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Switching robust control for a nanosatellite launch vehicle

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A B S T R A C T

The attitude control of a launch vehicle is a challenging task due to the dramatically varying vehicle dynamics along a flight path. The objective of this paper is to design a switching robust control strategy for launch vehicles, applied here to a notional nanosat launch vehicle. In order to control the rocket along a trajectory ascending through the Earth's atmosphere, a set of operating points at different times along the flight path are selected, the corresponding dynamics models of the rocket are obtained via linearization, and a robust H_∞ controller is designed for each operating point using the linear matrix inequality approach. These controllers are applied to the nonlinear plant model via a switching strategy when the rocket flies along the flight path. Both linear and nonlinear simulation results are given to show the performance of the closed-loop system.

1. Introduction

The attitude control of a launch vehicle is a challenging task for control designers due to its varying mass and inertial properties, flexible dynamics, inherent instability, and varying atmospheric conditions. Further complications can also be introduced by sloshing of liquid propellants and the inertia effects of swiveling engines [6]. During the last ten years, some attempts have been made to tackle the complex problem of robust attitude control of a launch vehicle via modern control synthesis methods, including H_∞ and μ-synthesis. One great advantage with the robust control technique is that it allows designers to systematically design controllers with uncertainties, disturbances, sensor noises, actuator constraints, and performance measures explicitly taken into account. Also, a set of linearized models simplifies the control design process, and the inherent nonlinearity of the plant can be taken care of using the gain scheduling approach.

For instance, μ-synthesis has been applied for the attitude and vibration control of the M–V launch vehicle of Japan Aerospace Exploration Agency [9,10]. The effectiveness of the design to get robustness not only in stability but also in tracking performance has been verified by the back-to-back successful flights of the vehicle. The CNES (French Space Agency) and EADS Launch Vehicles have investigated the launch vehicle control during the atmospheric flight. Robust synthesis methodologies have been proposed, ranging from stationary control methodologies (e.g., H_∞ design [8], multi-objective H_2/H_∞ control [1,11]) to gain-scheduling approach [4]. The results have been demonstrated with a nonlinear simulator.

However, the order of the μ-controllers in Refs. [9,10] is very high and it has to be reduced for the purpose of practical applications while at the same time maintaining the performance of the controller within a specified tolerance limit. This process has been done by trial-and-error in order to find the best order. For the H_∞-based design in Refs. [1,4,8,11], the control synthesis and gain scheduling processes are quite tedious. The design is based on the Youla parameterization, which involves initial synthesis, observer-based structure parameterization, and finally optimization. The controllers are scheduled based on linear interpolations, which are performed for the state-feedback gains, the observer gains, as well as the Youla parameter.

To avoid those problems, the H_∞ control design approach based on the linear matrix inequality (LMI) technique [5] is applied in this paper. The LMI technique has been successfully used to design a robust output-feedback controller, for which the state-space data are constructed from the solutions of a set of LMIs. The order of the resulting controller can be kept as same as that of the generalized plant with weighting functions. For a launch vehicle, using multiple H_∞ controllers is a reasonable strategy to deal with its time-varying nonlinear dynamics. The key is to select a suitable rule, which is usually state-dependent, time-dependent, or parameter-dependent, to orchestrate the switching between different controllers. In this paper, a simple time-dependent switching rule is proposed to schedule the control gains, and it requires much less computational effort than the interpolation-based gain scheduling approach.

