DYNAMIC SURFACE CONTROL OF CONSTRAINED HYPERSONIC FLIGHT MODELS WITH PARAMETER ESTIMATION AND ACTUATOR COMPENSATION

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ABSTRACT

In this paper, the robust adaptive controller is investigated for the longitudinal dynamics of a generic hypersonic flight vehicle. The proposed methodology addresses the issue of controller design and stability analysis with respect to parametric model uncertainty and input saturations for the control-oriented model. The velocity and attitude subsystems are transformed into the linearly parameterized form. Based on the parameter projection estimation, the dynamic inverse control is proposed via the back-stepping scheme. In order to avoid the problem of “explosion of complexity,” by introducing a first-order filtering of the synthetic input at each step, the dynamic surface control is designed. The closed-loop system achieves uniform ultimately bounded stability. The compensation design is employed when the input saturations occur. Simulation results show that the proposed approach achieves good tracking performance.

Key Words: Hypersonic flight vehicle, linearly parameterized form, dynamic surface control, input saturation.

Notation.

\( C_{D} \) = \( i \)th order coefficient of \( \alpha \) contribution to drag
\( C_{L} \) = \( i \)th order coefficient of \( \alpha \) contribution to lift
\( \delta_{e} \) = coefficient of \( \delta_{e} \) contribution to lift
\( \delta_{M} \) = coefficient of \( \delta_{e} \) contribution to moment
\( C_{M} \) = \( i \)th order coefficient of \( \alpha \) contribution to moment
\( \bar{c} \) = mean aerodynamic chord
\( D \) = drag
\( g \) = acceleration due to gravity
\( h \) = altitude
\( h_{c} \) = altitude command
\( h_{0} \) = nominal altitude for air density approximation
\( I_{yy} \) = moment of inertia axis
\( L \) = lift
\( M_{yy} \) = pitching moment
\( m \) = mass

\( g \) = pitch rate
\( q \) = dynamic pressure
\( S \) = reference area
\( T \) = thrust
\( V \) = velocity
\( V_{c} \) = velocity command
\( V_{r} \) = reference velocity
\( W_{r} \) = control Lyapunov function
\( z_{T} \) = thrust to moment coupling coefficient
\( \alpha \) = the attack angle
\( \beta_{i}(h, \bar{q}), \cdots, \beta_{i}(h, \bar{q}) \) = thrust fit parameters
\( \delta_{e} \) = elevator deflection
\( \gamma \) = flight path angle
\( \gamma_{d} \) = desired flight path angle
\( \rho \) = air density
\( \rho_{0} \) = nominal air density for air density approximation
\( \theta_{p} \) = pitch angle
\( \Gamma_{\beta_{i}}, \Gamma_{\phi_{i}} \) = matrices of the adaption gains
\( \Phi \) = fuel equivalence ratio
\( M_{i} \) = supreme of the derivative of the virtual control
\( e_{i} \) = filter parameter
\( 1/h_{c} \) = air density decay rate

I. INTRODUCTION

Hypersonic flight vehicles (HFVs) are intended to present a cost effective way to access space by reducing the flight time. The success of NASA’s X-43A experimental
airplane in flight testing has confirmed the feasibility of this technology. The failure of HTV-II in 2011 focused more attention on the control of HFV. The longitudinal model of the dynamics is known to be unstable, non-minimum phase with respect to the regulated output, and it is affected by significant model uncertainty. Therefore, hypersonic flight vehicles are extremely sensitive to changes in atmospheric conditions as well as physical and aerodynamic parameters.

Control of HFVs presents numerous challenges, stemming from the complexity of the dynamics and the unprecedented level of coupling between the airframe and the propulsion system. Most of the control schemes focus on the longitudinal dynamics. Based on linearizing the model at the trim state, for the design of guidance and control systems of hypersonic vehicles, the pivotal early works [1,2] employed classic and multivariable linear control. The adaptive control [3] combines feedforward input, nominal feedback and adaptive feedback terms. Based on the input-output linearization using Lie derivative notation, the sliding mode control [4] has been applied to a winged-cone configuration [5,6]. The genetic algorithm [7] has been employed for robust adaptive controller design. In [8], the minimax linear quadratic regulator control was applied to HFV based on the uncertainty model.

Considering the cascade structure of HFV dynamics, the altitude subsystem in [9] was transformed into the strict-feedback form. Back-stepping design [10,11] is an effective way to deal with this kind of system. The neural networks and Kriging system based methods have been investigated on discrete hypersonic flight control with nominal feedback [12–14]. With the same problem, by system transformation [15], a high gain observer is taken to estimate the newly defined variables while a neural network is employed to approximate the lumped uncertainty. The sequential loop closure controller design [16] is based on the decomposition of the equations into functional subsystems with the model from the assumed-modes version [17]. This method follows the approach that combined robust adaptive dynamic inversion with back-stepping arguments to obtain the control architecture. In [18], each subsystem was defined by a locally valid linear-in-the-parameters nonlinear model. The unknown parameters were adapted by a Lyapunov-based updating law. Nevertheless, in the controller design, the back-stepping design needs repeated differentiations of the virtual control and introduces more unknown items [19].

To eliminate the problem of “explosion of complexity” during the back-stepping design, the dynamic surface control (DSC) was applied to the winged-cone model in [20,21]. In [20], the dynamics were transformed into the strict-feedback form. The pure feedback form was considered in [21]. In these two methods, the dynamics are considered unknown and are approximated by fuzzy systems or neural networks. For the simulation, the parametric uncertainty is considered but there is no special focus on modeling the uncertainty. A similar DSC design [22] was investigated on the control oriented model (COM) developed recently in [23] with input constraints. Nevertheless, all of these works have tried to model the dynamics into the classic strict-feedback form before designing a controller highly dependant on the approximation ability of the intelligent systems.

In this paper, the COM, including the coupling effect of the engine to the airframe dynamics, is studied. The subsystem is written into the linearly parameterized form. Instead of nominal feedback or fuzzy/neural approximation, the dynamic inverse control is proposed via back-stepping based on the parameter projection estimation. To avoid the “explosion of complexity” during the back-stepping design [16,18], the dynamic surface method is employed. Furthermore, to provide good control performance when physical limitations are in effect, the compensation design is applied on the elevator deflection and fuel equivalence ratio. The proposed methodology addresses the issue of controller design and stability analysis with respect to parametric model uncertainty and input saturations. The closed-loop system achieves uniformly ultimately bounded stability.

This paper is organized as follows. Section II briefly presents the COM of the generic HFV longitudinal dynamics. In Section III, the dynamic inverse control is designed for the subsystems. Section IV presents the stability analysis. The compensation design is proposed in Section V. The simulation is included in Section VI. Section VII presents several comments and final remarks.

II. HYPERSONIC VEHICLE MODELING

The control-oriented model of the longitudinal dynamics of a generic hypersonic aircraft from [23] is considered in this study. This model is comprised of five state variables \( X_b = [V, h, \alpha, \gamma, q]^T \) and two control inputs \( U_b = [\delta_e, \Phi]^T \).

\[
\dot{V} = \frac{T \cos \alpha - D}{m} - g \sin \gamma \\
\dot{h} = V \sin \gamma \\
\dot{\gamma} = \frac{L + T \sin \alpha - g \cos \gamma}{mV} - \frac{g \cos \gamma}{V} \\
\dot{\alpha} = q - \gamma
\]
\[
\dot{q} = \frac{M_{\nu}}{I_{\nu}} \tag{5}
\]

where
\[
T = T_0(\alpha) + T_\nu(\alpha) = [\beta_1(h, \bar{q}) + \beta_2(h, \bar{q})] \alpha^2 + [\beta_3(h, \bar{q}) + \beta_4(h, \bar{q})] \alpha^2 + [\beta_5(h, \bar{q}) + \beta_6(h, \bar{q})] + [\beta_7(h, \bar{q}) + \beta_8(h, \bar{q})]
\]

\[
D = \bar{q}S(C_{\alpha}^2 \alpha^2 + C_{\beta}^2 \alpha + C_{\gamma}^2)
\]

\[
L = L_0 + L_\nu(\alpha) = \bar{q}S(C_{\alpha}^0 \alpha^2 + \bar{q}S C_{\beta} \alpha)
\]

\[
M_{\nu} = M_{\nu} + M_\nu(\alpha) + M_\delta \bar{\delta}, \quad \bar{q}T + \bar{q}S(\bar{C}_{\alpha}^2 \alpha^2 + C_{\beta}^2 \alpha + C_{\gamma}^2) + \bar{q}S C_{\delta} \bar{\delta}
\]

\[
\bar{q} = \frac{1}{2} \rho V^2
\]

\[
\rho = \rho_0 \exp\left[-\frac{h - h_0}{h}\right]
\]

To facilitate the design in Section III with a compact form, the following definition is presented:
\[
T = \bar{q}S\left(C_{\alpha}^0 \alpha^2 + C_{\beta}^2 \alpha^2 + C_{\gamma}^2 \alpha + C_{\delta}^2\right)\Phi
\]

\[
+ \bar{q}S\left(C_{\alpha}^2 \alpha^2 + C_{\beta}^2 \alpha^2 + C_{\gamma}^2 \alpha + C_{\delta}^2\right)
\]

where
\[
C_{\alpha}^0 = \beta_1/(\bar{q}S), \quad C_{\beta}^0 = \beta_2/(\bar{q}S), \quad C_{\gamma}^0 = \beta_3/(\bar{q}S), \quad C_{\delta}^0 = \beta_4/(\bar{q}S), \quad C_{\alpha}^0 = \beta_5/(\bar{q}S), \quad C_{\beta}^0 = \beta_6/(\bar{q}S), \quad C_{\gamma}^0 = \beta_7/(\bar{q}S), \quad C_{\delta}^0 = \beta_8/(\bar{q}S).
\]

Remark 1. As stated in [23], the nonminimum phase behavior results from the momentary loss of lift that occurs when the elevator is actuated to initiate a climb and the additional effector can be used to compensate for the undesirable contribution of the elevator to lift. A canard is placed near the nose of the aircraft, forward of the center of gravity, and the deflection of the canard will be ganged with the elevator deflection using a negative gain. In this way, the $C_{\delta}^2$ item can be safely ignored while $C_{\gamma}^0$ becomes larger. So, in the COM, the $C_{\delta}^2$ item does not appear in the expression of lift force. In this paper, $C_{\gamma}^0$ is 1.5 times larger.

In developing the controller and assessing its closed-loop behavior, it is assumed that all of the coefficients of the model are subject to uncertainty, apart from obvious parameters corresponding to physically measurable quantities or known constants. The vector of all uncertain parameters, denoted by $p \in R^{2\delta}$, includes the vehicle inertial parameters and the coefficients that appear in the force and moment approximations. The nominal value of $p$ is denoted by $p_0$. It is assumed that $p \in \Omega_p$, where $\Omega_p$ is a compact convex set that represents the admissible range of variation of $\Delta p$ such that $p_0$ lies in its interior. For simplicity, the maximum uniform variation within 30% of the nominal value has been considered, yielding the parameter set $\Omega_p = \{p \in R^{2\delta} | p_i^l \leq p_i \leq p_i^U, i = 1, \ldots, L_p\}$ and $p_i^l = \min \{0.7 p_0^l, 1.3 p_0^U\}$, $p_i^U = \max \{0.7 p_0^U, 1.3 p_0^l\}$.

Remark 2. Since $p_i$ might be negative, instead of using $\Omega_p = \{p \in R^{2\delta} | 0.7 p_0^l \leq p_i \leq 1.3 p_0^U, i = 1, \ldots, L_p\}$, the parameter set is defined with the lower bound $p_i^l$ and upper bound $p_i^U$. The bound will be used during the parameter projection design.

