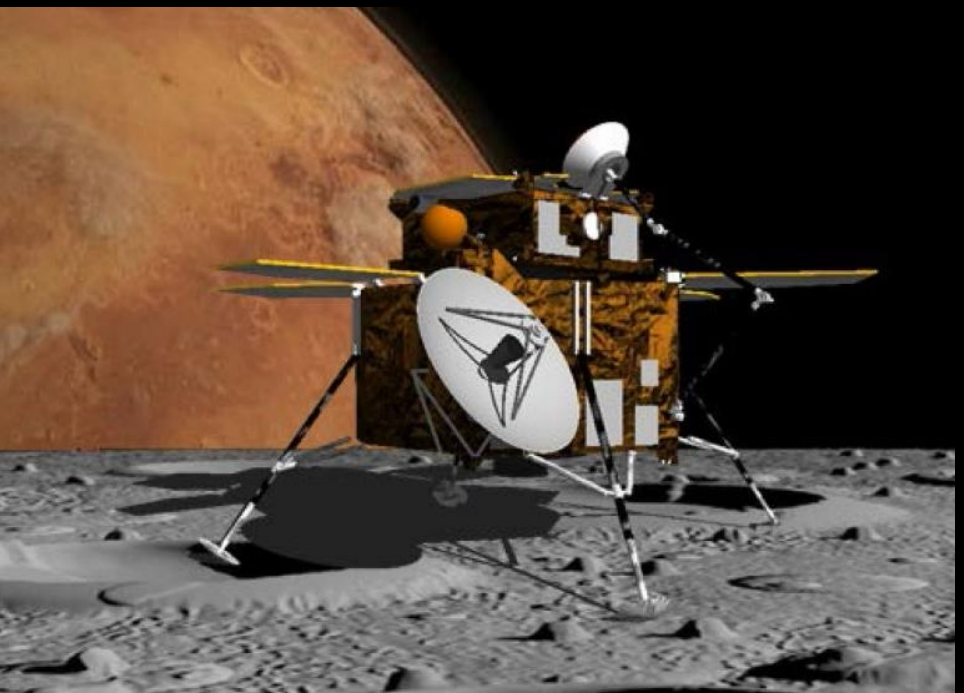
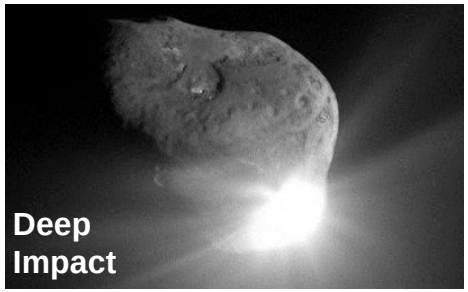
Robust Guidance and Control for Space Descent and Landing

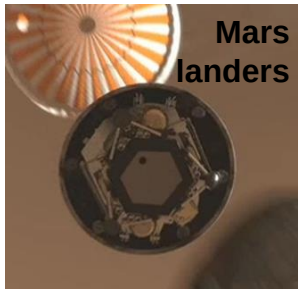


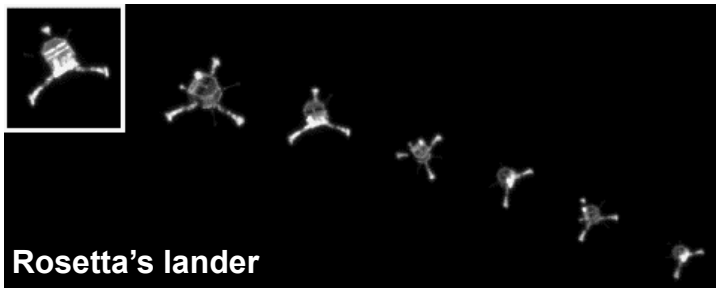
Pedro Simplício
Andrés Marcos
www.tasc-group.com
Technology for AeroSpace Control (TASC)
Aerospace Engineering Department
University of Bristol, U.K.

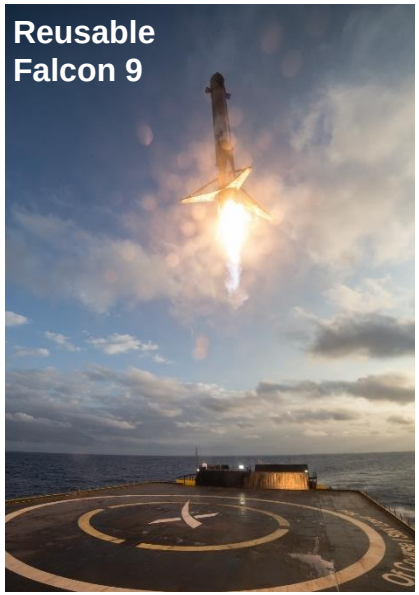
Project Introduction

Space D&L



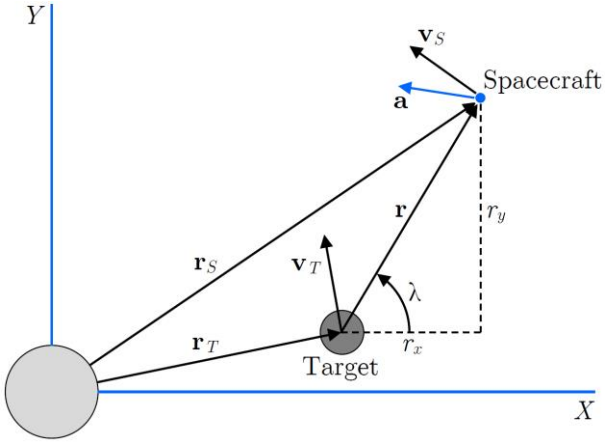






Many different missions, similar underlying problem: design acceleration profile $\mathbf{a}(t)$ between $[t_0, t_f]$ that

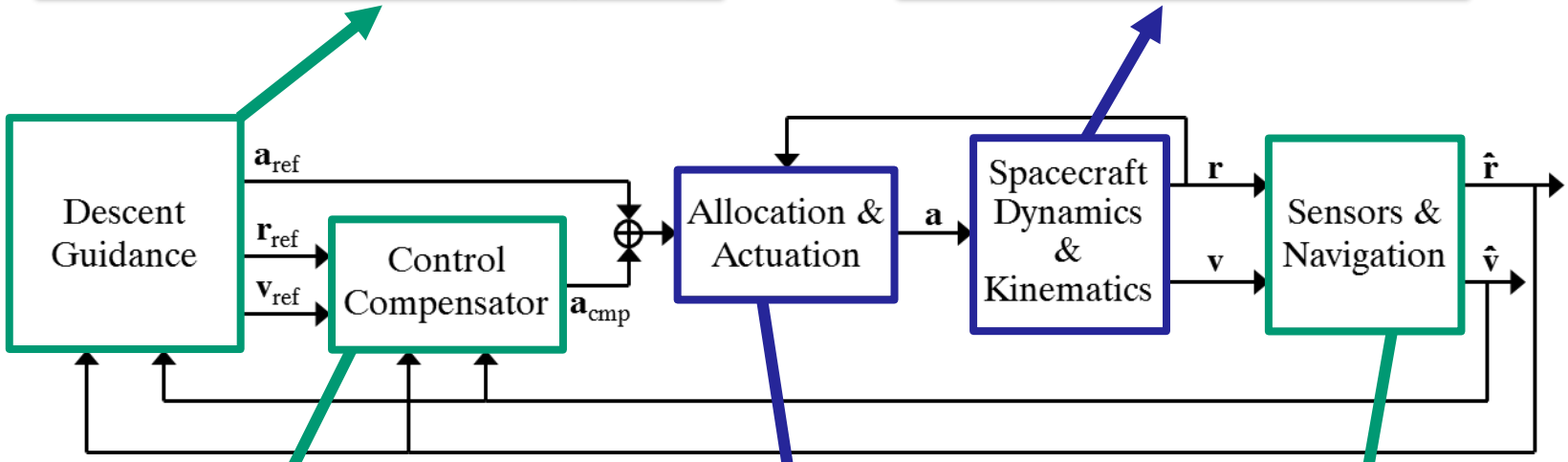
- Drives relative states from a set of initial to final conditions
  $\mathbf{r}(t_0) = \mathbf{r}_0 \rightarrow \mathbf{r}(t_f) = \mathbf{r}_f$
  $\mathbf{v}(t_0) = \mathbf{v}_0 \rightarrow \mathbf{v}(t_f) = \mathbf{v}_f$
- Ensures robustness against uncertainties and perturbations $\mathbf{p}(t)$



Robust and Nonlinear Guidance & Control for Landing on Small Bodies

1. Conventional techniques involve an extended period of forced motion, but significant fuel (ΔV) 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



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

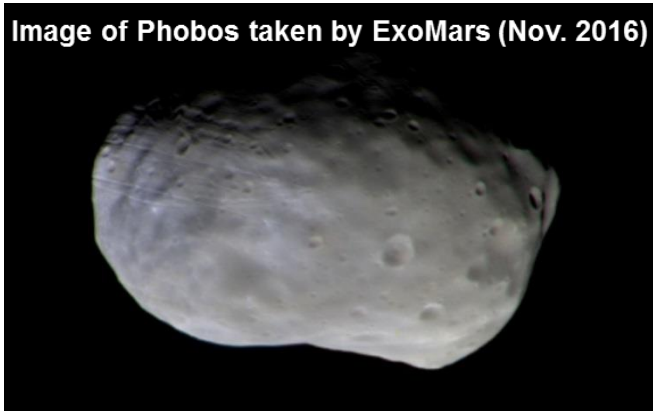
4. GNC algorithms must be able to cope with the chance of long-term subsystem degradation

3. High accuracy and reliability required for fully autonomous operations

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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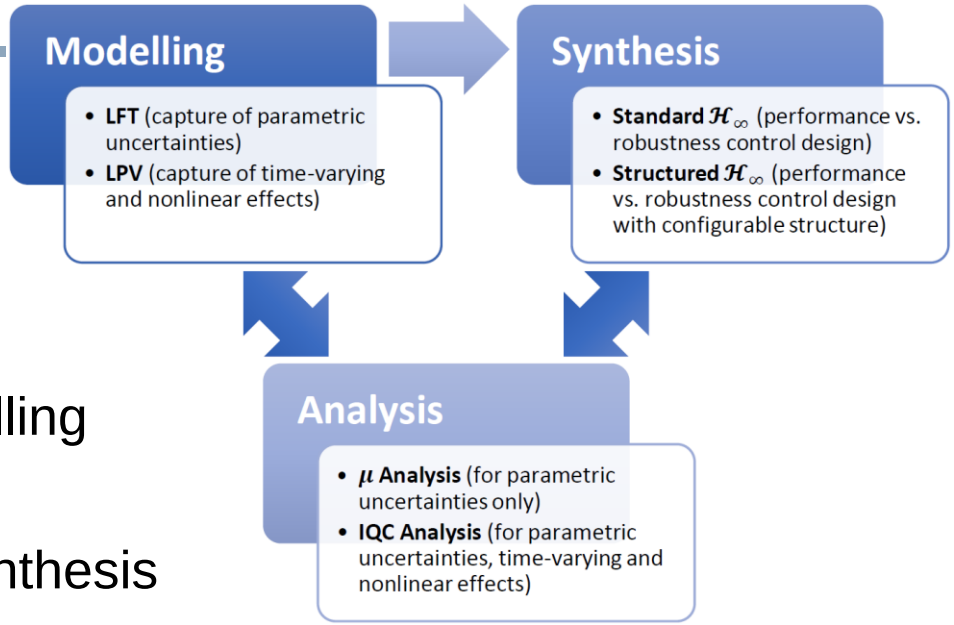
Airbus Defence and Space, Stevenage UK



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

1. Benchmark Introduction

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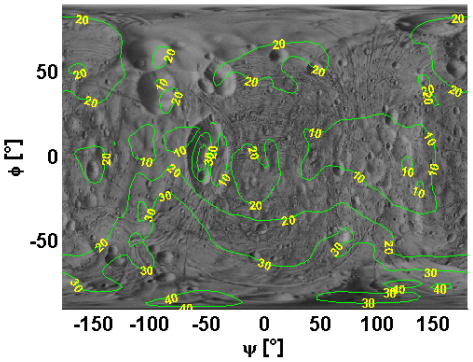
Benchmark Introduction

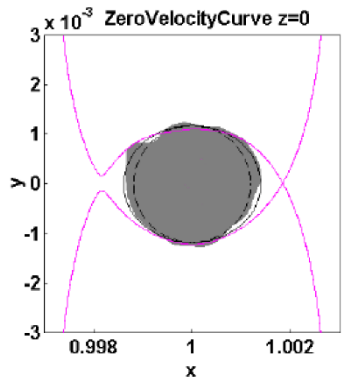
Phobos benchmark



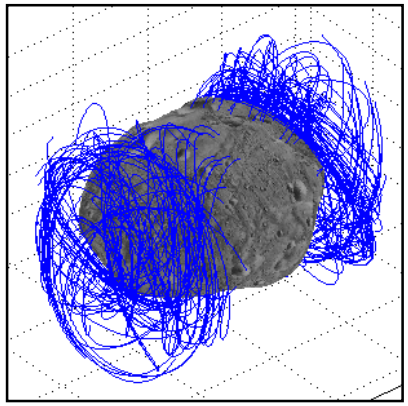
- Due to its irregular shape, Phobos gravity is described by a gravity harmonics (GH) model:

$$U_g(r,\theta,\phi) = \frac{\mu_g}{R}\sum_{n=0}^{\bar{n}}\left(\frac{R}{r}\right)^{n+1}\sum_{m=0}^{n} C_n^m(\phi)P_n^m(\cos\theta), \quad C_n^m(\phi) = C_{n,m}\cos m\phi + S_{n,m}\sin m\phi$$

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



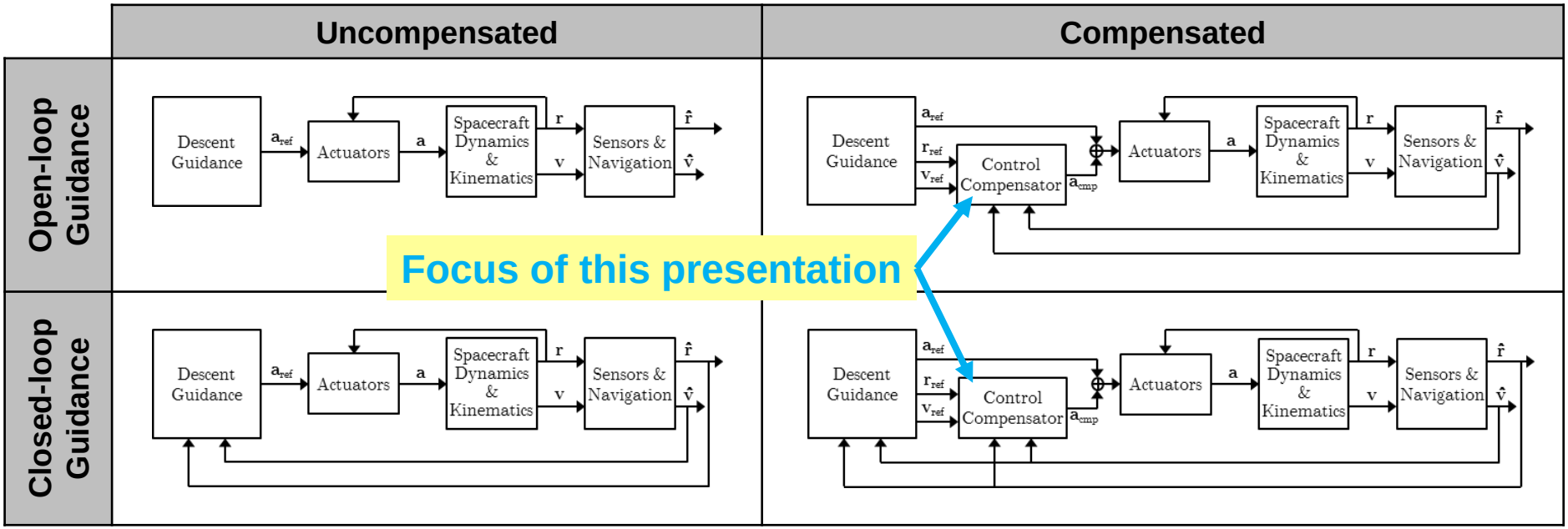
- Due to its reduced mass (8 orders magnitude smaller than Mars) and proximity to Mars (mean altitude of 6000 km), the planet's sphere of influence ends just 3.5 km above Phobos
- No possibility for Keplerian orbits and third-body perturbation of Mars cannot be neglected



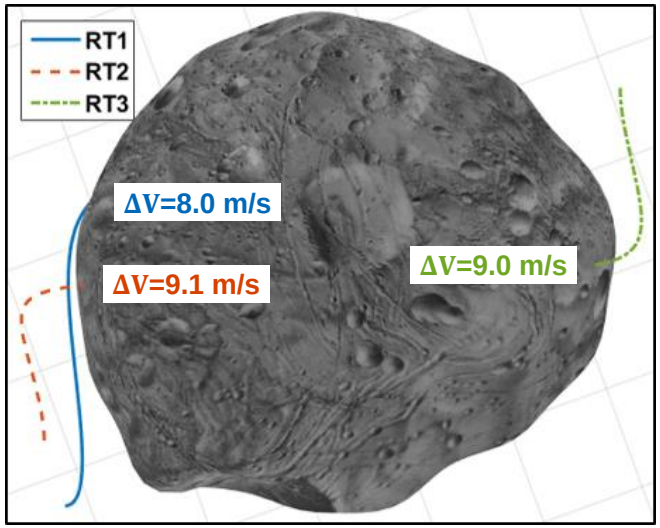
- Candidate descent trajectories are related to unstable manifolds originated at Libration Point Orbits that intersect Phobos
- This is a middle ground between the state-of-practice for asteroid interception (negligible gravity perturbations) and planet landing (gravity field is well-known and sometimes assumed constant)

Benchmark Introduction

Candidate GNC architectures



- 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



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Space D&L Subsystem Modelling

Orbital perturbation model

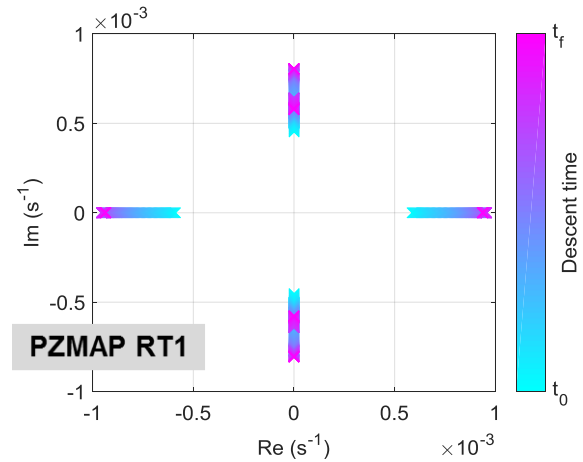
- Relative EOM variables defined as sum of reference values and small perturbations

$$\begin{bmatrix}\dot{\mathbf{r}}(t)\\ \dot{\mathbf{v}}(t)\\ \dot{\nu}(t)\end{bmatrix} = \mathbf{f}\left(\mathbf{r}(t), \mathbf{v}(t), \nu(t)\right) + \begin{bmatrix}0_{3\times3}\\ I_{3\times3}\\ 0_{1\times3}\end{bmatrix}\mathbf{a}(t)$$

$$\mathbf{r}(t) = \mathbf{r}_{\mathrm{ref}}(t) + \delta\mathbf{r}(t)$$
$$\mathbf{v}(t) = \mathbf{v}_{\mathrm{ref}}(t) + \delta\mathbf{v}(t)$$
$$\nu(t) = \nu_{\mathrm{ref}}(t) + \delta\nu(t)$$
$$\mathbf{a}(t) = \mathbf{a}_{\mathrm{ref}}(t) + \delta\mathbf{a}(t)$$

