Robust Guidance and Control for Space Descent and Landing

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Many different missions, similar underlying problem: design acceleration profile $a(t)$ between $[t_0, t_f]$ that

- Drives relative states from a set of initial to final conditions $\mathbf{r}(t_0) = \mathbf{r}_0 \rightarrow \mathbf{r}(t_f) = \mathbf{r}_f$ $\mathbf{v}(t_0) = \mathbf{v}_0 \rightarrow \mathbf{v}(t_f) = \mathbf{v}_f$

- Ensures robustness against uncertainties and perturbations $\mathbf{p}(t)$
Project Introduction

Motivation

Robust and Nonlinear Guidance & Control for Landing on Small Bodies

1. Conventional techniques involve an extended period of forced motion, but significant fuel ($\Delta V$) savings can be achieved by further exploiting the natural dynamics in the vicinity of the target body.

2. However, small bodies are characterised by highly irregular and poorly known shapes, which render their physical environment extremely uncertain and variable.

3. High accuracy and reliability required for fully autonomous operations.

4. GNC algorithms must be able to cope with the chance of long-term subsystem degradation.

5. Control compensation is typically over-simplified or even inexistent.
Project Introduction

Objectives

➢ Investigate robust and nonlinear control techniques for the design and optimisation of descent trajectories

➢ Focus on the Martian moon Phobos based on a candidate ESA sample return mission

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1. Benchmark Introduction

2. Space D&L Subsystem Modelling

3. Structured Robust Control Synthesis

4. Robustness Analysis against Uncertainties

5. Application to Guidance Tuning

6. Conclusions
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Benchmark Introduction

Phobos benchmark

- Due to its irregular shape, Phobos gravity is described by a gravity harmonics (GH) model:
  \[ U_\theta(r, \theta, \phi) = \frac{\mu g}{R} \sum_{n=0}^{\tilde{n}} \left( \frac{R}{r} \right)^{n+1} \sum_{m=0}^{n} C_n^m(\phi)P_n^m(\cos \theta), \quad C_n^m(\phi) = C_{n,m} \cos m\phi + S_{n,m} \sin m\phi \]

- 28 \( C_{n,m} \) and \( S_{n,m} \) GH coefficients (19 highly inaccurately known)

- Due to its reduced mass (8 orders magnitude smaller than Mars) and proximity to Mars (mean altitude of 6000 km), the planet’s sphere of influence ends just 3.5 km above Phobos

- No possibility for Keplerian orbits and third-body perturbation of Mars cannot be neglected

- Candidate descent trajectories are related to unstable manifolds originated at Libration Point Orbits that intersect Phobos

- This is a middle ground between the state-of-practice for asteroid interception (negligible gravity perturbations) and planet landing (gravity field is well-known and sometimes assumed constant)
### Benchmark Introduction

**Candidate GNC architectures**

<table>
<thead>
<tr>
<th>Uncompensated</th>
<th>Compensated</th>
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<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
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**Focus of this presentation**

- Control compensator is **independent** of the type of guidance
- **Missionization**: three reference trajectories are used, all designed with an approximated model of Mars-Phobos system

**Missionization details**:

- $\Delta V = 8.0 \text{ m/s}$
- $\Delta V = 9.1 \text{ m/s}$
- $\Delta V = 9.0 \text{ m/s}$
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Space D&L Subsystem Modelling
Orbital perturbation model

- Relative EOM variables defined as sum of reference values and small perturbations:

\[
\begin{bmatrix}
\dot{\mathbf{r}}(t) \\
\dot{\mathbf{v}}(t) \\
\dot{\nu}(t)
\end{bmatrix} = \mathbf{f}(\mathbf{r}(t), \mathbf{v}(t), \nu(t)) + \begin{bmatrix}
0_{3 \times 3} \\
I_{3 \times 3} \\
0_{1 \times 3}
\end{bmatrix} \mathbf{a}(t)
\]

- Using 1st order Taylor series approximation, LTI models \( G^i_{SDK}(s) \) obtained at different points:

\[
\begin{bmatrix}
\dot{x}_{SDK}(s) \\
\delta r(s) \\
\delta v(s)
\end{bmatrix} = \begin{bmatrix}
J_f^i & 0_{3 \times 3} \\
I_{6 \times 6} & 0_{6 \times 1} & 0_{6 \times 3}
\end{bmatrix} \begin{bmatrix}
x_{SDK}(s) \\
\delta a(s)
\end{bmatrix}
\]

- Bounded actuation error modelled by simple LFT, navigation error included using colouring filters:

\[
a(s) = \left( I_{3 \times 3} + \begin{bmatrix}
w_{ax0} \delta_{ax}(s) & w_{aod0} \delta_{aod}(s) & w_{aod0} \delta_{aod}(s) \\
w_{aod0} \delta_{aod}(s) & w_{ay0} \delta_{ay}(s) & w_{aod0} \delta_{aod}(s) \\
w_{aod0} \delta_{aod}(s) & w_{aod0} \delta_{aod}(s) & w_{az0} \delta_{az}(s)
\end{bmatrix} \right) a_{cmd}(s)
\]

\( \delta_i(s) \in [-1, +1] \)

\[
r(t) = r_{ref}(t) + \delta r(t) \\
v(t) = v_{ref}(t) + \delta v(t) \\
\nu(t) = \nu_{ref}(t) + \delta \nu(t) \\
a(t) = a_{ref}(t) + \delta a(t)
\]
Space D&L Subsystem Modelling
Inclusion of gravitational uncertainties

1. Sensitivity-based uncertainty selection

2. Jacobian sampling

3. Interpolation and transformation into LFT

4. LFT verification

$J_f^i(\rho_{GH})$

$\rho_{GH}$

$J_f^i$

$\Delta_{SDK}$

$G_{SDK}^i(s)$

$\delta a$

$\delta r$

$\delta v$

APRICOT library
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Structured Robust Control Synthesis

**Why structured $\mathcal{H}_\infty$?**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Classical Control</th>
<th>Standard $\mathcal{H}_\infty$ Control</th>
<th>Structured $\mathcal{H}_\infty$ Control</th>
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<tbody>
<tr>
<td>Explicit consideration of plant uncertainties</td>
<td>●</td>
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<td>Stability/performance guarantee by design</td>
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<td>●</td>
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<td>Frequency-wise insight on driving perturbations</td>
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<td>●</td>
</tr>
<tr>
<td>Multi-plant, multi-channel, multi-requirement design</td>
<td>●</td>
<td>●</td>
<td>●</td>
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<td>Reproducible control solution</td>
<td>●</td>
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<tr>
<td>Configurable controller size/architecture</td>
<td>●</td>
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<tr>
<td>Easy handling of design requirements</td>
<td>●</td>
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- Key advantages for D&L compensation
  - Consideration of gravitational uncertainties
  - Ability to keep controller size low by design

- Interest to further explore some of its additional features

**Multi-plant design possibilities**

- Single-plant controller
- Scheduled controller
- Multi-plant controller **Focus of this presentation**
- Self-scheduled controller

**Non-smooth optimisation shortcoming**

Proper choice of initial values & tuneable parameters critical for a good solution (e.g. no fast or unstable dynamics)

$$
\begin{bmatrix}
\dot{x}_K(s) \\
\delta r_{cmd}(s) \\
\delta r_{lpf}(s) \\
\delta v_{lpf}(s)
\end{bmatrix} =
\begin{bmatrix}
-0.01 I_{3\times3} & I_{3\times3} & -I_{3\times3} & 0_{3\times3} \\
I_{3\times3} & 0_{3\times3} & I_{3\times3} & I_{3\times3}
\end{bmatrix}
\begin{bmatrix}
x_K(s) \\
\delta r_{cmd}(s) \\
\delta r_{lpf}(s) \\
\delta v_{lpf}(s)
\end{bmatrix}
$$
Structured Robust Control Synthesis
Control synthesis steps (1/2)

- Controller shall introduce additional acceleration command to compensate for deviations wrt. reference trajectory.

- This formulation enables the direct application of the orbital perturbation model.

