Control/Structure Co-Design for Planetary Spacecraft with Large Flexible Appendages

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Final Presentation

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DEFENCE AND SPACE

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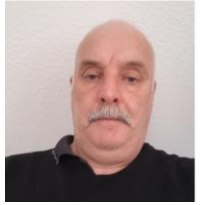
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Agenda

- Study context and concluded summary (5’)
- Co-design introduction (10’)
- Approach, modelling & optimisation methods trade-off (5’)
- Implementation (20’)
- Results (20’)
- Validation & verification (10’)
- Conclusions, summary and further work (10’)
- Open discussion & questions (30’)

Study context & concluded summary (5’)

Co-design introduction

Approach, modelling & optimisation methods trade-off

Implementation

Results

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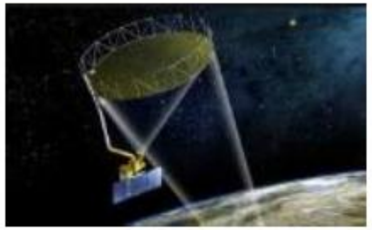
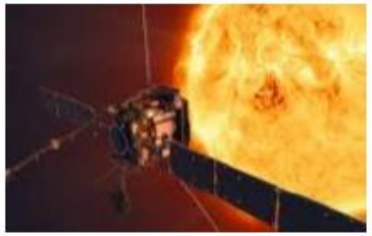
Conclusions, summary and further work

Open discussion & questions

Study Motivation

- **High precision pointing control design for flexible spacecraft with large appendages** is a challenging problem in multiple missions
- Traditional approaches in GNC design and structure design with teams working separately results in **conservative designs** with significant **mass penalties**
- This study pursues to define an integrated design approach between the GNC and structures process (**structure and control co-design)** towards a more optimal solution

Mission	Mission Challenge	Mission Animation
Biomass	The large reflector becomes a challenge through the whole mission. Particular challenges for deployment and observations in nominal mode.	
Solar Orbiter	Among the flexible appendages can be found the Solar Arrays, Boom and High Gain Antenna. Particular challenge for performance during science operations and safe mode design compatible with critical Sun illumination constraints.	
Juice	The larger solar arrays ever manufactured in Europe become a constraint for science operations and tranquilization after main engine boost manoeuvres.	

Study Objectives

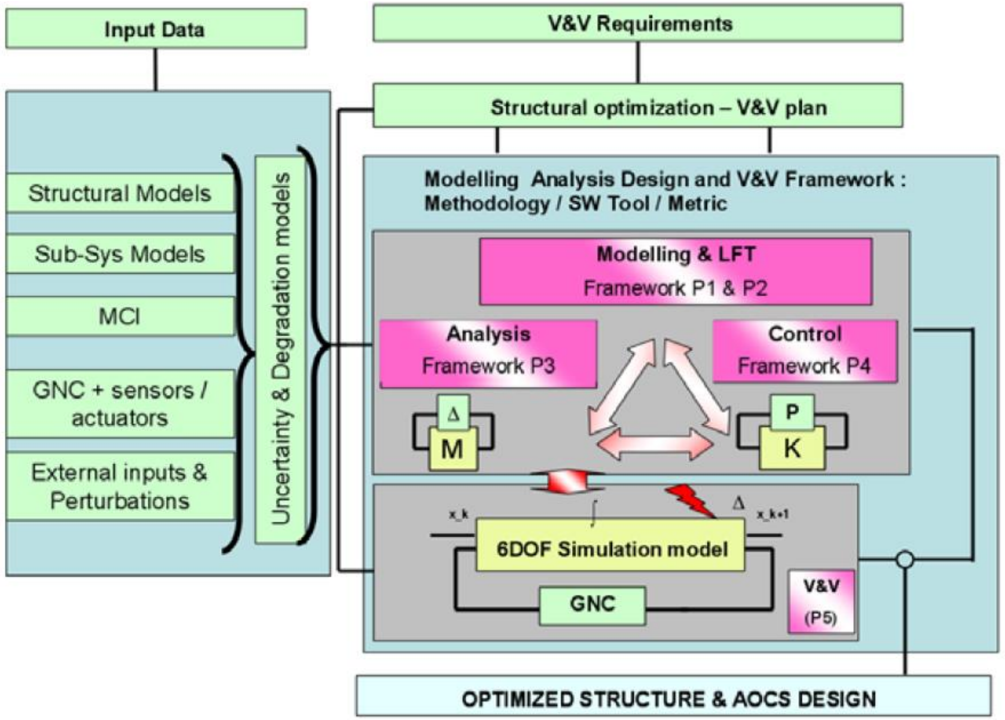
- **Derive a non-conservative control budget with optimized structural properties** for a selected science satellite concept, using an integrated control-structures approach

- **A clear methodology** for the integrated structural modelling of satellite dynamics with attitude control design

- **A modelling, design and verification process** that allows to size and trade-off in a multi-disciplinary fashion:
  - structural configuration of science satellites
  - optimal and robust GNC control tuning

- Benchmark against the classical control design solution

- Useable for a wider class of spacecraft



Study Concluded Summary

- A GNC design cycle was performed using an **integrated control-structures co-design** using a science spacecraft as a study case

- **Simultaneous optimisation** of the controller and key structural parameters was performed to find a solution with **minimal spacecraft mass** whilst simultaneously meeting the **AOCS requirements**

Control and Structure Co-Design method	Total Mass reduction
Direct co-design	42 Kg
Iterative co-design	41 Kg to 60 Kg

- A **generic framework** for integrated modelling, design and verification was developed which can be applied to a wider class of missions

- **Areas for further development** have been identified

Study context & concluded summary

Co-design Introduction (10’)

Approach, modelling & optimisation methods trade-off

Implementation

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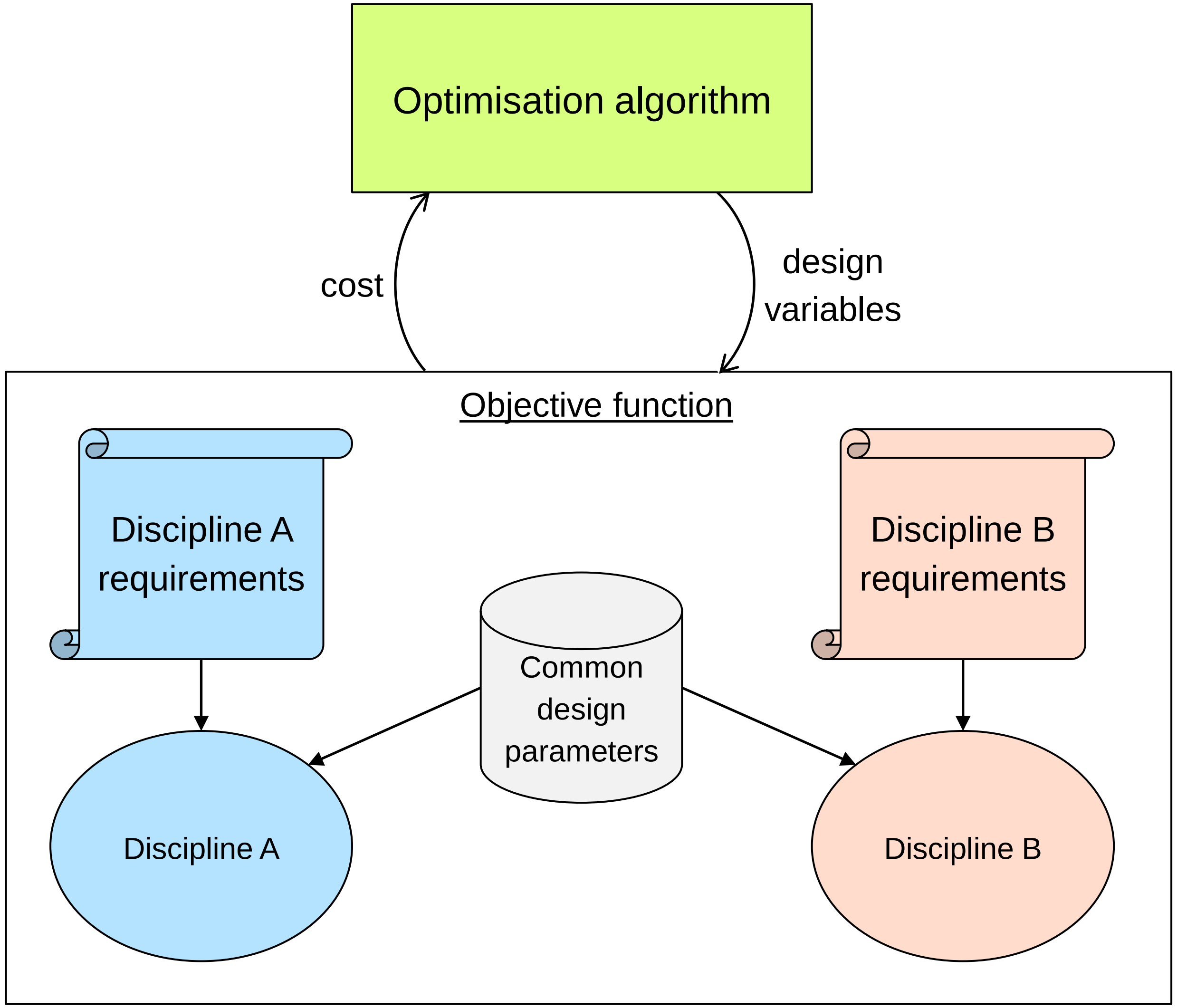
Open discussion & questions