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

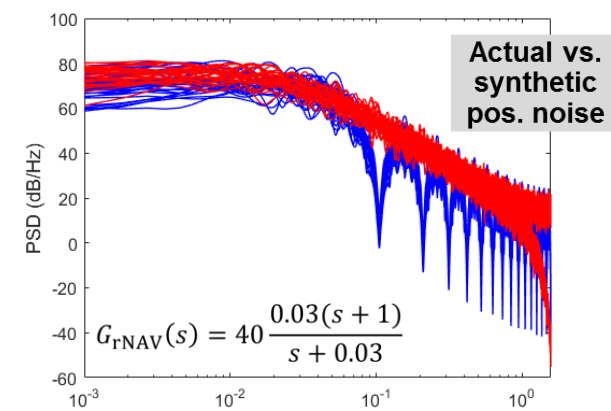
$$\begin{bmatrix}\dot{\mathbf{x}}_{\mathrm{SDK}}(s)\\ \hline \delta\mathbf{r}(s)\\ \delta\mathbf{v}(s)\end{bmatrix} = \left[\begin{array}{cc|c} \multicolumn{2}{c|}{J^i_{\mathbf{f}}} & \begin{matrix}0_{3\times3}\\ I_{3\times3}\\ 0_{1\times3}\end{matrix} \\ \hline I_{6\times6} & 0_{6\times1} & 0_{6\times3}\end{array}\right]\begin{bmatrix}\mathbf{x}_{\mathrm{SDK}}(s)\\ \hline \delta\mathbf{a}(s)\end{bmatrix}$$



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

$$\mathbf{a}(s) = \left(I_{3x3} + \begin{bmatrix} w_{\mathrm{ax}}\delta_{\mathrm{ax}}(s) & w_{\mathrm{aod}}\delta_{\mathrm{aod}}(s) & w_{\mathrm{aod}}\delta_{\mathrm{aod}}(s)\\ w_{\mathrm{aod}}\delta_{\mathrm{aod}}(s) & w_{\mathrm{ay}}\delta_{\mathrm{ay}}(s) & w_{\mathrm{aod}}\delta_{\mathrm{aod}}(s)\\ w_{\mathrm{aod}}\delta_{\mathrm{aod}}(s) & w_{\mathrm{aod}}\delta_{\mathrm{aod}}(s) & w_{\mathrm{az}}\delta_{\mathrm{az}}(s)\end{bmatrix}\right)\mathbf{a}_{\mathrm{cmd}}(s)$$

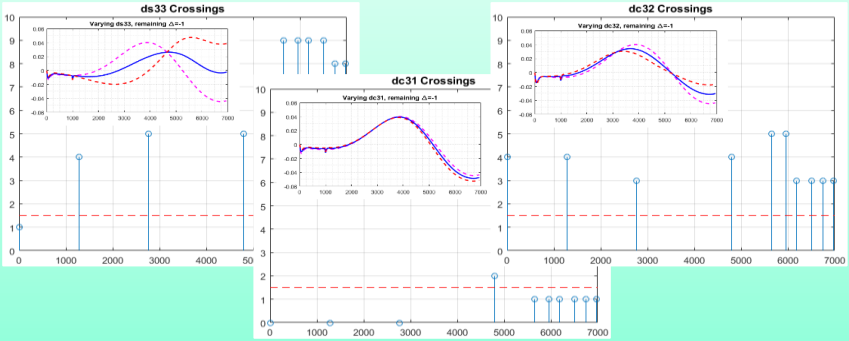
$$\delta_i(s) \in [-1, +1]$$



Space D&L Subsystem Modelling

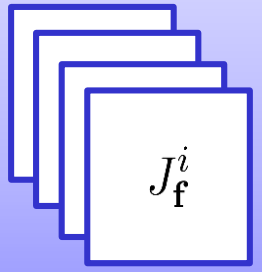
Inclusion of gravitational uncertainties

1. Sensitivity-based uncertainty selection



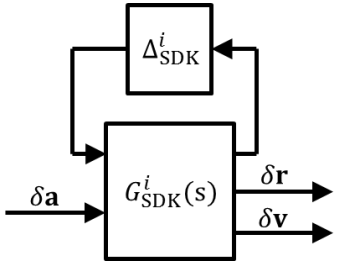
ρ_{GH}

2. Jacobian sampling

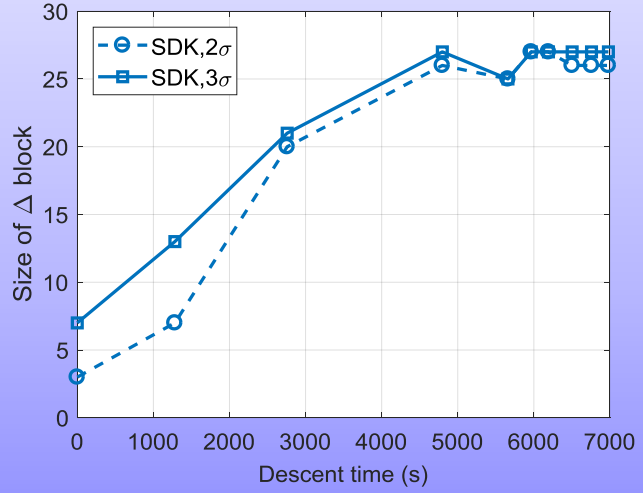


$J_{\mathbf{f}}^{i}(\rho_{\mathrm{GH}})$

3. Interpolation and transformation into LFT



4. LFT verification



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Structured Robust Control Synthesis

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

Feature	Classical Control	Standard $\mathcal{H}_\infty$ Control	Structured $\mathcal{H}_\infty$ Control
Explicit consideration of plant uncertainties	🔴	🟢	🟢
Stability/performance guarantee by design	🔴	🟢	🟢
Frequency-wise insight on driving perturbations	🔴	🟢	🟢
Multi-plant, multi-channel, multi-requirement design	🔴	🟡	🟢
Reproducible control solution	🟢	🟢	🔴
Configurable controller size/architecture	🟢	🔴	🟢
Easy handling of design requirements	🟡	🔴	🟢

- 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

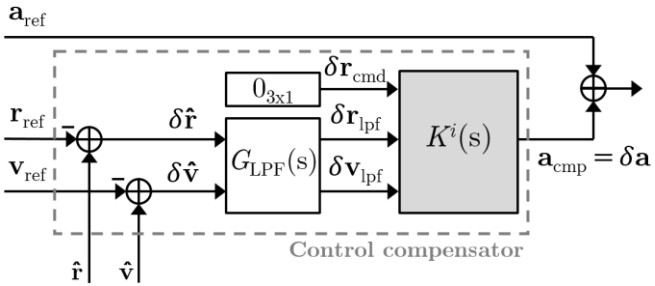
Proper choice of initial values & tuneable parameters critical for a good solution (e.g. no fast or unstable dynamics)

$$\begin{bmatrix} \dot{\mathbf{x}}_{\mathrm{K}}(\mathrm{s}) \\ \hline \mathbf{a}_{\mathrm{cmp}}(\mathrm{s}) \end{bmatrix} = \left[\begin{array}{c|ccc} -0.01\, I_{3\times3} & I_{3\times3} & -I_{3\times3} & 0_{3\times3} \\ \hline I_{3\times3} & 0_{3\times3} & I_{3\times3} & I_{3\times3} \end{array}\right] \begin{bmatrix} \mathbf{x}_{\mathrm{K}}(\mathrm{s}) \\ \hline \delta\mathbf{r}_{\mathrm{cmd}}(\mathrm{s}) \\ \delta\mathbf{r}_{\mathrm{lpf}}(\mathrm{s}) \\ \delta\mathbf{v}_{\mathrm{lpf}}(\mathrm{s}) \end{bmatrix}$$

