Attitude Control of Spacecraft with Flexible Appendages

dnr: 104/15

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Outline

- Project Overview
- Background
- Summary of Project Results
- Master Thesis Continuation
- Conclusions
Project Overview

- Project was defined with Linköping University
- Purpose of project has been to investigate performance limitations for the attitude control of satellites with flexible appendages
- Propose and analyze new and better methods with the purpose to improve the attitude control performance
- Secondary objective
  - Provide an opportunity for OHB Sweden to familiarize with modern control design methodologies and to arrive at a more efficient design process
# History of SSC/OHB Sweden designs

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
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<tbody>
<tr>
<td>Early Swedish satellites</td>
<td>Could be treated as rigid bodies.</td>
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<tr>
<td>Flexible solar panels on SMART-1</td>
<td>SMART-1 was a fundamental performance limitation and required special analysis</td>
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<tr>
<td>Small GEO and EDRS-C</td>
<td>Larger solar panels and propellant sloshing</td>
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<tr>
<td>Electra</td>
<td>Even larger solar panels resulting in significant performance limitations.</td>
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- Modeling of flexible dynamics not necessary for attitude control design.
- Design methodology developed based on classical control design techniques with straightforward investigation of robustness.
- Need to investigate if new control design techniques can lead to improved performance.
**Background**

**Trend in Attitude Control**

- Electric Propulsion is becoming more and more common and is also one of the key competence areas of OHB Sweden
- All such missions will have relatively large solar panels. Especially in for the different configurations studied for the Electra telecommunication platform developed by the OHB Group
- Flexible dynamics are also an essential ingredient in the analysis associated with different Active Debris Removal studies or with exploration missions to the outer solar system
- Customer demands tend to increase in terms of proving stability and performance in the presence of substantial system parameter variation and uncertainties (so called Robust Stability and Performance)

Need for a systematic and efficient design process based on modern multivariable Robust Control methodologies.
Project Outline

- Literature Study
- Modeling and Uncertainty Representation
- Investigation of Advanced Control Design Strategies
- Method Selection
- OHB Case Study
- Conclusions
Study Model

- Flexible appendages. E.g. solar panels and antennas
- Solar panels can rotate
- Rigid central body with collocated sensors and actuators
- Significant uncertainties in the flexible dynamics:
  - Eigen-frequencies
  - Damping factors
  - Dynamic coupling
  - Mass properties
Modeling and Uncertainty Description

- Standard modal model description used as starting point
- Partitioning of the dynamics into
  - Controlled flexible modes
  - Residual flexible modes
- Uncertainty Description
  - Neglected (residual) modes treated as uncertainty
  - Parametric uncertainty of controlled flexible modes
  - Demonstrated how the uncertainties arising from rotation of the solar panels can be treated as a vertex bounded representation - allows for gain scheduling control
  - Complete uncertainty here covered by a bound in the frequency domain
Control Design Methods and Selection

- Robust Control Design (μ-synthesis)
  - Guarantee robust stability and performance
  - Closed loop performance specifications in the frequency domain
  - Find controller that is "optimal" under the constraints of the structure of the model uncertainty
  - Advantage: Powerful way to specify performance criteria
  - Drawback: May be too conservative and may have difficulties in generating solutions. May lead to high-order controllers.

- 2DOF Collocated Output Feedback
  - Gain-scheduled control
  - Robustly stabilizing controllers
  - Based on H-infinity norm minimization
  - Performance through reference model following
  - Advantage: More straightforward
  - Disadvantage: No clear possibility to take modal parameter uncertainties into account to guarantee performance

Robust Control Design is selected for its suitability for the type of system studied.
**Design Results and Conclusion**

- Robust Control Design applied to a satellite with two solar panels that are possible to rotate
- Dynamics relevant for telecom satellite with large solar panels (typically a Electric Propulsion based platform)
- Extensive search was made in the parameter space of the selected design weights
- Results:
  - It was not possible to find robustly stabilizing controllers
  - Stabilizing controllers were possible to find in case the model uncertainties were reduced
  - Model uncertainty of dominating modes is too large to allow for robust control within the corresponding frequency region.
  - Lowest flexible modes are indeed a fundamental limitation of system performance
- Possible way forward:
  - Reduce model uncertainties (difficult for this type of systems)
  - Make use of on-board system identification (characterization of modal parameters) to allow for a “cautious” cancellation of dominating modes (Has been done in NASA missions)

- Way forward
  - We wanted to investigate further the possibilities to select weight functions to try to find solutions that guarantee robust stability and performance.
  - A master thesis project was defined with KTH to allow for further investigation
Master Thesis – taking one step back...

- Perform a first analysis with a simple system: SISO with one flexible mode
- Find out fundamental properties and investigate design methodologies
  - Mixed Sensitivity H-infinity (closed-loop specification)
  - Glover-McFarlane (open loop loop-shaping design similar to classical control design)
- When the right control architecture has been established
  - Move to MIMO system and successively add complexity to the dynamical model
- The work is almost finished and preliminary (positive) results have been obtained
Master Thesis – preliminary results

Benchmark

Glover-McFarlane

Improved Settling Time

Removal of actuation artefacts

Slightly worse disturbance suppression
Conclusions

- Slightly improved performance
- The benchmark design is near-optimal
- However, the real advantage is that the NRFP-project together with the Master Thesis project provides
  - An improved and fast design process
  - Systematic assessment of robust stability and performance margins
  - Familiarization with modern control design techniques

For OHB Sweden this means improved competitiveness and better possibilities to meet future customer expectations.
Thank You!