Nonlinear Adaptive Dynamic Inversion Applied to a Generic Hypersonic Vehicle

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Outline

Introduction

Nonlinear Adaptive Dynamic Inversion Control Architecture

Analysis of the Nonlinear Adaptive Dynamic Inversion Control Architecture During Inlet Unstarts

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- Nonlinear Adaptive Dynamic Inversion Control Architecture
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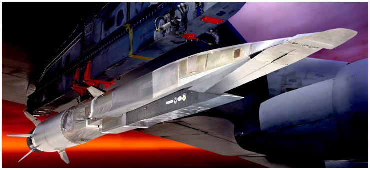
- Conclusions
- Extensions

Motivation

Control of Hypersonic Vehicles

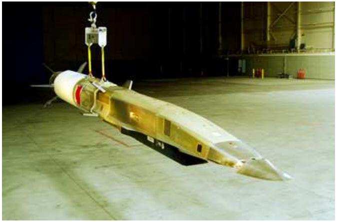
- Wide range of flight conditions
- Highly integrated elastic vehicle
- Uncertainties



Motivation

Inlet Unstart

- Safety concern in hypersonic flight
- Three main causes of inlet unstarts:
  1. A flow to the inlet that is slower than the required operating Mach number for the engine,
  2. An altered flow that no longer passes through the throat of the engine, and
  3. An increase in the back pressure in the engine that causes the shock wave to move ahead of the throat [1].
- Example - Boeing X-51A Waverider



Literature Survey

- Use of linearized models of hypersonic vehicles to design controllers:
  - Annaswamy, A. M., Jang, J., and Lavretsky, E. "Adaptive Gain-Scheduled Controller in the Presence of Actuator Anomalies." 2008. [2]
  - Gibson, T. E. and Annaswamy, A. M. "Adaptive Control of Hypersonic Vehicles in the Presence of Thrust and Actuator Uncertainties." 2008. [3]
  - Groves, K. P., et al. "Reference Command Tracking for a Linearized Model of an Air-breathing Hypersonic Vehicle." 2005. [4]
  - Bolender, M. A., Staines, J. T., and Dolvin, D. J. "HIFiRE 6: An Adaptive Flight Control Experiment." 2012. [5]

Literature Survey

- Use of nonlinear models of hypersonic vehicles to design controllers:
  - Johnson, E. N., et al. "Adaptive Guidance and Control for Autonomous Hypersonic Vehicles." 2006. [6]
  - Fiorentini, L., et al. "Nonlinear Robust Adaptive Control of Flexible Air-breathing Hypersonic Vehicles." 2009. [7]
  - Parker, J. T., et al. "Approximate Feedback Linearization of an Air-breathing Hypersonic Vehicle." 2006. [8]
  - Brocanelli, M., et al. "Robust Control for Unstart Recovery in Hypersonic Vehicles." 2012. [9]

Research Issues

- Control of hypersonic flight vehicles modeled as coupled nonlinear equations with significant parametric uncertainty in the aerodynamics
- Preventing inlet unstart due to exceeding limits on states
- Preventing inlet unstart due to control surface failures
- Maintaining reasonable tracking following an inlet unstart

Objectives

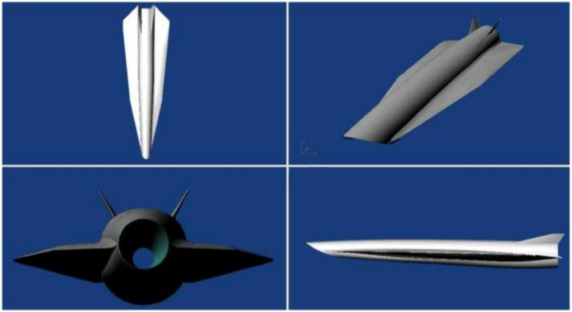
Develop a nonlinear adaptive dynamic inversion control architecture that:

1. Uses the complete coupled nonlinear dynamic equations for an inelastic, rigid body model of a hypersonic vehicle
2. Can enforce state constraints to prevent inlet unstarts that occur because of changes in angle-of-attack (α) and sideslip angle (β)
3. Is capable of preventing the loss of the vehicle following an inlet unstart
4. Is easily extensible to fault tolerant control methods

