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Title

ReFEx: Reusability Flight Experiment – Design of an Exoatmospheric Control System

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Abstract

The Reusability Flight Experiment (ReFEx) aims to demonstrate the return flight of an aerodynamically controlled reusable launch vehicle (RLV) [1]. After separation from a sounding rocket, the vehicle follows a ballistic trajectory before reentering into earth's atmosphere. During this exoatmospheric flight phase several maneuvers have to be performed to detumble the vehicle, rotate it for navigation system calibration and finally align it for reentry. Therefore, the demonstrator is equipped with eight cold gas thrusters. They are oriented such that each of them primarily produces a torque around one of the main body axes and they enable a certain degree of redundancy.

During the exoatmospheric flight phase the guidance system only provides fixed final states. To enable a smooth transition between the vehicle's current and the desired reference state a trajectory is planned by means of spherical linear interpolation and polynomial progression. The resulting trajectory uses the shortest rotational direction and ensures that the commanded torques do not exceed the thrusters' capabilities. Due to the limited amount of fuel and the discrete behavior of cold gas thrusters, a PD-controller including a deadband is implemented. The controller is extended by feedback linearization such that controller gains can be approximately determined by pole placement. As a result, it can be guaranteed that the vehicle transitions without overshoots.

In order to allocate commanded torques to discrete thruster on/off-commands, a pulse modulation scheme is applied for each body axis. Based on the work of Kienitz et al [2], the pulse-width pulse-frequency (PWPF) modulation explicitly considers switching restrictions like minimum pulse duration and minimum rest between successive pulses. This design is improved by correcting for the delayed actuator actions caused by signal processing delays and the transient behavior of the gas flow. In contrast to classical PWPF modulators the implemented pulse modulator is capable of accurately realizing the commanded torques. Individual thruster commands are allocated by a switching logic which aims to use the maximum number of thrusters that can produce the desired torques. This results in accurate maneuvers and a fault tolerance for the failure of up to two thrusters in the roll and pitch direction.

The implemented control system is capable of stabilizing the vehicle during the entire exoatmospheric flight phase and enables smooth transitions between different states while compensating for a certain level of thruster failures. Additionally, it is very fuel-efficient by consuming only slightly more than half of the fuel that was predicted in an early design phase of the project. Results for representative maneuvers show its robust performance in the presence of model uncertainties, disturbances and actuator failures.

References

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