### III. CONTROL DESIGN

The control problem considered in this work takes into account only cruise trajectories and does not consider the ascent or the re-entry of the vehicle. In [9,12,14,18], by functional decomposition, the velocity is independent of the other subsystems. The goal pursued in this study is to design a dynamic controller $\Phi$ and $\delta$ to steer system velocity and altitude from a given set of initial values to desired trim conditions with the tracking reference $V$ and $h$. Furthermore, the altitude command is transformed into the flight path angle (FPA) tracking [15,20,22]. Define the altitude tracking error $\bar{h} = h - h_0$. The demand of FPA is generated as:

\[
\gamma_d = \arcsin\left(-\frac{k_0 \bar{h} + \bar{h}}{V}\right) \tag{6}
\]

where $k_0 > 0$ is the design parameter.

Remark 3. Hypersonic flight vehicles are flying at a high speed. In [18,22], the value is greater than 7500 ft/s. Compared with the magnitude of the velocity, the $\bar{h}$ and $h$ are really small. So, $\left(-\frac{k_0 \bar{h} + \bar{h}}{V}\right) \ll 1$. The conclusion can also be verified by the flight path angle response in the simulation study. The efforts on controlling the altitude system focus now on the tracking of $\gamma_d$.

In this paper, by functional decomposition, the dynamics are decoupled into velocity and altitude subsystems.

#### 3.1 Dynamic inversion control of velocity subsystem

Define the velocity error:
\[
\dot{V} = V - V_r \tag{7}
\]
From (7), the velocity dynamics are derived as:

$$\dot{V} = \frac{T_v \cos \alpha}{m} \Phi + \frac{T_v \cos \alpha - D}{m} - g \sin \gamma - \dot{V} \quad (8)$$

Define $g_v = \frac{T_v \cos \alpha}{m}$, $f_v = \frac{T_v \cos \alpha - D}{m}$. Then (8), becomes

$$\dot{V} = g_v \Phi + f_v - g \sin \gamma - \dot{V} \quad (9)$$

where $f_v = \omega_v^T \theta_v$, $g_v = \omega_v^T \theta_v$, with

$$\omega_v = \eta S \begin{bmatrix} \alpha^1 \cos \alpha, \alpha^2 \cos \alpha, \alpha \cos \alpha, \cos \alpha \end{bmatrix}^T$$

$$\theta_v = \frac{1}{m} \begin{bmatrix} C_0^g, C_1^g, C_2^g, C_2^\alpha, C_3^\gamma, C_3^\alpha \end{bmatrix}^T$$

$$\omega_g = \omega S \begin{bmatrix} \alpha^1 \cos \alpha, \alpha^2 \cos \alpha, \alpha \cos \alpha, \cos \alpha \end{bmatrix}^T$$

$$\theta_g = \frac{1}{m} \begin{bmatrix} C_0^g, C_1^g, C_2^g, C_2^\alpha, C_3^\gamma, C_3^\alpha \end{bmatrix}^T$$

The control Lyapunov function candidate for the velocity error dynamics is selected as:

$$W_v = \frac{1}{2} \left( \dot{V}^2 + \dot{\theta}_v^T \Gamma_g \dot{\theta}_v + \dot{\theta}_v^T \Gamma_{gg} \dot{\theta}_v \right)$$

The derivative of $W_v$ is

$$\dot{W_v} = \dot{V} \dot{V}^2 - \dot{\theta}_v^T \Gamma_{g} \dot{\theta}_v - \dot{\theta}_v^T \Gamma_{gg} \dot{\theta}_v$$

$$= -k_v \dot{V}^2 + \dot{V} \omega_v^T \theta_v + \dot{V} \omega_v^T \Phi - \dot{V} \omega_v^T \Gamma_g \dot{\theta}_v - \dot{V} \omega_v^T \Gamma_{gg} \dot{\theta}_v \quad (13)$$

The adaptive law is designed as:

$$\dot{\theta}_v = \text{Proj} \left( \Gamma_g \dot{V} \omega_v \right) \quad (14)$$

$$\dot{\theta}_g = \text{Proj} \left( \Gamma_g \dot{V} \omega_v \phi \right)$$

where the smooth parameter projection has the following form:

$$\text{Proj}(r) = \begin{cases} \tau_i & \text{if } \dot{\phi}_i \in \Omega \tau \vspace{1em} \text{or } \dot{\phi}_i = p_i, \tau \geq 0 \vspace{1em} \text{or } \dot{\phi}_i = p_i, \tau \leq 0 \vspace{1em} 0 & \text{otherwise} \end{cases}$$

Then

$$\dot{W_v} = -k_v \dot{V}^2$$

One can see that the velocity is asymptotically stable.

### 3.2 Dynamic surface control of attitude subsystem

Define $x_1 = \gamma, x_2 = \theta_v, x_3 = q, \theta_p = \alpha + \gamma, u = \delta$.

The following subsystem can be obtained:

$$\dot{x}_1 = g_1 x_2 + f_1 - \frac{g_2}{V} \cos x_1$$

$$\dot{x}_2 = x_3$$

$$\dot{x}_3 = g_3 u + f_3$$

where

$$f_1 = \frac{L_0 - L_0 \gamma + T \sin \alpha}{mV} = \omega_v^T \theta_f$$

$$g_1 = \frac{L_0}{mV} = \omega_v^T \theta_g$$

$$f_3 = \frac{M_x + M_0(\alpha)}{I_{xy}} = \omega_g^T \theta_f$$

$$g_3 = \frac{M_{\delta}}{I_{xy}} = \omega_g^T \theta_g$$

with

$$\omega_y = \frac{\eta S}{V} \begin{bmatrix} 1, -\gamma, \alpha^1 \Phi \sin \alpha, \alpha^2 \Phi \sin \alpha, \alpha \Phi \sin \alpha, \alpha \Phi \sin \alpha \end{bmatrix}^T$$