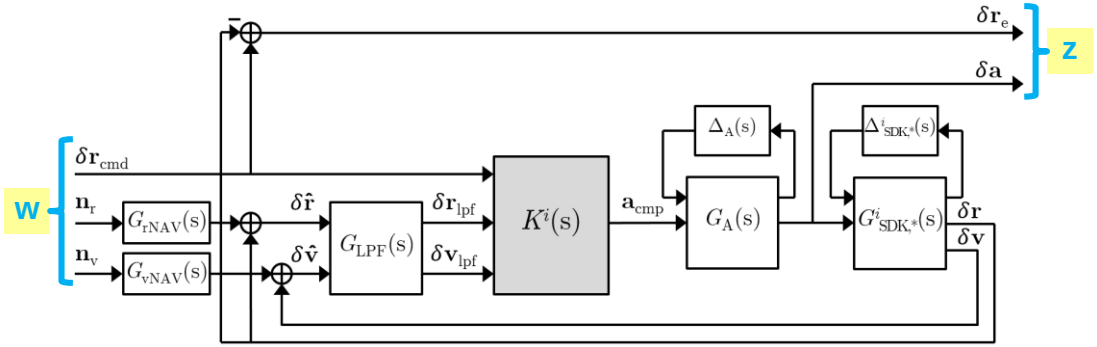
Structured Robust Control Synthesis

Control synthesis steps (1/2)

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

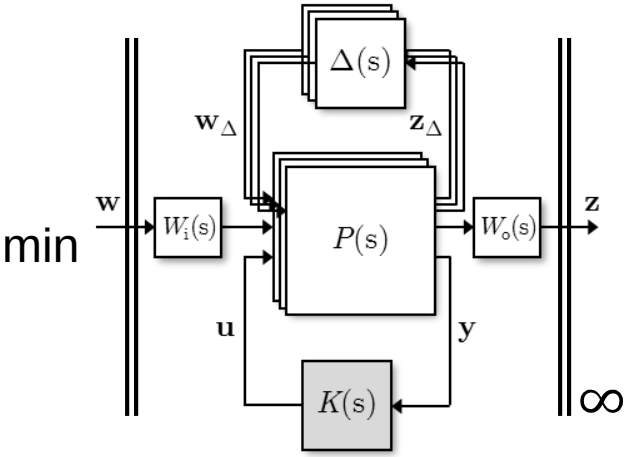


- This formulation enables the direct application of the orbital perturbation model



- Actuator and gravitational uncertainties encapsulated in a single Δ 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

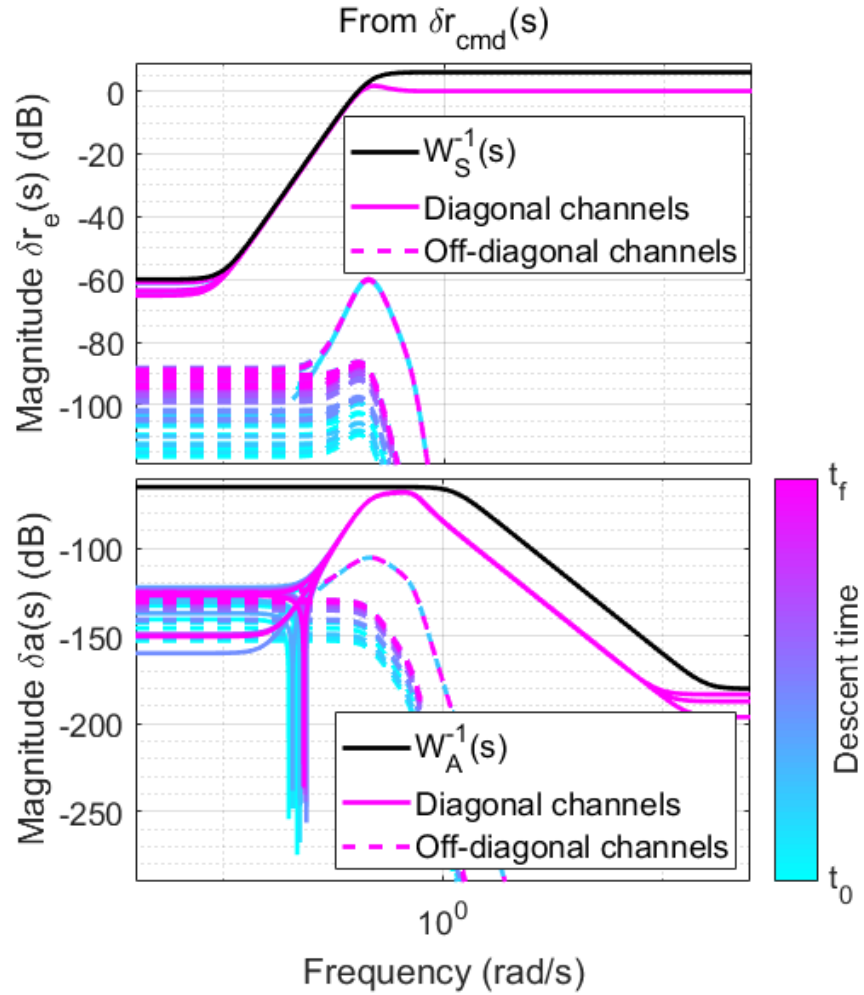
$\delta \mathbf{r}_e(s)$ bounded by $W_S^{-1}(s)$ for:

- ❑ Small steady-state error
- ❑ Good stability margins
- ❑ Bandwidth adequate to D&L dynamics

Actuation requirements

$\delta \mathbf{a}(s)$ bounded by $W_A^{-1}(s)$ for:

- ❑ Limited control effort
- ❑ Little reactivity to noisy signals
- ❑ Roll-off frequency suitable for tracking



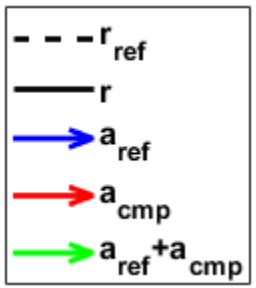
Structured Robust Control Synthesis

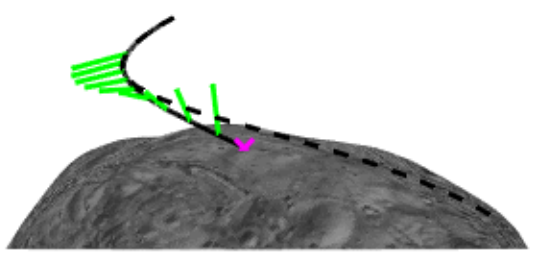
Behaviour of the compensators designed

Four compensators have been benchmarked:

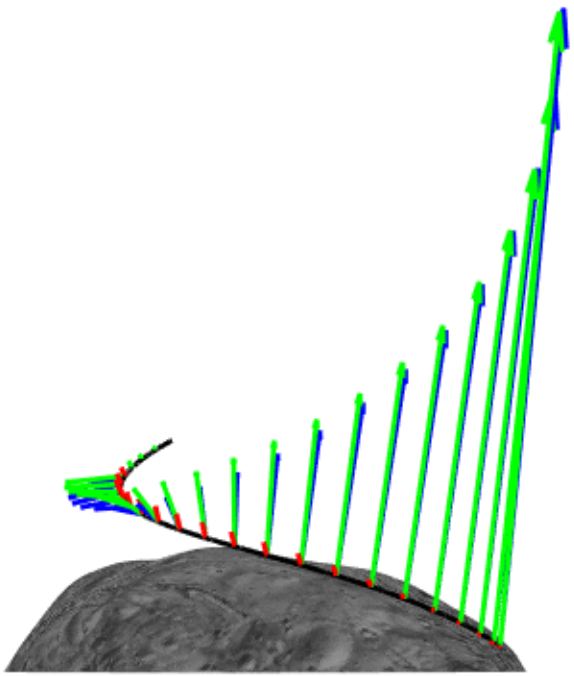
- K_0 ➔ No uncertainties considered in the design
- K_A ➔ Designed against $\Delta_A(s)$ only
- $K_{A,2\sigma}$ ➔ Designed against $\Delta_A(s)$ and $\Delta^i_{SDK,2\sigma}(s)$
- $K_{A,3\sigma}$ ➔ Designed against $\Delta_A(s)$ and $\Delta^i_{SDK,3\sigma}(s)$

RT1 Nominal NL simulation





Uncompensated



Compensated using K_0

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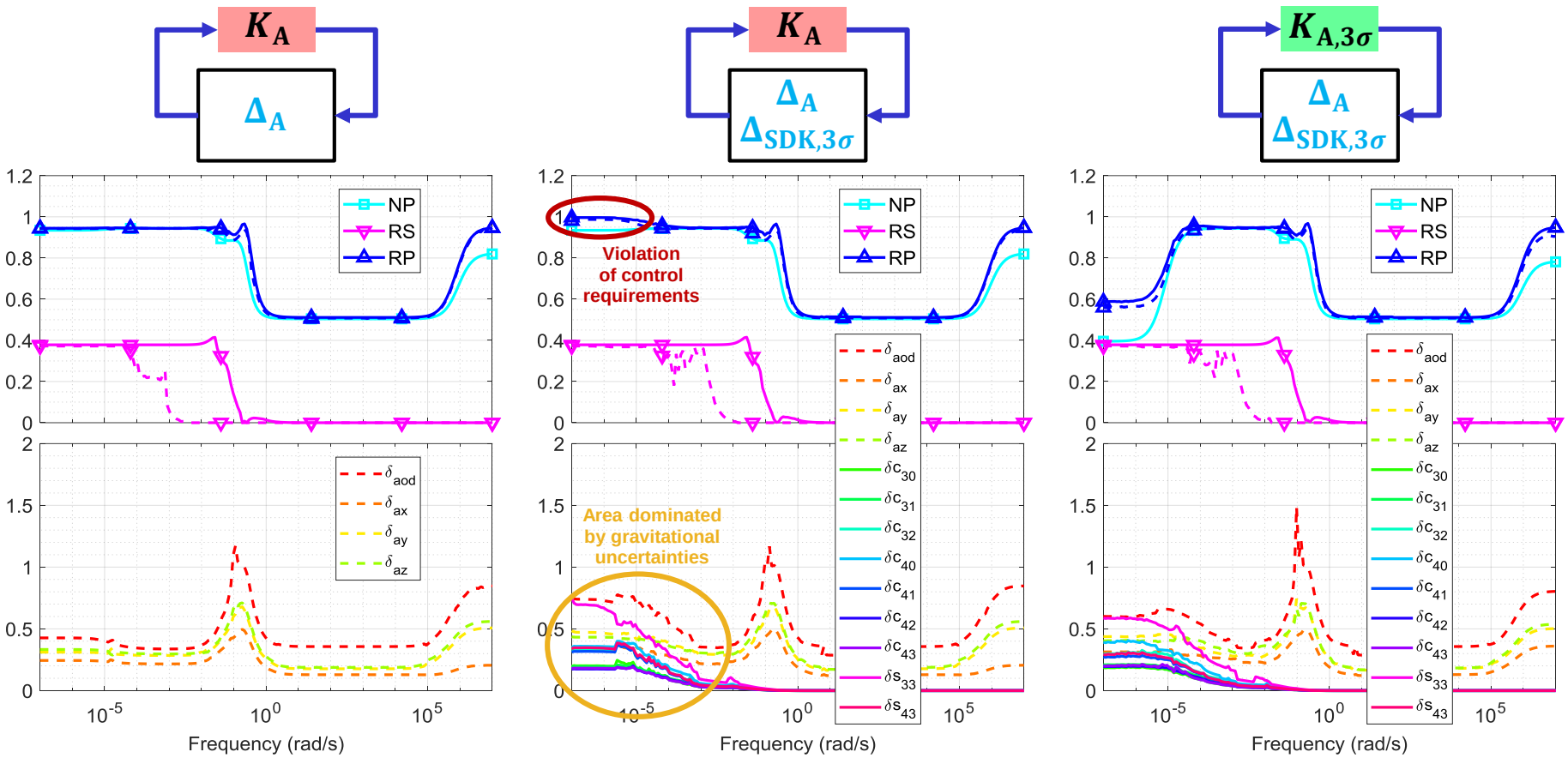
Robustness Analysis against Uncertainties