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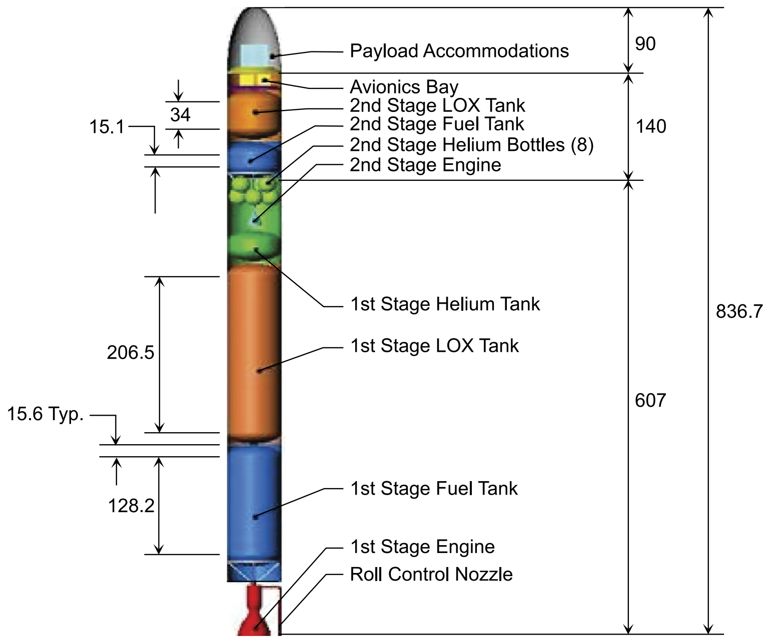

Fig. 1. NLV baseline concept.

The main objective of this research is to examine the applicability and effectiveness of the switching robust control technique for a notional nanosat launch vehicle such as the one defined by team members of the California Launch Vehicle Education Initiative (CALVEIN). The CALVEIN program was initiated in 2001 as collaboration between California State University, Long Beach (CSULB) and Garvey Spacecraft Corporation at Long Beach, California. The program provides students the opportunity to gain hands-on experience and provides an avenue for research and technology developments for next generation of low cost launch vehicles. Over the years, the team has developed 18 liquid-propelled prototype launch vehicles and conducted over 20 suborbital flights (for a typical vehicle). Notable accomplishments include the development and flight test of aerospike engine technology, liquid oxygen/methane engine technology, as well as nanosatellite launch vehicle (NLV) technology.

An NLV is a small launch vehicle capable of launching a payload less than 10 kg into low Earth orbit. The baseline concept is a two-stage vehicle with both stages powered by liquid rocket engines using liquid oxygen and propylene as propellants (see Fig. 1). Since 2002, the team has conducted a series of projects to develop and demonstrate the reusable NLV technology. Fig. 2 shows the flight test of the P-9A vehicle in October, 2008. The CALVEIN program, with its emphasis on flight testing, places CSULB in a unique position to conduct state-of-the-art research in the area of control design, implementation, and flight test for launch vehicles.

In this paper, the switching robust control technique is applied to the NLV as shown in Fig. 1. The paper is organized as follows. In Section 2, the mathematical model of the NLV is given, including rigid body dynamics, propellant slosh, bending modes, aerodynamics, mass properties, and actuator dynamics. In order to control the rocket along a trajectory ascending through the Earth's atmosphere, a set of operating points at different times along the flight path are selected, and the corresponding dynamics models of the rocket are obtained via linearization. In Section 3, a robust H_∞ controller is designed for each operating point. A switching mechanism is proposed, based on which this family of H_∞ controllers are scheduled when the rocket flies from one operating point to another along the flight path. Section 4 shows both linear and nonlinear simulation results, and also wind disturbances and sensor noise are simultaneously considered in the nonlinear simulation. Conclusions are given in Section 5. Note that the results presented in this paper represent an initial but significant step toward future research, i.e., evaluating the stability and performance of the proposed switching robust control strategy via flight tests.

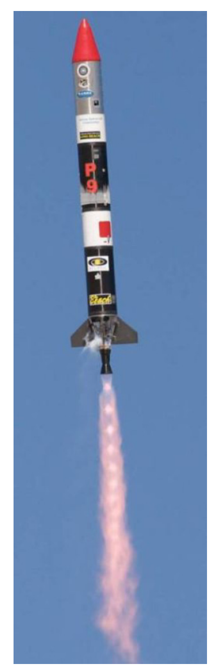

Fig. 2. P-9A vehicle in powered flight.

2. Linearized model of the nanosatellite launch vehicle

Only is the pitch axis considered in this paper because of the negligible coupling between the pitch, roll, and yaw axes for attitude control. To get an analytical model of the NLV, two additional simplifying assumptions are made: