2\eta_i + N_i, \quad i = 1, 2, 3 \end{cases} \tag{1}$$

where $\xi_i$ and $\omega_i$ denote damping ratio and national frequency for the flexible states $\eta_i$, respectively, and $m$ is the vehicle mass. This model is composed of five rigid-body state variables $V$, $h$, $\gamma$, $\alpha$, $Q$ which represent velocity, altitude, flight path angle (FPA), angle of attack (AOA), and pitch rate respectively, and six flexible states $\eta = [\eta_1, \dot{\eta}_1, \eta_2, \dot{\eta}_2, \eta_3, \dot{\eta}_3]^T$ corresponding to the first three bending modes of the fuselage. To cancel the lift generated by the elevator deflection, a canard is added to be ganged with the elevator by choosing $\delta_c = k_{ec}\delta_e$, where $\delta_e$ denotes the elevator deflection, $\delta_c$ denotes the canard deflection, and $k_{ec}$ represents the interconnection gain between the elevator deflection and the canard deflection, i.e., $k_{ec} = -C_L^{\delta_e}/C_L^{\delta_c}$. Therefore, the control inputs are selected as $u = [\phi, \delta_e]^T$, where $\phi$ represents the fuel equivalence ratio. The outputs to be controlled are selected as $y = [V, h]^T$.

To facilitate the control design, a simplified model has been derived in [26] for control design and analysis, which retains the relevant dynamic characteristics of the simulation model. The approximations of lift, drag, thrust, pitching moment, and generalized forces are given as follows:

$$\begin{cases} T \approx \bar{q}S\big[C_{T,\phi}(\alpha)\phi + C_T(\alpha) + C_T^{\eta}\eta\big] \\ L \approx \bar{q}SC_L(\alpha, \delta, \eta) \\ D \approx \bar{q}SC_D(\alpha, \delta, \eta) \\ M \approx z_T T + \bar{q}S\bar{c}C_M(\alpha, \delta, \eta) \\ N_i \approx \bar{q}S\big[N_i^{\alpha^2}\alpha^2 + N_i^{\alpha}\alpha + N_i^{\delta_e}\delta_e + N_i^{\delta_c}\delta_c + N_i^0 + N_i^{\eta}\eta\big] \end{cases} \tag{2}$$

where $\delta = [\delta_c, \delta_e]^T$, and $\bar{q}$, $S$ and $\bar{c}$ represent the dynamic pressure, the reference area, and the reference length, respectively. The coefficients are obtained using curve-fitted approximations, which are presented as

$$\begin{cases} C_{T,\phi}(\alpha) = C_T^{\phi\alpha^3}\alpha^3 + C_T^{\phi\alpha^2}\alpha^2 + C_T^{\phi\alpha}\alpha + C_T^0 \\ C_T(\alpha) = C_T^3\alpha^3 + C_T^2\alpha^2 + C_T^1\alpha^1 + C_T^0 \\ C_M(\alpha, \delta, \eta) = C_M^{\alpha^2}\alpha^2 + C_M^{\alpha}\alpha + C_M^{\delta_e}\delta_e + C_M^{\delta_c}\delta_c + C_M^0 + C_M^{\eta}\eta \\ C_L(\alpha, \delta, \eta) = C_L^{\alpha}\alpha + C_L^{\delta_e}\delta_e + C_L^{\delta_c}\delta_c + C_L^0 + C_L^{\eta}\eta \\ C_D(\alpha, \delta, \eta) \ = C_D^{\alpha^2}\alpha^2 + C_D^{\alpha}\alpha + C_D^{\delta_e^2}\delta_e^2 + C_D^{\delta_e}\delta_e + C_D^{\delta_c^2}\delta_c^2 \\ \qquad\qquad + C_D^{\delta_c}\delta_c + C_D^0 + C_D^{\eta}\eta \\ C_j^{\eta} = \begin{bmatrix} C_j^{\eta_1} & 0 & C_j^{\eta_2} & 0 & C_j^{\eta_3} & 0 \end{bmatrix}, \quad j = T, M, L, D \\ N_i^{\eta} = \begin{bmatrix} N_i^{\eta_1} & 0 & N_i^{\eta_2} & 0 & N_i^{\eta_3} & 0 \end{bmatrix}, \quad i = 1, 2, 3 \end{cases} \tag{3}$$

In contrast to [26], the lift, drag, thrust, and moment coefficients presented above depend explicitly on the flexible modes. To facilitate the design, the dynamic equations of the AHVs are transformed into a strict feedback form. Without loss of generality, the aerodynamic uncertainties and flexible modes are regarded as lumped disturbances. As a result, the strict feedback equations are expressed as



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