$$\theta_f = \frac{1}{m} \begin{bmatrix} C_0^g, C_1^g, C_2^g, C_3^2, C_3^\alpha, C_3^\gamma \end{bmatrix}^T$$

$$\theta_g = \frac{1}{m} \begin{bmatrix} C_0^g, C_1^g, C_2^g, C_3^2, C_3^\alpha, C_3^\gamma \end{bmatrix}^T$$
\[ \omega_{g1} = \frac{\bar{q}S}{V} \]

\[ \theta_{g1} = \frac{1}{m} C_L^a \]

\[ \omega_{f3} = \bar{q}S \left[ \alpha'\Phi, \alpha^2\Phi, \alpha\Phi, \Phi, \alpha', \alpha^2, \alpha, 1, \alpha^2, \alpha \right]^T \]

\[ \theta_{f3} = \frac{1}{I_y} \begin{bmatrix} \bar{z}_f(C_{10}^{\alpha}, C_{10}^{\beta}, C_{10}^{\Phi}, C_{10}^{\nu}) \end{bmatrix}^T \]

\[ \omega_{g3} = \bar{q}S \]

\[ \theta_{g3} = \frac{1}{I_y} C_{2\delta} \]

**Step 1.** Define \( \tilde{x}_i = x_i - x_{id} \). The dynamics of the flight path angle tracking error \( \tilde{x}_i \) are written as:

\[
\hat{\tilde{x}}_i = \tilde{x}_i - \tilde{x}_{id} = g_i x_i + f_i - \frac{g}{V} \cos \gamma - \tilde{x}_{id}
\]

Take \( \theta_e \) as the virtual control and design \( x_{2e} \) as:

\[
\hat{g}_i \dot{x}_{2e} = -k_i \hat{x}_i + \frac{g}{V} \cos x_i + x_{id}
\]

where \( k_i > 0 \) is the design parameter, \( \hat{f}_i = \omega_{f1}^T \hat{\phi}_{f1} \), \( \hat{g}_i = \omega_{g1}^T \hat{\phi}_{g1} \).

Introduce a new state variable \( x_{2e} \), which can be obtained by the following first-order filter:

\[
e_{3\hat{x}}_{2e} + x_{2e} = x_{2e} (0) = x_{2e} (0)
\]

Define \( y_2 = x_{2e} - x_{2e} \), \( \tilde{x}_2 = x_2 - x_{2e} \)

\[
\hat{\tilde{x}}_2 = g_i x_2 + f_i - \frac{g}{V} \cos \gamma - \tilde{x}_{2e}
\]

\[
= g_i (x_2 - x_{2e}) + g_i x_{2e} - \hat{g}_i x_{2e} + \hat{g}_i x_{2e} + f_i - \frac{g}{V} \cos \gamma - \tilde{x}_{2e}
\]

\[
= g_i (x_2 - x_{2e}) + \hat{g}_i x_{2e} + \hat{f}_i - k_i \hat{x}_i
\]

\[
= g_i \tilde{x}_2 + \hat{g}_i x_{2e} + \hat{f}_i - k_i \hat{x}_i
\]

The adaption laws of the estimated parameters are

\[
\dot{\hat{\phi}}_{f1} = \text{Proj}(\Gamma_{f\theta} \hat{\phi}_{f1} \tilde{x}_i)
\]

\[
\dot{\hat{\phi}}_{g1} = \text{Proj}(\Gamma_{g\theta} \hat{\phi}_{g1} \tilde{x}_2)
\]

**Step 2.** The dynamics of the pitch angle tracking error \( \tilde{x}_2 \) are written as:

\[
\hat{\tilde{x}}_2 = \tilde{x}_2 - \tilde{x}_{2d} = x_3 - \tilde{x}_{2d}
\]

Take \( q \) as virtual control and design \( x_{3e} \) as:

\[
\dot{x}_{3e} = -k_2 \tilde{x}_2 + \tilde{x}_{2d}
\]

where \( k_2 > 0 \) is the design parameter.

Introduce a new state variable \( x_{3e} \), which can be obtained by the following first-order filter:

\[
e_{3\hat{x}}_{3e} + x_{3e} = x_{3e} (0) = x_{3e} (0)
\]

Define \( y_3 = x_{3e} - x_{3e} \), \( \tilde{x}_3 = x_3 - x_{3e} \).

\[
\hat{\tilde{x}}_3 = x_3 - \tilde{x}_{3d}
\]

\[
= x_3 - x_{3e} + x_{3e} - x_{3e} + x_{3e} - \tilde{x}_{2e} = \tilde{x}_3 + y_3 - k_2 \tilde{x}_2
\]

**Step 3.** The dynamics of the pitch rate tracking error \( \tilde{x}_3 \) are written as:

\[
\dot{\tilde{x}}_3 = \tilde{x}_3 - \tilde{x}_{3d} = g_3 u + f_3 - \tilde{x}_{3d}
\]

Design the elevator deflection \( \delta_t \) as:

\[
\dot{\tilde{\delta}}_3 = -k_3 \tilde{x}_3 - \tilde{f}_3 + \tilde{x}_{3d}
\]

where \( k_3 > 0 \) is the design parameter, \( \tilde{f}_3 = \omega_{f3}^T \hat{\phi}_{f3} \), \( \dot{\tilde{\delta}}_3 = \omega_{\delta}^T \hat{\phi}_{\delta3} \).

The error dynamics are derived as:

\[
\dot{\tilde{x}}_3 = g_3 u + f_3 - \tilde{x}_{3d} = (\hat{g}_3 + \hat{g}_3) u + f_3 - \tilde{x}_{3d} = \tilde{g}_3 u - k_3 \tilde{x}_3 + \tilde{f}_3
\]

The adaption laws of the estimated parameters are

\[
\dot{\hat{\phi}}_{f3} = \text{Proj}(\Gamma_{f\theta} \hat{\phi}_{f3} \tilde{x}_3)
\]

\[
\dot{\hat{\phi}}_{g3} = \text{Proj}(\Gamma_{g\theta} \hat{\phi}_{g3} \tilde{x}_3 u)
\]

**Remark 4.**

1. The controller is designed with the linearly parameterized form.
2. To avoid the calculation of the derivative of the virtual control, the dynamic surface method is employed.
3. The parameter adaption law is proposed according to the Lyapunov stability analysis, which will be conducted in Section IV.

