Adaptive Integrated Guidance and Control for Air-breathing Phase of Reusable Launch Vehicle

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

Doctor of Philosophy

by

Rani Radhakrishnan

Department of Avionics
Indian Institute of Space Science and Technology
Thiruvananthapuram, India

February 2025

Abstract

Air-breathing satellite launch vehicles are winged vehicles containing all features and challenges of reusable launch vehicle with additional complexity of air-breathing propulsion. Air-Breathing Satellite Launch Vehicle (ABSLV) uses scramjet propulsion during the ascent phase which makes the system complex due to severe interaction between propulsion, aerodynamics and structural subsystems. Guidance and control design for an air-breathing launch vehicle is highly challenging due to the small frequency of separation between the two and high control structure interaction due to slender geometry of the vehicle. In conventional launch vehicle open loop guidance scheme is preferred in the atmospheric phase. But for air-breathing vehicle as the trajectory is sensitive to propulsion and aerodynamic forces, a closed loop guidance scheme is essential in this phase.

The thesis deals with the design of 6D trajectory, guidance and controller for the air-breathing phase of ABSLV. The 6D trajectory development for a hyper-sonic air-breathing vehicle involves the development of models for aerodynamics, propulsion, vehicle dynamics, earth model, guidance and control covering the ascent phase of the flight regime. The vehicle propulsion model is based on the scramjet engine. Ascent phase guidance problem is formulated as an optimal control problem to find the control input u, which drives the vehicle to follow the trajectory where the performance index will be minimized. The performance index selected is to optimize the fuel taking velocity, altitude and mass as the states with angle of attack as the control input. The control philosophy is to simultaneously control the states to follow the reference trajectory without defining any authority to particular state. Thus, an integrated multi input multi output control law is developed with input/output decoupling using state feedback and then classical controllers are designed in each channel to ensure stability and robustness. All the control surfaces work together to handle the aero-propulsive couplings and parameter uncertainties. Integrated guidance and controller for the air-breathing phase handles the coupling between longitudinal and lateral dynamics as well as translational and rotational dynamics and provides robustness to 40% of parametric perturbations.

In general, the integrated guidance and controller for ABSLV is subjected to sudden changes in the parameters due to the dynamic flight envelope, the vehicle has to cater. Hence uncertainties associated with parameters and the possible presence of unmodelled dynamics during scramjet operation are state and time dependent. To address this problem, an adaptive control and guidance law augmentation is developed for the integrated guidance and controller in the air-breathing phase. Due to this unmodelled dynamics and plant uncertainties, there is fast variation in the ideal weights as system undergo sudden changes in dynamics. Thus the new adaptive control law using derivative free update algorithm can improve the robustness by tuning the adaption gain instead of compromising for the closed loop performance as in the case of derivative or projection based update laws. Similarly a novel predictor-corrector guidance method based on all-coefficient adaptive control theory is developed to take care of control surface failure condition or for degraded propulsion performance. This is achieved by re-commanding the angle of attack to achieve the predicted final states following a sub optimal trajectory to save the mission in case of degraded performance.

Finally, the usefulness and performance of the integrated controller augmented with adaptive control and guidance algorithm has been successfully demonstrated and established through 6D and Monte-Carlo (MC) simulations.