Co-design Philosophy

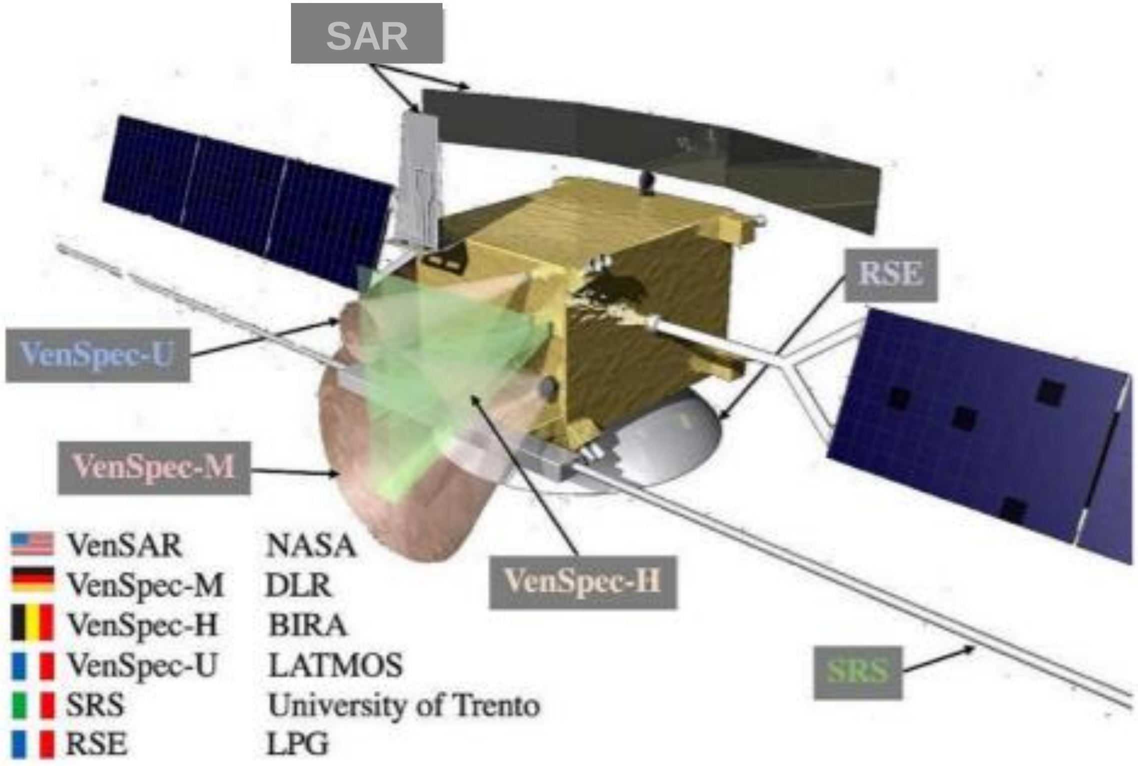
- Generally, the optimization objectives in **different disciplines** are conflicting and the classical sequential approach commonly adopted by industry can **fail** to efficiently find global optimal solutions
  - For example, a frequency separation between control bandwidth and flexible modes is typically enforced a priori, which may leave significant room for performance improvement
- Co-design involves **simultaneously optimising multiple distinct disciplines**
  - In this study, the disciplines are control (**AOCS**) and **structures**
- Co-design is a Multidisciplinary Design Optimization (**MDO**)
- **Two types** of MDO architecture:
  - **Monolithic**: a **single** multi-disciplinary optimisation problem is solved → 'direct co-design'
  - **Distributed**: problem is partitioned into multiple sub-problems containing **smaller subsets** of the variables and constraints → 'iterative co-design'