IV. STABILITY ANALYSIS

Assumption 1. The FPA reference signal and its derivatives are smooth bounded functions.

Remark 5. This assumption is commonly employed for DSC design [19, 22] to make the upper bound of the derivative of the virtual control available during the stability analysis.

Assumption 2. There exists a constant \( \bar{g}_i > |g_i| > 0 \).

Theorem 1. Consider System (18) with virtual control (20), (26), actual control (30) with adaption laws (23), (24), (32), and (33) under Assumptions 1–2. Then, all of the signals of (34) are uniformly ultimately bounded.

Proof. Select Lyapunov function

\[
W = \sum_{i=1}^{3} W_i
\]

with

\[
W_1 = \frac{1}{2} \left( \dot{x}_i^2 + \dot{\varphi}_j^2 \Gamma_j \dot{\varphi}_1 + \dot{\varphi}_j^2 \Gamma_j \dot{\varphi}_3 + y_i^2 \right)
\]

\[
W_2 = \frac{1}{2} (\dot{x}_1^2 + y_1^2)
\]

\[
W_3 = \frac{1}{2} (\dot{x}_1^2 + \dot{\varphi}_j^2 \Gamma_j \dot{\varphi}_1 + \dot{\varphi}_j^2 \Gamma_j \dot{\varphi}_3)
\]

According to the definition of \( y_i \), \( i = 2, 3 \), the following equations can be obtained:

\[
\dot{y}_i = \ddot{x}_i - \dot{x}_i - \frac{y_i}{\varepsilon_i} + B_i(\cdot)
\]

\[
B_i(\cdot) = -\dot{x}_i
\]

According to the virtual control (20), (26), together with Assumption 1, we know there exist constants \( M_i > 0, i = 2, 3 \) with

\[
|B_i(\cdot)| \leq M_i
\]

Take the derivative of \( W_i \):

\[
\dot{W}_i = \ddot{x}_i \dot{x}_i - \dot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_1 - \dot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_3 + y_i \ddot{y}_i
\]

\[
= -k_i \dot{x}_1^2 + g_i \dot{x}_3 \dot{x}_1 + g_i \dot{y}_2 \dot{x}_1 - \dot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_1 - \ddot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_3 - \dot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_1 \left( \Gamma_j \ddot{\varphi}_1 - \omega_j \dot{x}_1 \right)
\]

\[
= -\dot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_1 \left( \Gamma_j \ddot{\varphi}_1 - \omega_j \dot{x}_1 \right) - \frac{y_i^2}{\varepsilon_i^2} + B_i y_i
\]

Substituting the adaption law into (37) and using \( ab < a^2/2 + b^2/2 \), we have:

\[
\dot{W}_i = -k_i \dot{x}_1^2 + g_i \dot{x}_3 \dot{x}_1 + g_i \dot{y}_2 \dot{x}_1 - \frac{y_i^2}{\varepsilon_i^2} + B_i y_i
\]

\[
\leq -k_i \dot{x}_1^2 + g_i \left[ \dot{x}_3 \dot{x}_1 + \dot{y}_2 \dot{x}_1 \right] - \frac{y_i^2}{\varepsilon_i^2} + |B_i y_i|
\]

\[
\leq -(k_i - g_i) \dot{x}_1^2 + \frac{\dot{x}_1^2}{2} \left( \frac{1}{\varepsilon_i^2} - \frac{g_i}{\varepsilon_i^2} - \frac{1}{2} \right) y_i^2 + \frac{M_i^2}{2} \quad (38)
\]

\[
= -k_{i0} \dot{x}_1^2 + g_i \frac{\dot{x}_1^2}{2} - k_{i1} y_i^2 + \frac{M_i^2}{2}
\]

\[
\leq -\eta_i (\dot{x}_1^2 + y_i^2) + g_i \frac{\dot{x}_1^2}{2} + \frac{M_i^2}{2}
\]

where \( k_{i0} = k_i - g_i > 0, \ k_{i1} = \frac{1}{\varepsilon_i^2} - \frac{g_i}{\varepsilon_i^2} - \frac{1}{2} > 0, \ \eta_i = \min[k_{i0}, k_{i1}]. \)

\[
\dot{W}_2 = \ddot{x}_2 \dot{x}_2 + y_2 \ddot{y}_2 = \ddot{x}_2 \left( \ddot{x}_1 + y_3 - k_2 \dot{x}_2 \right) - \frac{y_2^2}{\varepsilon_3} + y_3 B_3
\]

\[
\leq \frac{\dot{x}_1^2}{2} + \frac{\dot{x}_1^2}{2} + \frac{\dot{x}_1^2}{2} - k_2 \dot{x}_2^2 - \frac{y_2^2}{\varepsilon_3^2} + \frac{y_3^2}{\varepsilon_3^2} + \frac{M_3^2}{2}
\]

\[
= -k_{20} \dot{x}_2^2 - k_{21} y_2^2 + \frac{\dot{x}_1^2}{2} + \frac{M_3^2}{2} - g_i \dot{x}_1^2
\]

\[
\leq -\eta_2 (\dot{x}_2^2 + y_2^2) + \frac{M_3^2}{2} + \frac{\dot{x}_1^2}{2} - g_i \dot{x}_1^2
\]

where \( k_{20} = k_2 - \frac{g_i}{\varepsilon_3^2} > 0, \ k_{21} = \frac{1}{\varepsilon_3^2} - 1 > 0, \ \eta_2 = \min[k_{20}, k_{21}]. \)

\[
\dot{W}_3 = \ddot{x}_3 \dot{x}_3 + \ddot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_1 + \ddot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_3 + \ddot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_3
\]

