Worst-case Analysis of Space Systems

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Abstract

Worst-case analysis is one of the most important elements in the verification and validation process used to ensure the reliable operation of safety-critical systems for defence, aerospace and space applications. In this thesis, an optimization-based worst-case analysis framework is developed for space applications. The proposed framework has been applied and successfully validated on a number of European Space Agency funded research projects in the areas of flexible satellites, hypersonic re-entry vehicles, and autonomous rendezvous systems.

Firstly, the problem of analyzing the robustness of an Attitude and Orbital Control Systems (AOCS) for a flexible scientific satellite with a large number of uncertainties is considered. The analysis employs a detailed simulation model of a flexible satellite and multivariable controller, together with a number of frequency and time domain performance criteria which are commonly used by the space industry to verify correct functionality of full-authority multivariable satellite control systems. Second, the flying qualities analysis of a re-entry vehicle is investigated for a number of complex scenarios involving different types of uncertainties and disturbances. Specific methods are utilized to deal with analysis problems involving probabilistic uncertainties, physically correlated uncertainties and highly dynamical disturbances. In another study, an integrated analytical/optimization-based analysis framework is proposed for the robustness analysis of AOCS for a telecoms satellite with flexible appendages. We develop detailed Linear
Fractional Transformation (LFT)-based models of the uncertainties present in a modern telecom satellite and apply \( \mu \)-analysis to these models in order to generate robustness guarantees. We validate these models and results by cross-checking them against worst-case analysis results produced by global optimization algorithms applied to the original system model. Finally, the optimization-based framework developed in this thesis is employed to analyze the robustness of the Guidance, Navigation and Control (GNC) system for autonomous spacecraft. This study considers the autonomous rendezvous problem over the terminal flight phase in the presence of a large number of realistic parametric uncertainties and a number of safety criteria related to the capture specification. An integrated analytical/optimization-based approach was also developed for this problem so that the computational cost of simulation-based analyses can be reduced, through leveraging results from robust control tools such as \( \mu \)-analysis.

The main contributions of the thesis are (a) to provide convincing demonstrations of the usefulness of optimization-based worst-case analysis on a number of different space applications, each of which involves highly complex simulators developed by leading industrial companies from the European Space sector, and (b) to show how optimization-based analysis methods may be combined with analytical tools from robust control theory to create a more integrated, efficient and reliable verification and validation process for space applications.
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