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Robust Nonlinear Adaptive Control For Longitudinal Dynamics of Hypersonic Aircraft Vehicle

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ABSTRACT

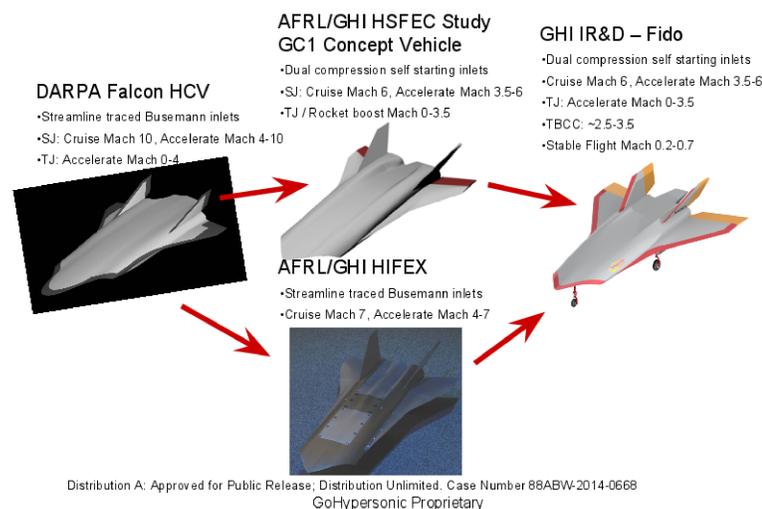
A hypersonic aircraft vehicle is a highly complex nonlinear system, which includes uncertainties in the dynamics. This paper presents the design of robust nonlinear adaptive control for a hypersonic aircraft vehicle. The complexity of the dynamic system is considered into the design structure of the control in order to address robustness issues. Design of a robust control system should decouple the longitudinal and lateral dynamics to handle the flight of hypersonic vehicle under certain specific conditions.

INTRODUCTION

- Studies of hypersonic aircraft vehicles have been made to be a consistent technologies for access to space.
- NASA and the U.S. Air Force in past years have conducted simulation studies, whereas success of experimental vehicles remains limited.
- We present here design of a control system for hypersonic vehicles in low speed and altitude (subsonic speed conditions, $V_p < 480$ m/s, and $h < 4000$ m), where the Mach number is less than 1.2.
- The control objectives are achieving robust tracking of the outputs $y_{LD} = [V_p, \gamma]^T$, by using $u_{LD} = [T, \delta_E]^T$ as the control inputs.
- The longitudinal aircraft dynamics are given by

$$\begin{aligned} \dot{V}_p &= \frac{1}{m}(T \cos \alpha - D) - g \sin \gamma, \quad \dot{\gamma} = q - \dot{\alpha} \\ \dot{\alpha} &= \frac{-1}{mV_p}(T \sin \alpha + L_i) + \frac{g}{V_p} \cos \gamma + q, \quad \dot{q} = \frac{1}{I_y}M, \end{aligned} \quad (1)$$

- where $V_p, T, \alpha, q, h, \delta_E, D, L_i$, and M denote forward speed, thrust, longitudinal angle of attack, pitch angular rate, altitude, elevator deflection angle, drag, lift, and aerodynamic pitching moment, respectively.



CONTROL OF SPEED SUBSYSTEM

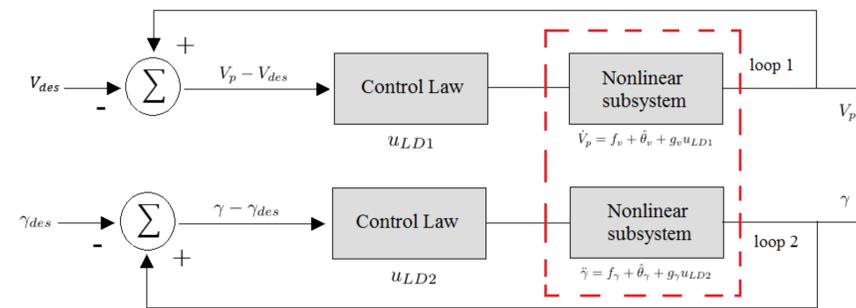


Figure 1: Block diagram of two SISO adaptive control.

- Based on longitudinal dynamic equations (1), the vehicle speed is presented as the output of V_p subsystem.
- Because the drag D contains uncertain parameters, a function approximator can be used instead, so that

$$\dot{V}_p = \frac{T}{m} \cos \alpha - \frac{\bar{q}S}{m} \Theta_A^{*\top} \xi_A - w_A(z) - g \sin \gamma, \quad (2)$$

- The adaptive control law T is defined by

$$T = \frac{1}{g_A(z)} (g \sin \gamma + \frac{\bar{q}S}{m} \hat{\Theta}_A^\top \xi_A + v_A + u_{sA}), \quad (3)$$

where

$$\hat{\Theta}_A = [\hat{\theta}_{A,C_{D0}}, \hat{\theta}_{A,\alpha}, \hat{\theta}_{A,\alpha^2}, \hat{\theta}_{A,\delta_E}, \hat{\theta}_{A,q}]^\top, \quad g_A(z) = \frac{\cos \alpha}{m}, \quad v_A = -k_A \tilde{e}_A + \dot{V}_{des}.$$