Scope

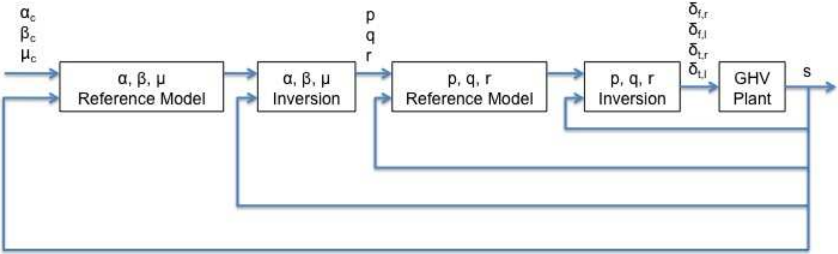
Plant: The Generic Hypersonic Vehicle (GHV)

- Academic hypersonic vehicle model created at AFRL.
- Nonlinear, 6-DOF, inelastic, no rotors, CFD aero from shock-expansion viscous corrected. [10]
- Four control surfaces - Two elevons, two ruddervators.



Outline

Nonlinear Adaptive Dynamic Inversion Control Architecture for the GHV



Case 1: Equal Number of Controls and Controlled Variables

Given a general nonlinear equation of a system in the form

$$\dot{x} = f(x) + g(x)u \tag{1}$$

the dynamic equations for α, β, and μ can be written in the same form as Equation (1) as

$$\begin{bmatrix} \dot{\beta} \\ \dot{\alpha} \\ \dot{\mu} \end{bmatrix} = \begin{bmatrix} \frac{1}{mV_T}\Big((Y_s + F_{T_y})C_\beta + mgS_\mu C_\gamma - F_{T_x}C_\alpha S_\beta - F_{T_z}S_\alpha S_\beta\Big) \\ \frac{1}{mV_T C_\beta}\left(-L_s + mgC_\mu C_\gamma - F_{T_x}S_\alpha + F_{T_z}C_\alpha\right) \\ \frac{1}{mV_T}\Big(L_s(T_\beta + T_\gamma S_\mu) + (Y_s + F_{T_y})T_\gamma C_\mu C_\beta - mgC_\gamma C_\mu T_\beta \\ \quad + (F_{T_x}S_\alpha - F_{T_z}C_\alpha)(T_\gamma S_\mu + T_\beta) - (F_{T_x}C_\alpha + F_{T_z}S_\alpha)T_\gamma C_\mu S_\beta\Big) \end{bmatrix}$$
$$+ \begin{bmatrix} S_\alpha & 0 & -C_\alpha \\ -T_\beta C_\alpha & 1 & -T_\beta S_\alpha \\ C_\alpha/C_\beta & 0 & S_\alpha/C_\beta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}.$$

Case 1: Equal Number of Controls and Controlled Variables

Suppose that a desired reference model for the system is chosen to be

$$\dot{x}_m = Ax_m + Br. \tag{2}$$

The equation for the error between the reference model and the actual system is

$$e = x_m - x. \tag{3}$$

Case 1: Equal Number of Controls and Controlled Variables

Taking the time derivative of Equation (3) results in

$$\dot{e} = \dot{x}_m - \dot{x} = \dot{x}_m - f(x) - g(x)u. \tag{4}$$

The control u is chosen to be

$$u = [g(x)]^{-1}[\dot{x}_m - \hat{f}(x) + Ke - \nu]. \tag{5}$$

Substituting Equation (5) into Equation (4) and defining $\Delta = \hat{f}(x) - f(x)$ produces the error dynamics

$$\dot{e} = -Ke + \Delta + \nu. \tag{6}$$

Case 1: Equal Number of Controls and Controlled Variables

Assume that Δ can be represented in the form $\Delta = W^T \beta(x; d)$, where d is a vector of bounded continuous exogenous inputs. Choose ν to be $\nu = -\widehat{W}^T \beta(x; d)$. Then, Equation (6) can be written as

$$\dot{e} = -Ke - \widetilde{W}^T \beta(x; d) \quad (7)$$

where $\widetilde{W} = \widehat{W} - W$, which is the weight estimation error.