- Actuator and gravitational uncertainties encapsulated in a single $\Delta$ block.

- Control requirements imposed through the definition of input/output channels and frequency-domain weights.

- Different LTI plants aggregated in a block-diagonal structure for multi-plant control design.
Structured Robust Control Synthesis
Control synthesis steps (2/2)

**Tracking requirements**
\[ \delta r_e(s) \text{ bounded by } W_S^{-1}(s) \text{ for:} \]
- Small steady-state error
- Good stability margins
- Bandwidth adequate to D&L dynamics

**Actuation requirements**
\[ \delta a(s) \text{ bounded by } W_A^{-1}(s) \text{ for:} \]
- Limited control effort
- Little reactivity to noisy signals
- Roll-off frequency suitable for tracking
Structured Robust Control Synthesis

Behaviour of the compensators designed

Four compensators have been benchmarked:

- $K_0$ ➔ No uncertainties considered in the design
- $K_A$ ➔ Designed against $\Delta_A(s)$ only
- $K_{A,2\sigma}$ ➔ Designed against $\Delta_A(s)$ and $\Delta^i_{SDK,2\sigma}(s)$
- $K_{A,3\sigma}$ ➔ Designed against $\Delta_A(s)$ and $\Delta^i_{SDK,3\sigma}(s)$

RT1 Nominal NL simulation
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Robustness Analysis against Uncertainties

μ analysis and RP sensitivities at RT1 \( t_{go} = 8 \text{ min} \)

μ analysis provides much more than a binominal answer
Robustness Analysis against Uncertainties

Monte-Carlo verification

- 2000 Monte-Carlo runs perturbing 19 GH coefficients with Gaussian distribution
- 18 to 24 Worst-Case combinations extracted from RP peak of every plant with remaining coefficients set to min/nom/max

NL Simulation using $K_{A,2\sigma}$

- $K_{A,2\sigma}$ outperforms $K_{A,3\sigma}$: hinfstruct solution restricted by over-conservative uncertainty specification
- Accounting for RT1 only enough for the design of a compensator able to cope with other trajectories
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Application to Guidance Tuning

Parametric closed-loop guidance

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Closed-loop laws expressed in terms of zero-effort errors (ZEM, ZEV) and tuneable via \( \{k_r, k_v\} \):

\[
a(t) = \begin{bmatrix} k_r & k_v \end{bmatrix} \begin{bmatrix} \frac{ZEM(t)}{t_{go}^2(t)} \\ ZEV(t) \frac{1}{t_{go}(t)} \end{bmatrix} - \phi f(ZEM(t), ZEV(t), t_{go}(t))
\]

- Optional nonlinear function \( f(\cdot) \) of feedback variables, weighted by \( \phi \)
- State-of-practice gains \( \{6, -2\} \) derived analytically for \( \{k_r, k_v\} \) assuming simplified and well-known gravitational fields

Does not hold for Phobos
**Application to Guidance Tuning**

**Tuning results**

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**Tuning via systematic simulation**

Generation of trade-off maps using nominal & dispersed touchdown performance indicators

- Trade-off maps able to identify improved guidance solutions

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**Tuning via structured $\mathcal{H}_\infty$ optimisation**

Formulation of a multi-plant $\mathcal{H}_\infty$ problem using sltuner & accuracy/efficiency trade-offs

- Hinfstruct able to recover standard tuning selection, but unable to capture solutions related to higher nonlinear effects
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Conclusions

➢ Application of the Robust Modelling-Design-Analysis (Robust-MDA) cycle to the Space D&L control design problem for the first time

▪ Illustration of strengths and challenges of structured $\mathcal{H}_\infty$ optimisation using D&L trajectories on Phobos

▪ Demonstration of how $\mu$ analysis can be used to validate modelling choices and complement Monte-Carlo campaigns

▪ Reconciliati\on D&L guidance & control concepts in unified framework

➢ Extension of the approach to D&L guidance tuning, but results show that further research is still required when dealing with nonlinear effects

Transfer of techniques to industry

⇒ currently the Airbus team is using them for ESA Solar Orbiter mission!!!
Thank you for your attention

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