CONTROL OF FLIGHT-PATH ANGLE SUBSYSTEM

- For control of flight-path angle, the second derivative is required to achieve asymptotic stability,

$$\begin{aligned} \ddot{\gamma} &= \frac{\dot{T}}{mV_p} \sin \alpha - \frac{T}{mV_p^2} \dot{V}_p \sin \alpha + \frac{T}{mV_p} \dot{\alpha} \cos \alpha + \frac{\rho S}{2m} \dot{V}_p \Theta_B^{*\top} \xi_B + w_B(z) \\ &\quad + \frac{\rho S}{2m} V_p \Theta_c^{*\top} \xi_c + w_c(z) + \frac{g}{V_p^2} \dot{V}_p \cos \gamma + \frac{g}{V_p} \dot{\gamma} \sin \gamma, \end{aligned} \quad (4)$$

- We redefine the control law to be V_δ with the choice below

$$\begin{aligned} V_\delta &= \frac{1}{\hat{g}_c(z)} \left(\frac{-\dot{T}}{mV_p} \sin \alpha + \frac{T}{mV_p^2} \dot{V}_p \sin \alpha - \frac{T}{mV_p} \dot{\alpha} \cos \alpha - \frac{\rho S}{2m} \dot{V}_p \Theta_B^\top \xi_B \right. \\ &\quad \left. - \frac{\rho S}{2m} V_p \Theta_c^\top \xi_c - \frac{g}{V_p^2} \dot{V}_p \cos \gamma - \frac{g}{V_p} \dot{\gamma} \sin \gamma + v_c + u_{sc} \right), \end{aligned} \quad (5)$$

$$\hat{\Theta}_B = [\hat{\theta}_{B,C_{L0}}, \hat{\theta}_{B,\alpha}, \hat{\theta}_{B,\delta_E}, \hat{\theta}_{B,q}]^\top, \quad \hat{\Theta}_c = [\hat{\theta}_{c,\alpha}, \hat{\theta}_{c,\Gamma}, \hat{\theta}_{c,\dot{q}}]^\top,$$

$$\hat{g}_c(z) = \frac{\rho S}{2m} V_p \Gamma_2 \hat{\theta}_{V_\delta}, \quad v_c = -\chi_c - k_c \tilde{e}_c.$$

NUMERICAL SIMULATIONS

- The adaptive control design has been tested using MATLAB for the simulation model.

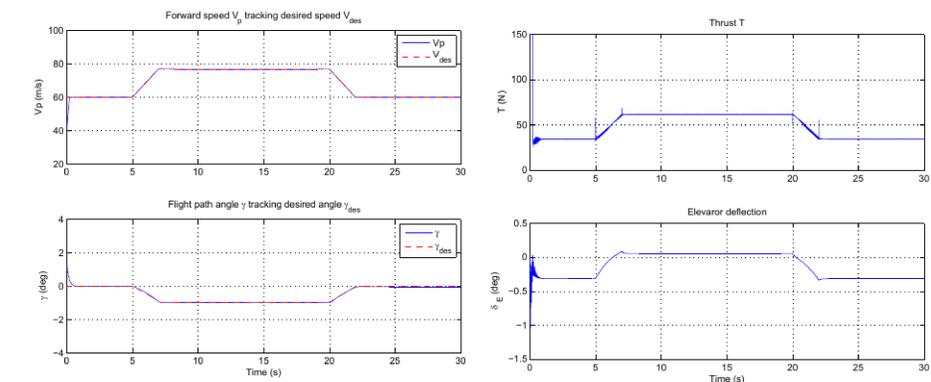


Figure 2: V_p and γ tracking performance, and control inputs T, δ_E .

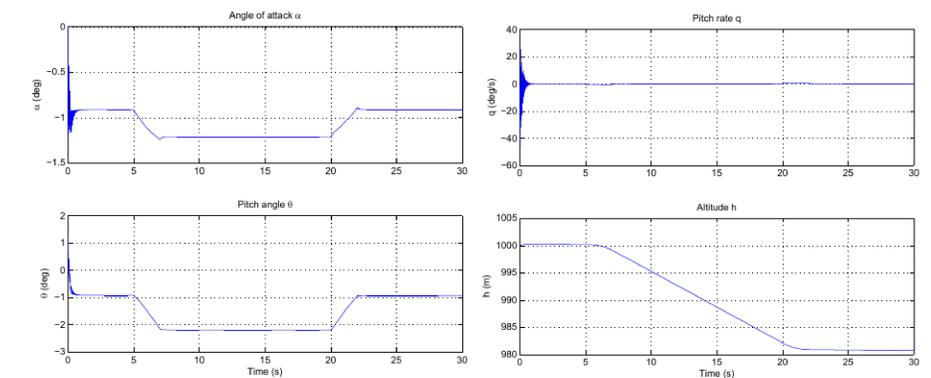


Figure 3: α, θ, q , and h behaviors.

CONCLUSION

- Adaptive control design achieves the stability conditions of control inputs with different combinations of forward speed and flight-path angle.
- The simulations and validations for adaptive control indicate that these perform well for flight control.
- Additionally, the longitudinal dynamics showed the control inputs behavior, and correct tracking conditions for V_p and γ were confirmed.
- The adaptive control is a robust because the tracking of the outputs require less than 2 s.
- The control inputs also reach the stability condition in short time, without significant oscillation.