μ analysis

μ analysis and RP sensitivities at RT1 t_{go} = 8 min

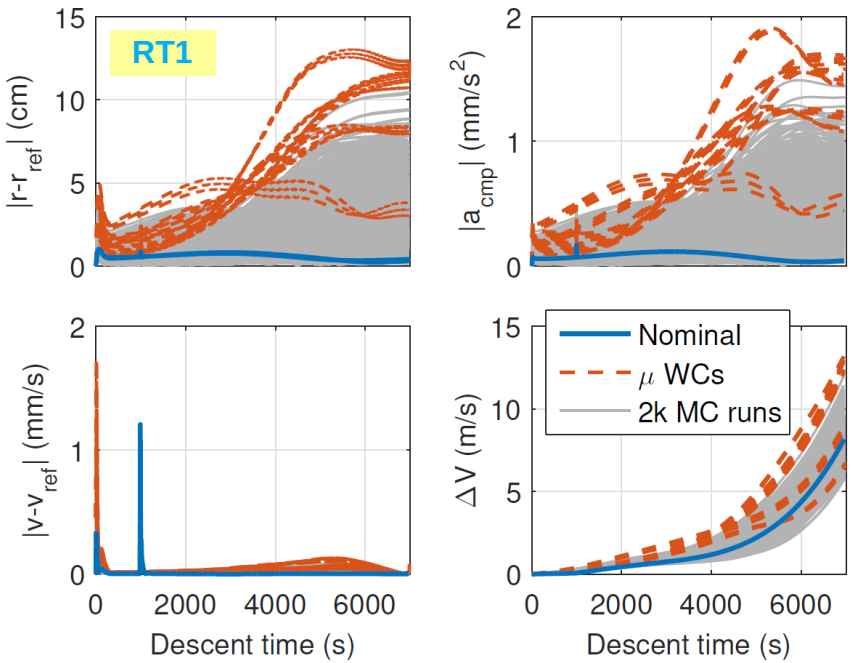


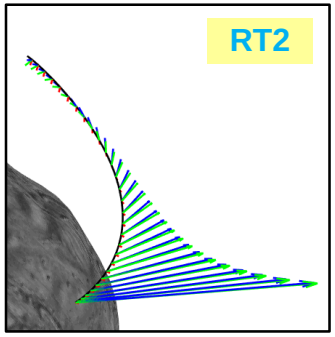
μ analysis provides much more than a binominal answer

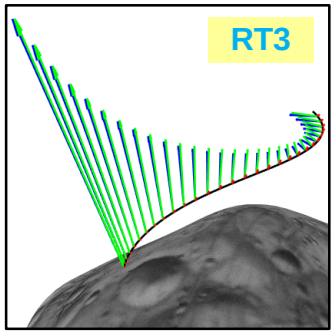
Robustness Analysis against Uncertainties

Monte-Carlo verification

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







- 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

	K_0		K_A		$K_{A,2\sigma}$		$K_{A,3\sigma}$	
Max. MC values	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.
$\lvert\mathbf{r}-\mathbf{r}_{\text{ref}}\rvert$ (m)	0.503	0.259	0.029	0.013	0.030	0.014	0.038	0.020
$\lvert\mathbf{v}-\mathbf{v}_{\text{ref}}\rvert$ (mm/s)	1.234	0.130	1.206	0.008	1.208	0.007	1.212	0.013
$\lvert\mathbf{a}_{\text{cmp}}\rvert$ (mm/s^2)	0.411	0.207	0.431	0.208	0.430	0.208	0.429	0.206
ΔV (m/s)	8.793	0.630	8.326	0.966	8.326	0.965	8.329	0.955
MC failures (%)	44.15		0.00		0.00 ☺		0.10	
WC failures (%)	33.33		12.50		0.00		16.67	

- $K_{A,2\sigma}$ outperforms $K_{A,3\sigma}$: hinfstruct solution restricted by over-conservative uncertainty specification

	RT1		RT2		RT3	
Max. MC values	Avg.	Std.	Avg.	Std.	Avg.	Std.
$\lvert\mathbf{r}-\mathbf{r}_{\text{ref}}\rvert$ (m)	0.030	0.014	0.026	0.010	0.026	0.011
$\lvert\mathbf{v}-\mathbf{v}_{\text{ref}}\rvert$ (mm/s)	1.208	0.007	0.694	0.253	0.661	0.325
$\lvert\mathbf{a}_{\text{cmp}}\rvert$ (mm/s^2)	0.430	0.208	0.332	0.160	0.326	0.164
ΔV (m/s)	8.326	0.965	8.714	0.831	7.989	0.830
MC failures (%)	0.00 ☺		0.00 ☺		0.00 ☺	

- Accounting for RT1 only enough for the design of a compensator able to cope with other trajectories

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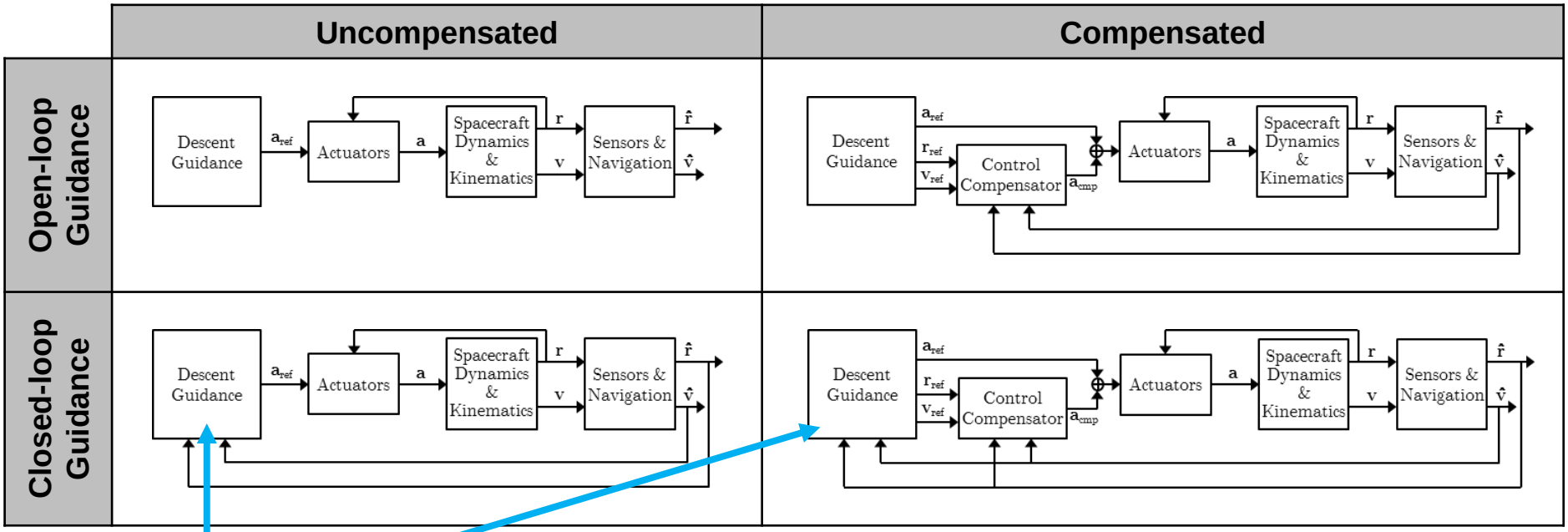
Application to Guidance Tuning