Finally, the adaptive law to ensure Lyapunov stability is defined as

$$\dot{\widehat{W}} = \Gamma_W \operatorname{Proj}(\widehat{W}, \beta(x; d) e^T) \quad (8)$$

where Proj represents the projection operator [11], which is used to maintain specified bounds on the weights

Case 2: Number of Controls > Number of Controlled Variables

Given a general nonlinear equation of a system in the form

$$\dot{x} = f(x) + g(x)\Lambda u \tag{9}$$

the dynamic equations for p, q, and r can be written in the same form as

$$\underline{\dot{\omega}} = \underbrace{I^{-1}(\underline{\omega} \times I\underline{\omega}) + I^{-1}(\underline{M}_T + \underline{M}_A(\delta = 0))}_{f(x)} + \underbrace{I^{-1}M_\delta\underline{\delta}}_{g(x)\Lambda u}$$

Case 2: Number of Controls > Number of Controlled Variables

$$\underline{\dot{\omega}} = \underbrace{I^{-1}(\underline{\omega} \times I\underline{\omega}) + I^{-1}(\underline{M}_T + \underline{M}_A(\delta = 0))}_{f(x)} + \underbrace{I^{-1}M_\delta\underline{\delta}}_{g(x)\Lambda u}$$

where

$$(\underline{\omega} \times I\underline{\omega}) = -\begin{bmatrix} -J_{xz}pq + (J_z - J_y)qr \\ (J_x - J_z)pr + J_{xz}(p^2 - r^2) \\ J_{xz}qr + (J_y - J_x)pq \end{bmatrix}$$

$$\underline{M}_A(\delta = 0) = \begin{bmatrix} \bar{q}Sb\left(C_{\ell,baseline} + \frac{b}{2V_T}(C_{\ell_p}p)\right) \\ \bar{q}S\bar{c}\left(C_{m,baseline} + \dfrac{\bar{c}}{2V_T}(C_{m_q}q + C_{m_{\dot{\alpha}}}\dot{\alpha}) + 2C_{m_{\delta_{f,r}}}(\delta_{f,r} = 0) + 2C_{m_{\delta_{t,r}}}(\delta_{t,r} = 0)\right) \\ -2C_{N_{\delta_{f,r}}}(\delta_{f,r} = 0)\bar{q}Sx_{cg} - 2C_{N_{\delta_{t,r}}}(\delta_{t,r} = 0)\bar{q}Sx_{cg} \\ \bar{q}Sb\left(C_{r,baseline} + \frac{b}{2V_T}(C_{n_r}r)\right) - 2C_{Y_{\delta_{f,r}}}(\delta_{f,r} = 0)\bar{q}Sx_{cg} - 2C_{Y_{\delta_{t,r}}}(\delta_{t,r} = 0)\bar{q}Sx_{cg} \end{bmatrix}$$

$$M_\delta = \begin{bmatrix} b\frac{\partial C_\ell}{\partial \delta_{f,r}} & b\frac{\partial C_\ell}{\partial \delta_{f,l}} & b\frac{\partial C_\ell}{\partial \delta_{t,r}} & b\frac{\partial C_\ell}{\partial \delta_{t,l}} \\ \left(\bar{c}\frac{\partial C_m}{\partial \delta_{f,r}} - x_{cg}\frac{\partial C_N}{\partial \delta_{f,r}}\right) & \left(\bar{c}\frac{\partial C_m}{\partial \delta_{f,l}} - x_{cg}\frac{\partial C_N}{\partial \delta_{f,l}}\right) & \left(\bar{c}\frac{\partial C_m}{\partial \delta_{t,r}} - x_{cg}\frac{\partial C_N}{\partial \delta_{t,r}}\right) & \left(\bar{c}\frac{\partial C_m}{\partial \delta_{t,l}} - x_{cg}\frac{\partial C_N}{\partial \delta_{t,l}}\right) \\ \left(b\frac{\partial C_n}{\partial \delta_{f,r}} - x_{cg}\frac{\partial C_Y}{\partial \delta_{f,r}}\right) & \left(b\frac{\partial C_n}{\partial \delta_{f,l}} - x_{cg}\frac{\partial C_Y}{\partial \delta_{f,l}}\right) & \left(b\frac{\partial C_n}{\partial \delta_{t,r}} - x_{cg}\frac{\partial C_Y}{\partial \delta_{t,r}}\right) & \left(b\frac{\partial C_n}{\partial \delta_{t,l}} - x_{cg}\frac{\partial C_Y}{\partial \delta_{t,l}}\right) \end{bmatrix}$$

