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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, $V_p < 480 \text{ m/s}$, and $h < 4000 \text{ m}$), where the Mach number is less than 1.2.
- The control objectives are achieving robust tacking of the outputs $y_{LD} = [V_p \; \gamma]^\top$, by using $u_{LD} = [T, \delta]^\top$ as the control inputs.
- The longitudinal aircraft dynamics are given by
  \[ V_p = \frac{1}{m} \left( T \cos \alpha - D - g \sin \gamma \right), \quad \gamma = \dot{\alpha} - \alpha 
  \]
  \[ \alpha = \frac{1}{m} \left( T \sin \alpha + L \right) + \frac{8}{V_p} \cos \psi + q, \quad \dot{q} = \frac{1}{m} \Gamma, \]
  where $V_p, T, \alpha, q, h, \delta, D, L, \psi$ 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
The adaptive control design has been tested using MATLAB for the simulation model.
- 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
  \[ V_p = \frac{1}{m} \left( T \cos \alpha - \frac{\partial D}{\partial \alpha} \xi_A - w_A(z) - g \sin \gamma \right), \]
  \[ T = \frac{1}{\partial \alpha} \left( g \sin \gamma + \frac{\partial S}{\partial \alpha} \xi_A \dot{\alpha} + v_A + u_A \right), \]
  where $\theta_A = [\theta_A_{\text{cor}}, \theta_A_{\text{rad}}, \theta_A_{\text{ang}}, \theta_A_{\text{ext}}]^\top$, $g_A(z) = \frac{\cos \alpha}{m} v_A = -k_A \xi_A + V_{\text{des}}$.

CONTROL OF FLIGHT-PATH ANGLE SUBSYSTEM
- For control of flight-path angle, the second derivative is required to achieve asymptotic stability.
  \[ \gamma = \frac{T}{m V_p} \cos \alpha + \frac{T}{m V_p} \dot{V}_p \sin \alpha + \frac{T}{m V_p} \cos \alpha + \frac{\rho \xi_B}{2m} V_p \theta_B \xi_B - w_B(z) \]
  \[ + \frac{\rho \xi_B}{2m} V_p \theta_B \xi_B + v_A + u_A \]
  \[ \dot{\xi}_B = [\dot{\theta}_B_{\text{cor}}, \dot{\theta}_B_{\text{rad}}, \dot{\theta}_B_{\text{ang}}, \dot{\theta}_B_{\text{ext}}]^\top, \quad \dot{\xi}_B = [\dot{\theta}_B_{\text{cor}}, \dot{\theta}_B_{\text{rad}}, \dot{\theta}_B_{\text{ang}}, \dot{\theta}_B_{\text{ext}}]^\top, \]
  \[ \xi_B(z) = \frac{\rho \xi_B}{2m} V_p \xi_B + v_A + u_A \]

Conclusions
- 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 $\gamma$ 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.

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