\[
= \ddot{x}_3 \dot{x}_3 - \ddot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_1 - \ddot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_3 - \ddot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_1 \left( \Gamma_j \ddot{\varphi}_1 - \omega_j \dot{x}_1 \right)
\]

\[
= -k_3 \dot{x}_3^2 - \ddot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_3 - \ddot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_3 - \ddot{\varphi}_j^2 \Gamma_j \ddot{\varphi}_1 \left( \Gamma_j \ddot{\varphi}_1 - \omega_j \dot{x}_1 \right)
\]

\[
\leq -\eta_3 (\dot{x}_3^2 + y_3^2) - \frac{y_3^2}{\varepsilon_3^2} + \frac{M_3^2}{2}
\]

where \( \eta_3 = k_3 - 1/2 > 0. \)
Finally, we have:

$$\dot{W} = \sum_{i=1}^{3} \dot{W}_i$$

$$\leq -\eta_i (\tilde{x}_i^2 + y_i^2) - \eta_i (\tilde{x}_i^2 + y_i^2) - \eta_i \tilde{x}_i^2 + \frac{1}{2} M_i^2 + \frac{1}{2} M_i^2$$

(42)

where $M_d = \frac{1}{2} \sum_{i=2}^{3} M_i^2$, $\eta = \min[\eta_1, \eta_2, \eta_3]$, $\tilde{W} = \sum_{i=1}^{3} \tilde{x}_i^2 + \sum_{j=2}^{3} y_j^2$. According to the Lasalle-Yoshizawa Theorem, the closed-system stability is uniformly ultimately bounded.

This completes the proof.

**Remark 6.** If the initial value $W_i |_{t=0} = p_0$, then $\dot{W} \leq -\eta p_0 + M_d$. If $p_0 > M_d / \eta$, then $\dot{W} < 0$.

The system is stable in the following compact

$$\mathcal{Y} = \{ \tilde{x}_0, y_1 | \tilde{W} \leq M_d / \eta \}$$

(43)

The radius can be made arbitrarily small by increasing the control gain ($k_1, k_2, k_3$) and decreasing the filter parameter ($\epsilon_2, \epsilon_3$).

**V. ACTUATOR CONSTRAINT COMPENSATION**

The design in this part is to ensure stability even when physical limitations are in effect. Note that, when physical constraints are in effect, the tracking error can increase because the necessary control signal to achieve the tracking cannot be implemented within the physical constraints imposed on the system [24].

Define

$$z_3 = \tilde{x}_3 - e_3$$

(44)

where

$$\dot{e}_3 = -k_3 e_3 - g_3 (u_e - u)$$

(45)

We redesign the virtual control in Step 2 as:

$$x_{3e} = -k_3 \tilde{x}_3 + \dot{x}_{3d} - e_3$$

(46)

Then, the error dynamics are derived as:

$$\dot{z}_3 = \tilde{x}_3 - \dot{z}_{3d} = x_3 - x_{3d} + x_{3c} - x_{3c} - \dot{x}_{3d}$$

$$= z_3 + y_3 - k_2 \tilde{x}_3$$

(47)

For error dynamics (31), the controller derived from (30) is defined as $u_c$.

$$\dot{g}_3 u_c = -k_3 \tilde{x}_3 - \dot{f}_3 + x_{3d}$$

(48)

Then, we have the following error dynamics:

$$\dot{z}_3 = -k_3 \tilde{x}_3 + \dot{f}_3 + g_3 u - \dot{g}_3 u_c$$

(49)

Let $u_c$ go through the filter with constraint depicted in Fig. 1 to obtain $u$.

**Remark 7.** When the limiter is not in effect, we have the following relationship:

$$\frac{u(s)}{u_c(s)} = \frac{\omega^3}{s^2 + 2\omega s + \omega^2}$$

(50)

The derivative of $z_3$ is obtained as:

$$\dot{z}_3 = \dot{\tilde{x}}_3 - \dot{e}_3 = -k_3 \tilde{x}_3 + \dot{f}_3 + g_3 u - \dot{g}_3 u_c + k_3 e_3 - \dot{g}_3 (u - u_c)$$

$$= -k_3 z_3 + \dot{f}_3 + \dot{g}_3 u$$

(51)

The adaptation laws of the estimated parameters are modified as:

$$\dot{\theta}_{\omega_3} = \text{Proj}(\Gamma_{\omega_3} \theta_{\omega_3} z_3)$$

(52)

$$\dot{\theta}_{g_3} = \text{Proj}(\Gamma_{g_3} \theta_{g_3} z_3 u)$$

(53)

Select Lyapunov function $W = \sum_{i=1}^{3} W_i$ with

$$W_i = \frac{1}{2} (\tilde{x}_i^2 + \dot{\theta}_{\omega_i} \Gamma_i \dot{\theta}_{\omega_i} + \dot{\theta}_{g_i} \Gamma_i^{-1} \dot{\theta}_{g_i} + y_i^2)$$

$$W = \frac{1}{2} \sum_{i=1}^{3} (\tilde{x}_i^2 + \dot{\theta}_{\omega_i} \Gamma_i \dot{\theta}_{\omega_i} + \dot{\theta}_{g_i} \Gamma_i^{-1} \dot{\theta}_{g_i} + y_i^2)$$

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\[ W_2 = \frac{1}{2} (\dot{x}_2^2 + y_2^2) \]

\[ W_3 = \frac{1}{2} (x_3^2 + \tilde{\theta}_f^T \Gamma_3 \dot{\theta}_f + \tilde{\theta}_g^T \Gamma_3^{-1} \dot{\theta}_g) \]

The derivatives of \( W_1 \) are the same as (38):

\[ \dot{W}_1 = -\eta_i (x_i^2 + y_i^2) + \frac{1}{2} M_i^2 + \tilde{\xi}_i^2 / 2 \]