Case 2: Number of Controls > Number of Controlled Variables

Suppose that the desired dynamics of the closed loop system are given by

$$\dot{x}_m = Ax_m + Br. \tag{10}$$

The equation for the error between the reference model and the actual system is

$$e = x_m - x. \tag{11}$$

Case 2: Number of Controls > Number of Controlled Variables

Taking the time derivative of Equation (11) results in

$$\dot{e} = \dot{x}_m - \dot{x} = \dot{x}_m - f(x) - g(x)\Lambda u. \tag{12}$$

The desired final form for $\dot{e}$ is

$$\dot{e} = -Ke - \widetilde{W}^T \beta(x; d) + g(x)\widetilde{\Lambda} u \tag{13}$$

which is the same as the final form for $\dot{e}$ in Case 1, except for the final term $g(x)\widetilde{\Lambda}u$.

Case 2: Number of Controls > Number of Controlled Variables

In order to express $\dot{e}$ in the final desired form of Equation (13), the term $g(x)\widehat{\Lambda}u$ is added and subtracted from Equation (12) to produce

$$\dot{e} = \dot{x}_m - f(x) - g(x)\widehat{\Lambda}u + g(x)\widetilde{\Lambda}u. \tag{14}$$

Case 2: Number of Controls > Number of Controlled Variables

In order to determine a specific control law for the system, a constrained optimization problem is solved in which the cost function

$$J = u^T Q u \tag{15}$$

where $Q = Q^T > 0$, will be minimized, subject to the constraint $g(x)\widehat{\Lambda}u = \ell$, which must be satisfied at all times. The term ℓ is based on the control from Case 1 and is expressed as

$$\ell = \dot{x}_m - \hat{f}(x) + Ke - \nu. \tag{16}$$

Case 2: Number of Controls > Number of Controlled Variables

To derive the control law, first the constraint must be included in the cost function to form the augmented cost function

$$\bar{J} = u^T Q u + \lambda^T (g(x)\widehat{\Lambda} u - \ell) \tag{17}$$

where $\lambda \in \mathbb{R}^n$ is a Lagrange multiplier. The first order necessary conditions for minimizing $\bar{J}$ are given by

$$\frac{\partial \bar{J}}{\partial \lambda} = g(x)\widehat{\Lambda} u - \ell = 0 \tag{18}$$

$$\frac{\partial \bar{J}}{\partial u} = 2Qu + \widehat{\Lambda}^T g^T(x)\lambda = 0. \tag{19}$$

Case 2: Number of Controls > Number of Controlled Variables

From the first order necessary conditions, the control law is determined to be

$$u = Q^{-1}\widehat{\Lambda}^T g^T(x)(g(x)\widehat{\Lambda}Q^{-1}\widehat{\Lambda}^T g^T(x))^{-1}\ell. \tag{20}$$

where

$$\ell = \dot{x}_m - \hat{f}(x) + Ke - \nu \tag{21}$$

Note that for the case where n = m, Equation (20) simplifies to the control law in Case 1, which is

$$u = [g(x)]^{-1}[\dot{x}_m - \hat{f}(x) + Ke - \nu]. \tag{22}$$

Case 2: Number of Controls > Number of Controlled Variables

Continuing with the derivation of $\dot{e}$, let $\Delta = \hat{f}(x) - f(x)$. Substituting Equation (20) and Equation (16) into Equation (14) produces the equation

$$\dot{e} = -Ke + \Delta + \nu + g(x)\widetilde{\Lambda}u. \tag{23}$$

Again, assume that Δ can be represented in the form $\Delta = W^T\beta(x;d)$, and choose ν to be $\nu = -\widehat{W}^T\beta(x;d)$, where d is a vector of bounded continuous exogenous inputs. Then, Equation (23) can be written as

$$\dot{e} = -Ke - \widetilde{W}^T\beta(x;d) + g(x)\widetilde{\Lambda}u \tag{24}$$

where $\widetilde{W} = \widehat{W} - W$, which is the weight estimation error.

