Lyapunov Based Stable and Robust Adaptive Control Design for a Class of Space Transportation Systems

A thesis submitted
in partial fulfillment for the award of the degree of

Doctor of Philosophy

by

Asha P Nair

Department of Avionics
INDIAN INSTITUTE OF SPACE SCIENCE AND TECHNOLOGY
Thiruvananthapuram, India

January 2023

ABSTRACT

A Satellite Launch Vehicle (SLV) is a dynamic system with time-varying characteristics whose model consists of highly uncertain and nonlinear parameters. During the ascent phase, the SLV experiences continuous variations in atmospheric density, Mach number and aerodynamic forces and moments. The presence of lightly damped structural and slosh modes whose frequency is closer to the control frequency, further complicates the attitude control problem. Current practice in the flight control design is to linearise the plant dynamics about various points of a nominal trajectory designed to satisfy the mission requirements. For this purpose, the plant is assumed to be frozen between the operating points. The classical gain scheduled control design works perfectly for the existing Space Transportation Systems (STS). However, these controllers cannot be applied to modern STS where the systems are highly non-linear and coupled. The flight control system for such systems has to work for a wide spectrum of flight conditions.

This thesis proposes the use of adaptive controllers for the flight control of various STS, such as structurally optimized slender launch vehicles and winged re-entry vehicles. These controllers replace the existing gain-scheduled controllers and maintain the performance of the closed-loop system in the event of failure of sub-systems and also in the presence of parametric and non-parametric uncertainties.

The initial phase of the research work focuses on dynamic modelling and ascent flight control of a highly unstable and flexible launch vehicle. Stabilising adaptive PD/PID controllers are developed in MRAC framework using standard quadratic Lyapunov function to control the time-varying rigid body dynamics during the atmospheric phase of flight. Further, Lyapunov stability and Barbalat's Lemma are applied to prove the stability of the time-varying system. These controllers are robust to parametric uncertainties and all the signals are uniformly ultimately bounded. To reduce the effect of sensor noise, a continuous form of dead zone is applied on the tracking error. The lack of robustness of these control algorithms for unstructured uncertainty is shown analytically and through simulations. A stable adaptive control design that completely avoids actuator position and slew rate saturation is proposed using the standard quadratic Lyapunov function. Here both the control and reference inputs are adaptively adjusted.

Two adaptive control laws are proposed to improve the robustness of the adaptive controllers to non-parametric uncertainties. These controllers are developed in MRAC framework using Lyapunov functions. Time-varying reference models are used, which capture the desired behaviour of the closed-loop plant at various operating points along the nominal trajectory. Classical stability margin requirements are to be met for flight control certification. Hence, reference models are selected to satisfy these requirements. A continuous projection operator constrains the adapted parameters within the user-defined bounds in the first algorithm, which helps maintain the stability of the time-varying plant and avoids actuator saturation. The robustness of this algorithm to structured and unstructured uncertainty is proved analytically. The second algorithm uses a Barrier Lyapunov Function to constrain the trajectory tracking error and the adapted parameters within the user-defined constraint compact sets. These two algorithms require full state feedback. An extended Kalman filter is designed to estimate the plant's states from the available noisy measurements. Proposed adaptive controllers are used in the ascent phase of a highly flexible, unstable launch vehicle, and the results are compared with the existing gain scheduled controller.

In the second phase of the research work, projection and barrier Lyapunov based adaptive controllers are proposed for the descent phase flight control of a winged re-entry vehicle. A rectangular projection operator is used in the adaptive control design to simultaneously constrain the adapted gains within a maximum and minimum limit. Extensive simulation studies are conducted with non-linear actuator models, wind and extreme parametric perturbations to demonstrate the robustness of the proposed algorithms.