For the second item, we have:

\[
\begin{align*}
\dot{W}_2 &= \dot{x}_2 \ddot{x}_2 + y_3 \ddot{y}_3 = \dot{x}_2 (z_3 + y_3 - k_3 \ddot{x}_2) - \frac{y_3}{\varepsilon_3} + y_3 B_3 \\
&\leq -k_2 \ddot{x}_2^2 + \frac{y_3}{\varepsilon_3} + y_3 B_3 \\
&= -k_2 \ddot{x}_2^2 - k_3 \ddot{y}_3^2 + \frac{M_i^2}{2} - \frac{\tilde{G}_i \ddot{\xi}_i^2}{2} \\
&\leq -\eta_i (\ddot{x}_2^2 + \ddot{y}_3^2) + \frac{M_i^2}{2} - \frac{\tilde{G}_i \ddot{\xi}_i^2}{2} \quad (54)
\end{align*}
\]

For the third item, we have:

\[
\begin{align*}
\dot{W}_3 &= \dot{z}_3 \ddot{z}_3 - \tilde{\theta}_f^T \Gamma_3 \dot{\theta}_f - \tilde{\theta}_g^T \Gamma_3^{-1} \dot{\theta}_g \\
&= -k_2 \ddot{z}_3^2 - \tilde{\theta}_f^T \Gamma_3 \dot{\theta}_f - \tilde{\theta}_g^T \Gamma_3^{-1} \dot{\theta}_g \\
&= -k_2 \ddot{z}_3^2 \leq \left( k_1 - \frac{1}{2} \right) \ddot{z}_3^2 - \frac{k_3}{2} \ddot{z}_3^2 = -\eta_i \ddot{z}_3^2 - \frac{1}{2} \ddot{z}_3^2 \quad (55)
\end{align*}
\]

Remark 8.

1. The definition of \( k_{i1}, k_{i2}, k_{i3}, \eta_i \), \( i = 1, 2, 3 \) is the same as in Section IV.
2. The compensation error item \( e_i \) is added in the virtual control (46). So, the derivative of \( W_i \) obtains the information for \( z_i \).

Now, we have:

\[
\begin{align*}
\dot{W} &= \sum_{i=1}^{3} \dot{W}_i \\
&= -\eta_i (\ddot{x}_i^2 + \ddot{y}_i^2) - \eta_2 (\ddot{x}_2^2 + \ddot{y}_2^2) - \eta_3 \ddot{z}_3^2 + \frac{1}{2} M_i^2 + \frac{1}{2} M_i^2 \\
&\leq -\eta \ddot{\bar{w}}_{new} + M_{new} \quad (56)
\end{align*}
\]

where \( M_{new} = \frac{1}{2} \sum_{i=1}^{3} M_i^2 \), \( \eta = \min \{ \eta_i, \eta_2, \eta_3 \} \).

\[ \ddot{\bar{w}}_{new} = \sum_{i=1}^{3} \ddot{x}_i^2 + \sum_{i=2}^{3} \ddot{y}_i^2 + \ddot{z}_3^2 \]. Then, we know the closed-system stability is uniformly ultimately bounded.

For the setting of \( \Phi \), the controller is modified as:

\[ \hat{g}, \Phi = -k \ddot{V} - \dot{f} + g \sin \gamma + \nu \quad (57) \]

Let \( \Phi \) go through the filter with the constraint to obtain \( \Phi \). The adaptation laws are

\[ \dot{\theta}_\mu = \text{Proj} \left( \Gamma_\mu \dot{z}_\mu \omega_\mu \right) \quad (58) \]

\[ \dot{\theta}_\phi = \text{Proj} \left( \Gamma_\phi \dot{z}_\phi \omega_\phi \Phi \right) \quad (59) \]

where

\[ \dot{z}_\mu = \ddot{V} - e_i \]

\[ \dot{e}_i = -k_i e_i - \hat{g}, (\Phi_e - \Phi) \]

Remark 9.

1. It should be noted that, if there is no compensation error feedback for the virtual control \( x_{32} \), the stability analysis will introduce the item \( e_{3i} \), which needs another Lyapunov function to prove that \( e_3 \) is bounded. Unfortunately, it is not analyzed in [22]. More detailed analysis can be found in [24,25].

2. The application with compensation technique can be found on the constrained trajectory control of an F-16 model [26]. In this paper, considering the saturation of elevator deflection and fuel equivalence ratio, the technique is combined with a dynamic surface control for a linearly parameterized form of the hypersonic flight dynamics with parameter projection.

VI. SIMULATIONS

The rigid body of the hypersonic flight vehicle is considered in the simulation study. The reference commands are generated by the filter:

\[ h_c = \frac{0.16^2}{(s^2 + 0.76s + 0.16)^2} \quad (60) \]

\[ V_c = \frac{0.16^2}{(s^2 + 0.76s + 0.16)^2} \quad (61) \]

The control gains for the dynamic surface controller are selected as \( k_v = 6, k_b = 0.3, k_i = 4, k_2 = 10, k_3 = 20 \), and the first-order filter parameter for dynamic surface design is \( \varepsilon_i = 0.1, i = 2, 3 \). Parameters for the projection algorithm are selected as \( \Gamma_{\mu} = 0.01I, \Gamma_{\phi} = 0.01I, i = 1, 3, v \). The filter parameters for real control inputs are selected as \( \omega_0 = 20 \text{ rad/s}, \omega_0 = 30 \text{ rad/s}, \xi = 1 \).
The initial values of the states are set as $v_0 = 7850$ ft/s, $h_0 = 86000$ ft, $\alpha_0 = 3.5$ deg, $\gamma_0 = 0$, $q_0 = 0$. The velocity tracks the step command with 400 ft/s for every 50 seconds. Meanwhile, the altitude follows the square command with period 100 s and magnitude 1000 ft.

**Example 1.** In this example, the actuator saturations of control inputs are $\Phi \in [0.05, 1.2]$ and $\delta \in [-15^\circ, 15^\circ]$.