Case 2: Number of Controls > Number of Controlled Variables

Finally, the adaptive laws to ensure Lyapunov stability are defined as

$$\dot{\widehat{W}} = \Gamma_W \, \mathrm{Proj}(\widehat{W}, \beta(x; d) e^T) \tag{25}$$

$$\dot{\widehat{\Lambda}} = \Gamma_\Lambda \, \mathrm{Proj}(\widehat{\Lambda}, -u e^T g(x)) \tag{26}$$

where Proj represents the projection operator, which is used to maintain specified bounds on $\widehat{W}$ and $\widehat{\Lambda}$.

Simulation Results

Objective: Evaluate tracking of a specified reference trajectory, 6/80K.

Commands to α, β, and μ are given as ramp signals from 0 degrees to a desired angle in a fixed amount of time.

Current simulation includes:

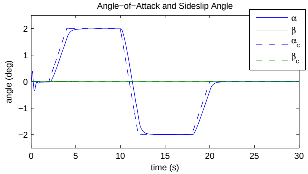
- Velocity PID Controller
- Second-order actuator dynamics with $\zeta = 0.7$ and $\omega_n = 25$ Hz
- Time delay of 0.03 s (Note: time delays of 0.04 s can be tolerated as well)

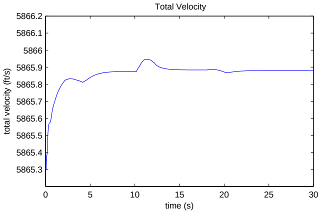
α, β, μ inversion controller: $\beta(x;d) = \begin{bmatrix} c & \alpha & \beta & \mu & M \end{bmatrix}^T$, where c is a constant bias term.

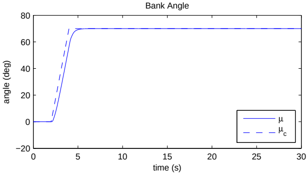
P, Q, R inversion controller: $\beta(x;d) = \begin{bmatrix} c & p & q & r & \alpha & \beta & M \end{bmatrix}^T$, where c is a constant bias term.

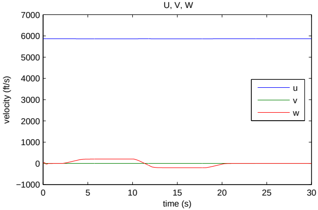
Simulation Results

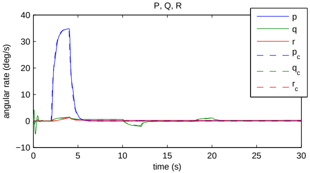
For $\alpha = \pm 2$ deg, $\beta = 0$ deg, and $\mu = 70$ deg,





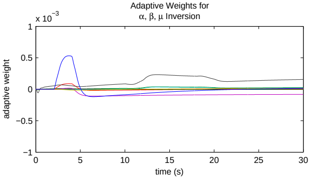


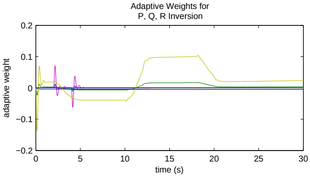


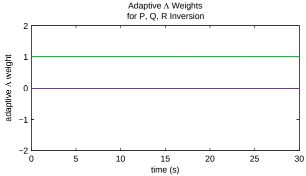


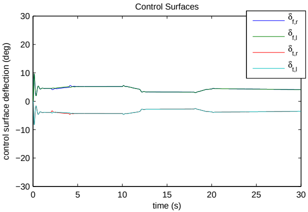
Simulation Results

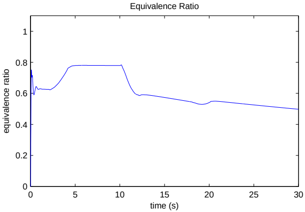
For $\alpha = \pm 2$ deg, $\beta = 0$ deg, and $\mu = 70$ deg,











Robustness Analysis

Uncertainties in the plant examined in the analysis include the additive uncertainties ΔC_{m_α}, ΔC_{n_β}, and ΔC_m and multiplicative gains D on the control surface deflections, given in terms of equations as

$$C_m = C_{m_{baseline}} + \Delta C_{m_\alpha}\alpha \tag{27}$$

$$C_n = C_{n_{baseline}} + \Delta C_{n_\beta}\beta \tag{28}$$

$$C_m = C_{m_{baseline}} + \Delta C_m \tag{29}$$

$$C_\delta = DC_{\delta_o}. \tag{30}$$

Robustness Analysis

Table 1: Additive uncertainty ΔC_{m_α} over a 30 s period with 0.03 s time delay.

α (deg)	β (deg)	μ (deg)	max ΔC_{m_α} (deg^{-1})	min ΔC_{m_α} (deg^{-1})
5	0	0	0.0005	-0.0013
5	1	20	0.0003	-0.0011

Table 2: Additive uncertainty ΔC_{n_β} over a 30 s period with 0.03 s time delay.

α (deg)	β (deg)	μ (deg)	max ΔC_{n_β} (deg^{-1})	min ΔC_{n_β} (deg^{-1})
0	1	0	0.007	-0.003
5	0	20	0.01	-0.004
5	1	20	0.006	-0.003

Robustness Analysis

Table 3: Additive uncertainty ΔC_m over a 30 s period with 0.03 s time delay.

α (deg)	β (deg)	μ (deg)	max ΔC_m	min ΔC_m
5	0	0	0.0005	-0.003
5	1	20	0.0005	-0.002

Robustness Analysis

Table 4: Multiplicative gains D on control surface deflection terms over a 30 s period with 0.03 s time delay.

α (deg)	β (deg)	μ (deg)	$D_{\delta_{f,r}}$	$D_{\delta_{f,l}}$	$D_{\delta_{t,r}}$	$D_{\delta_{t,l}}$
5	0	0	1	0.14	1	1
5	0	0	1	1	1	0.01
5	0	0	0.15	0.15	1	1
5	0	0	1	1	0.15	0.15
5	0	20	1	0.31	1	1
5	0	20	1	1	1	0.01
5	0	20	0.21	0.21	1	1
5	0	20	1	1	0.30	0.30
5	1	20	1	0.42	1	1
5	1	20	1	1	1	0.05
5	1	20	0.38	0.38	1	1
5	1	20	1	1	0.38	0.38

Outline

Modeling an Inlet Unstart

For this simplified model, an inlet unstart is triggered at a specified time, and the following changes occur in the GHV plant:

- Instantaneous loss of thrust,
- Slight increase in the coefficient of the axial force (C_A),
- Slight decrease in the coefficient of the normal force (C_N), and
- Inclusion of additive variations in C_{m_α} and C_{n_β} through the equations

$$C_m = C_{m_{baseline}} + \Delta C_{m_\alpha}\alpha \tag{31}$$

$$C_n = C_{n_{baseline}} + \Delta C_{n_\beta}\beta. \tag{32}$$

Flight Path Angle Reference Trajectory Generation

To allow the GHV simulation to track a flight path angle trajectory generated using a nonzero setpoint (NZSP) controller, a method from Reference [12] was applied in which the equation for $\ddot{h}$, where h represents the altitude of the aircraft, is written in the form

$$\ddot{h} = \left[b_0\dot{V} + b_1\dot{\beta} + b_2\dot{\alpha}\right] + \begin{bmatrix} a_0 & a_1 & a_2 \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{33}$$

where

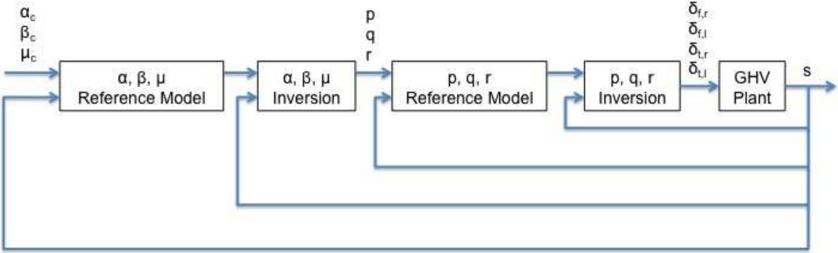
$$\begin{aligned} a_0 &= b_4 \\ a_1 &= b_3 C_\phi + b_4 S_\phi T_\theta \\ a_2 &= b_4 C_\phi T_\theta - b_3 S_\phi \end{aligned}$$

and

$$\begin{aligned} b_0 &= C_\beta C_\alpha S_\theta - S_\beta S_\phi C_\theta - C_\beta S_\alpha C_\phi C_\theta \\ b_1 &= V\left(-S_\beta C_\alpha S_\theta - C_\beta S_\phi C_\theta + S_\beta S_\alpha C_\phi C_\theta\right) \\ b_2 &= V\left(-C_\beta S_\alpha S_\theta - C_\beta C_\alpha C_\phi C_\theta\right) \\ b_3 &= V\left(C_\beta C_\alpha C_\theta + S_\beta S_\phi S_\theta + C_\beta S_\alpha C_\phi S_\theta\right) \\ b_4 &= V\left(-S_\beta C_\phi C_\theta + C_\beta S_\alpha S_\phi C_\theta\right). \end{aligned}$$