Parametric closed-loop guidance



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

$$\mathbf{a}(t) = \begin{bmatrix} k_r & k_v \end{bmatrix} \begin{bmatrix} \dfrac{\mathbf{ZEM}(t)}{t_{\mathrm{go}}^2(t)} \\ \\ \dfrac{\mathbf{ZEV}(t)}{t_{\mathrm{go}}(t)} \end{bmatrix} - \phi\, \mathbf{f}\left(\mathbf{ZEM}(t), \mathbf{ZEV}(t), t_{\mathrm{go}}(t)\right)$$

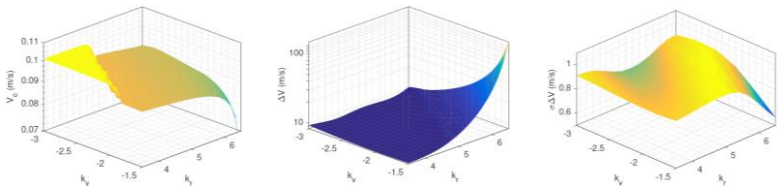
- Optional nonlinear function $\mathbf{f}(\cdot)$ of feedback variables, weighted by ϕ
- State-of-practice gains $\{6, -2\}$ derived analytically for $\{k_r, k_v\}$ assuming simplified and well-known gravitational fields **Does not hold for Phobos**

Application to Guidance Tuning

Tuning results

Tuning via systematic simulation

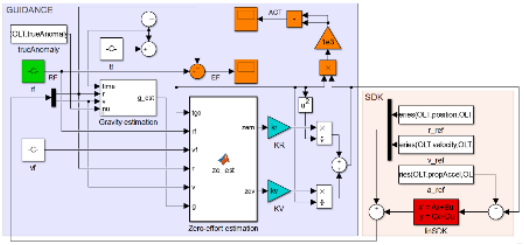
Generation of trade-off maps using nominal & dispersed touchdown performance indicators



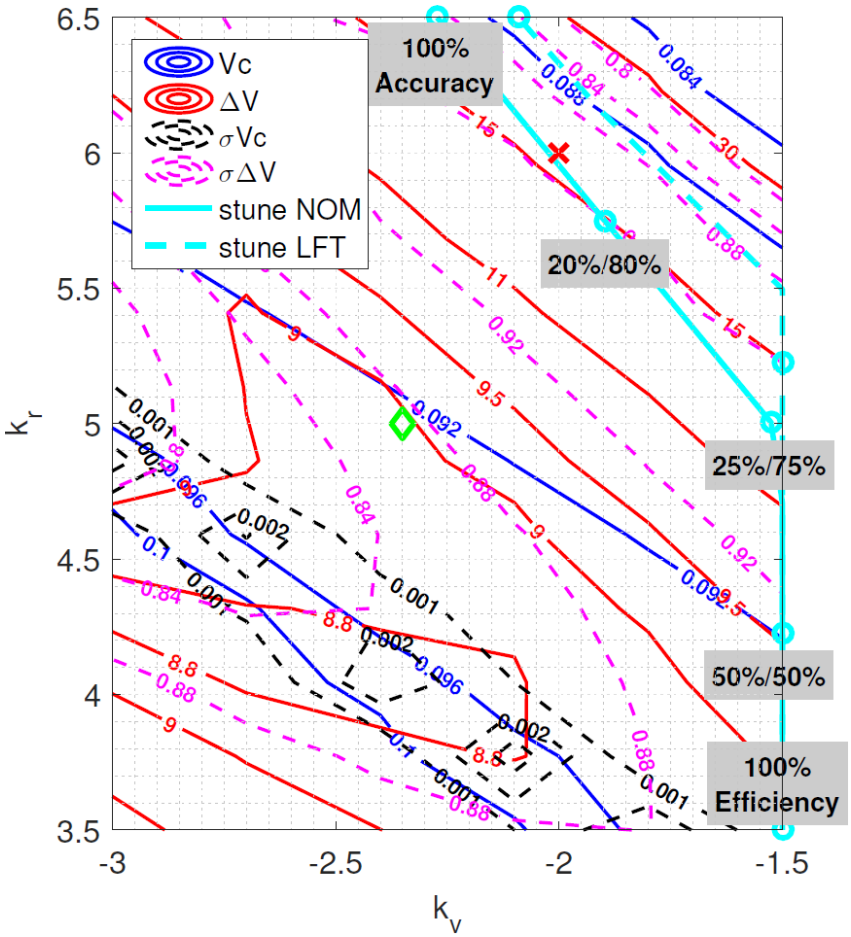
- Trade-off maps able to identify improved guidance solutions

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



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

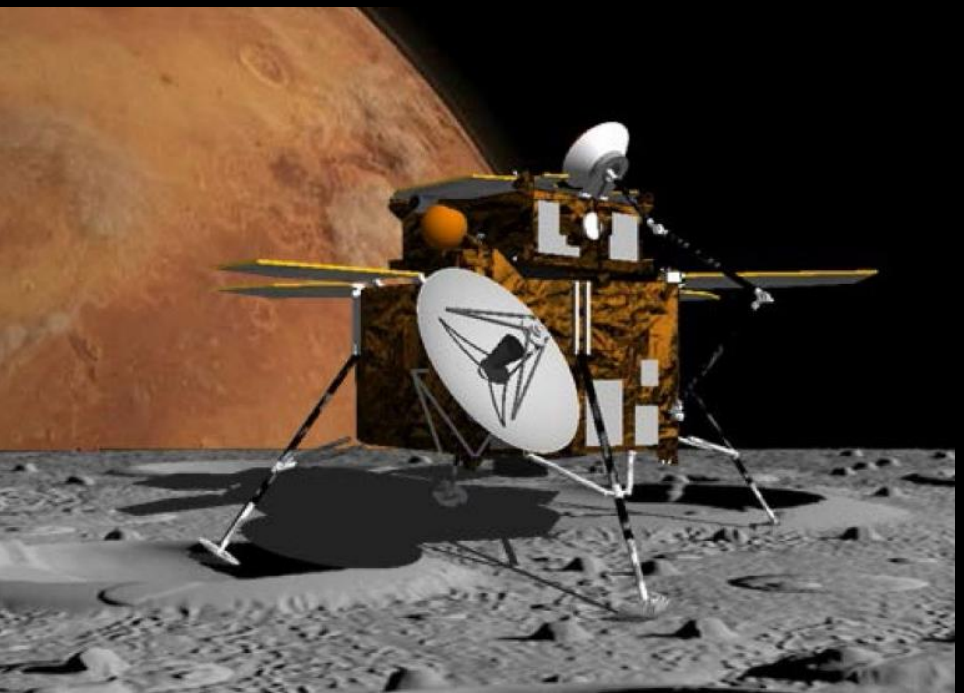
Conclusions

- 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 μ analysis can be used to validate modelling choices and complement Monte-Carlo campaigns
  - **Reconciliation 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



Pedro Simplício
Andrés Marcos
www.tasc-group.com
Technology for AeroSpace Control (TASC)
Aerospace Engineering Department
University of Bristol, U.K.