The simulation results are presented in Figs. 2–8. The altitude and velocity follow the reference trajectories depicted in Fig. 2 and Fig. 3. During the velocity climbing, due to the saturation, the system cannot provide a large enough fuel equivalence ratio, which results in certain tracking errors. Also, it causes a small vibration of elevator deflection. When
the fuel equivalence ratio is not saturated, the system then tracks the reference command very well. For the elevator deflection, at the beginning, the value is larger than 15°, the saturation is in effect and the output of the saturation is kept under the value. As demonstrated in Figs. 6–8, the system states track the desired value within a very small neighborhood of zero.

Example 2. The limitation is released for control inputs. The system response is depicted in Fig. 9 and Fig. 10. In this example, since enough control input could be provided, the tracking error, especially for the velocity, is smaller than in Example 1. The difference between the response of control inputs is demonstrated clearly in Figs. 11–12. The estimation of $C_{11}^\delta / I_{11}$ depicted in Fig. 13 is responding to the tracking error with a parameter projection algorithm.

VII. CONCLUSIONS

The dynamics of HFV are transformed into the linearly parameterized form. The parameter estimation is conducted for the nonlinear item $f_i$ and control gain $g_i$ separately. To avoid the “explosion of complexity,” the dynamic surface control is investigated on HFV. Considering the input saturations, the compensation design of elevator deflection and fuel equivalence ratio is employed. The closed-loop system achieves uniform ultimately bounded stability. The effectiveness is verified by simulation study with parametric model uncertainty and input saturations.
VIII. APPENDIX A

Tables I–V provide the coefficients of the HFV dynamics.

Table I. Miscellaneous coefficient values.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
<th>Units</th>
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<tbody>
<tr>
<td>S</td>
<td>$1.7000 \times 10^1$</td>
<td>ft$^2$·ft$^{-1}$</td>
</tr>
<tr>
<td>$\rho_0$</td>
<td>$6.7429 \times 10^{-3}$</td>
<td>slugs·ft$^{-3}$</td>
</tr>
<tr>
<td>$h_0$</td>
<td>$8.5000 \times 10^{4}$</td>
<td>ft</td>
</tr>
<tr>
<td>$h_1$</td>
<td>$2.1358 \times 10^{4}$</td>
<td>ft</td>
</tr>
<tr>
<td>$I_{yy}$</td>
<td>$5.0000 \times 10^{4}$</td>
<td>lb·ft</td>
</tr>
<tr>
<td>$m$</td>
<td>$3.0000 \times 10^{2}$</td>
<td>lb·ft$^{-1}$</td>
</tr>
<tr>
<td>$g$</td>
<td>$3.2000 \times 10^{1}$</td>
<td>ft·s$^{-2}$</td>
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Table II. Lift coefficient values.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_L^p$</td>
<td>$4.6773 \times 10^0$</td>
<td>rad$^{-1}$</td>
</tr>
<tr>
<td>$C_L^0$</td>
<td>$-1.8714 \times 10^{-2}$</td>
<td>—</td>
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Table III. Drag coefficient values.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_D^p$</td>
<td>$5.8224 \times 10^0$</td>
<td>rad$^{-2}$</td>
</tr>
<tr>
<td>$C_D^0$</td>
<td>$-4.5315 \times 10^{-2}$</td>
<td>rad$^{-1}$</td>
</tr>
<tr>
<td>$C_D^\delta$</td>
<td>$8.1993 \times 10^{-3}$</td>
<td>rad$^{-2}$</td>
</tr>
<tr>
<td>$C_D^\gamma$</td>
<td>$2.7699 \times 10^{-4}$</td>
<td>rad$^{-1}$</td>
</tr>
<tr>
<td>$C_D^\alpha$</td>
<td>$1.0131 \times 10^{-2}$</td>
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Table IV. Moment coefficient values.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_p$</td>
<td>$8.3600 \times 10^0$</td>
<td>ft</td>
</tr>
<tr>
<td>$\tau^\alpha$</td>
<td>$1.7000 \times 10^1$</td>
<td>ft</td>
</tr>
<tr>
<td>$C_M^p$</td>
<td>$6.2926 \times 10^0$</td>
<td>rad$^{-2}$</td>
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<tr>
<td>$C_M^0$</td>
<td>$2.1335 \times 10^0$</td>
<td>rad$^{-1}$</td>
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<tr>
<td>$C_M^\delta$</td>
<td>$1.8979 \times 10^{-1}$</td>
<td>—</td>
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<tr>
<td>$C_M^\gamma$</td>
<td>$-1.2897 \times 2.5 \times 10^0$</td>
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Table V. Thrust coefficient values.

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<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
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<td>$\beta_1$</td>
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<td>lb·ft$^{-1}$·rad$^{-3}$</td>
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<tr>
<td>$\beta_2$</td>
<td>$-3.7225 \times 10^4$</td>
<td>lb·ft$^{-1}$·rad$^{-3}$</td>
</tr>
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<td>$\beta_3$</td>
<td>$2.6814 \times 10^4$</td>
<td>lb·ft$^{-1}$·rad$^{-2}$</td>
</tr>
<tr>
<td>$\beta_4$</td>
<td>$-1.7277 \times 10^4$</td>
<td>lb·ft$^{-1}$·rad$^{-2}$</td>
</tr>
<tr>
<td>$\beta_5$</td>
<td>$3.5542 \times 10^4$</td>
<td>lb·ft$^{-1}$·rad$^{-1}$</td>
</tr>
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<td>$\beta_6$</td>
<td>$-2.4216 \times 10^4$</td>
<td>lb·ft$^{-1}$·rad$^{-1}$</td>
</tr>
<tr>
<td>$\beta_7$</td>
<td>$6.3785 \times 10^1$</td>
<td>lb·ft$^{-1}$</td>
</tr>
<tr>
<td>$\beta_8$</td>
<td>$-1.0090 \times 10^2$</td>
<td>lb·ft$^{-1}$</td>
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</table>
REFERENCES


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