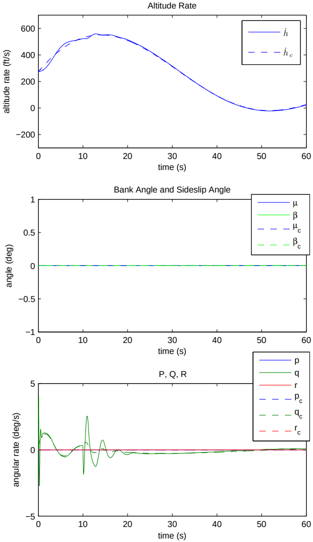
Flight Path Angle Reference Trajectory Generation

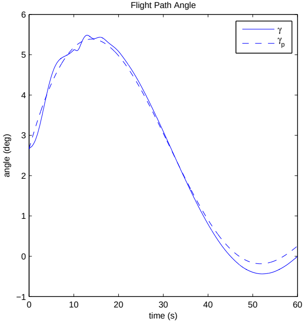
The original reference trajectory that is generated for γ using the NZSP controller can be converted to $\dot{h}$ using the relation from aircraft kinematics that $\dot{h} = VS_\gamma$. The $\dot{h}$, β, μ inversion controller replaces the original α, β, μ inversion controller in the GHV simulation, and now desired trajectories for γ can be tracked.



Simulation Results

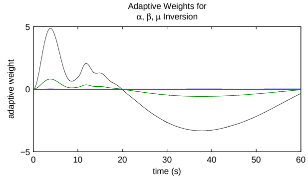
Track flight path angle trajectory during inlet unstart at 10 seconds, 6/80K.

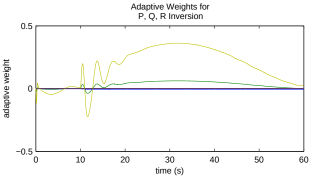


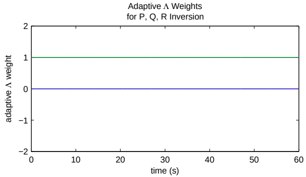


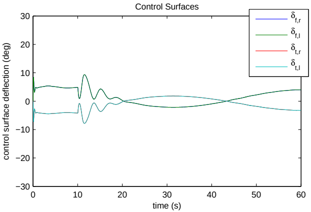
Simulation Results

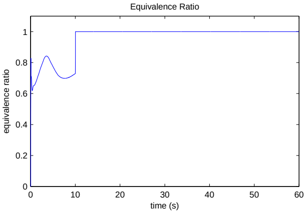
For the generated flight path angle trajectory during an inlet unstart at 10 seconds











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Outline

Conclusions

- The approach of nonlinear adaptive dynamic inversion control works well as a candidate control architecture for hypersonic vehicles because
  - the control architecture is able to maintain tracking performance without excessive control effort while being robust to
    - decreases in control surface effectiveness,
    - changes in system parameters, and
    - time delays of 0.04 seconds or less, and
  - the control architecture can tolerate an inlet unstart and maintain nominal tracking of a specified flight path angle trajectory.

Conclusions

- The nonlinear adaptive dynamic inversion control architecture can maintain reference trajectory tracking with only a slight degradation in tracking performance following an inlet unstart.
  - Through a robustness analysis on the GHV, it was determined that the maximum additive variations in C_{m_α} and C_{n_β} that the control architecture could tolerate were $\Delta C_{m_\alpha} = 0.001$ deg^{-1} and $\Delta C_{n_\beta} = -0.001$ deg^{-1}.

Outline

Extensions

- Enforcing state constraints with a projection operator, and including the projection operator in the control laws.
- Combine controllers that can enforce state constraints with fault-tolerant controllers.
- Development of control logic associated with the inlet unstart envelope for a hypersonic vehicle to determine the appropriate course of action to ensure its preservation.
- Development and testing of controllers using an elastic model of a hypersonic vehicle.

Questions?

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