Example of a monolithic MDO



Baseline Mission: EnVision

- EnVision is a Venus orbiter mission that will determine the nature and current state of **Venus' geological evolution** and its relationship with the atmosphere
- The EnVision mission was chosen due to its **fine pointing** requirements and its number of large **flexible appendages**:
  - **Synthetic Aperture Radar** antenna (SAR)
  - **SRS**: two very long, thin flexible booms
  - Large flexible **solar arrays**



🇺🇸	VenSAR	NASA
🇩🇪	VenSpec-M	DLR
🇧🇪	VenSpec-H	BIRA
🇫🇷	VenSpec-U	LATMOS
🇮🇹	SRS	University of Trento
🇫🇷	RSE	LPG

Co-design Metrics

- Metrics were defined based on the existing EnVision **system requirements**
- Metrics split between those assessed in the **linear** domain and in the **non-linear** simulation domain

Linear analysis metrics

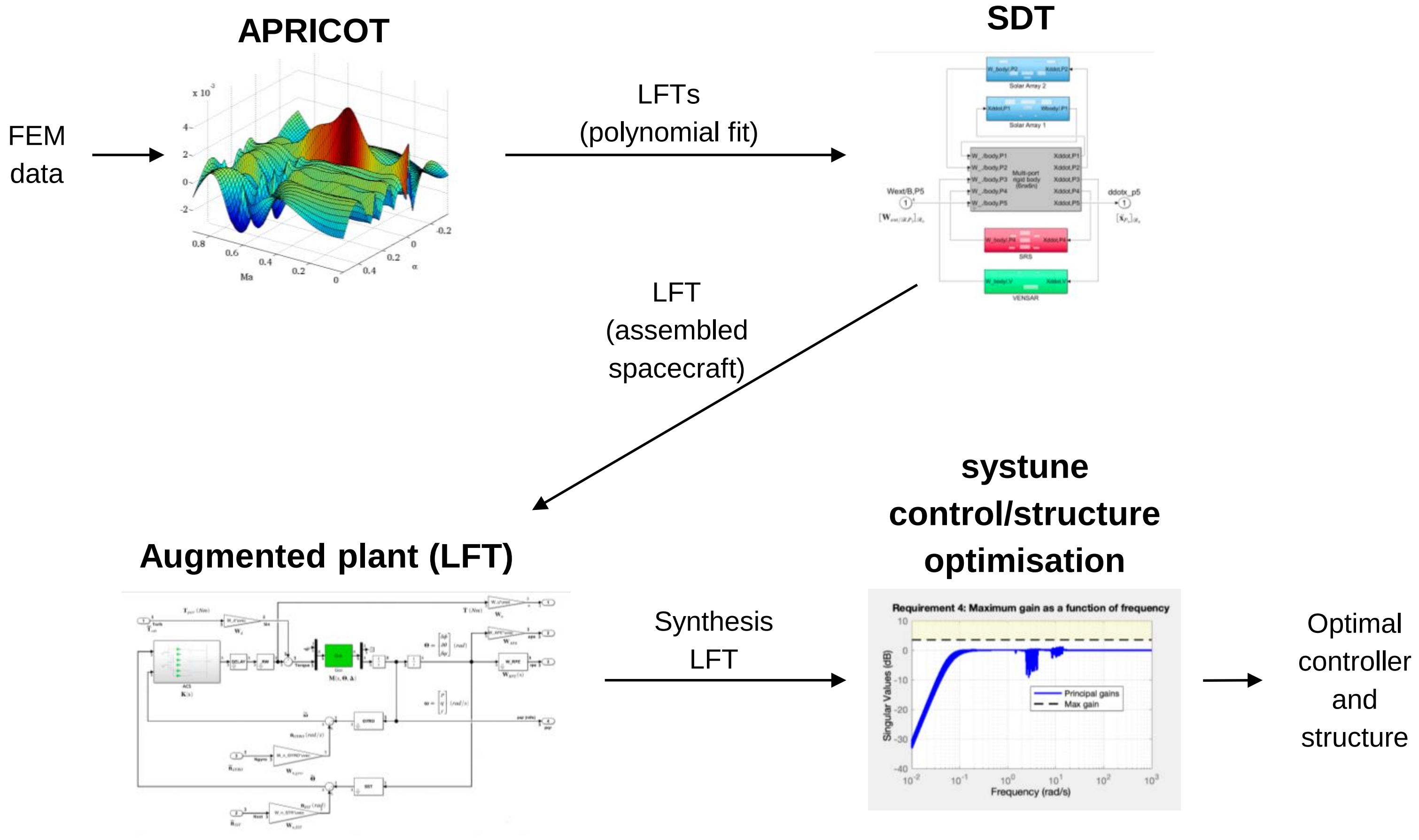
Metric	Description
lin_mu_RS	Structured singular value upper bound for stability
lin_wcg_T_2_APE	Worst case gain from disturbance torques to attitude Absolute Performance Error
lin_wcg_sens_2_APE	Worst case gain from sensor noise to attitude Absolute Performance Error
lin_wcg_T_2_AKE	Worst case gain from disturbance torques to attitude Absolute Knowledge Error
lin_wcg_sens_2_AKE	Worst case gain from sensor noise to attitude Absolute Knowledge Error
lin_wcg_T_2_RPE_15	Worst case gain from disturbance torques to attitude Relative Performance Error with 15 s window
lin_wcg_sens_2_RPE_15	Worst case gain from sensor noise to attitude Relative Performance Error with 15 s window
lin_wcg_T_2_RPE_60	Worst case gain from disturbance torques to attitude Relative Performance Error with 60 s window
lin_wcg_sens_2_RPE_60	Worst case gain from sensor noise to attitude Relative Performance Error with 60 s window
lin_wcg_T_2_RPE_1000	Worst case gain from disturbance torques to attitude Relative Performance Error with 1000 s window
wcg_d_sens_2_RPE_1000	Worst case gain from sensor noise to attitude Relative Performance Error with 1000 s window
lin_wcg_T_2_RPE_120	Worst case gain from disturbance torques to attitude Relative Performance Error with 120 s window
lin_wcg_sens_2_RPE_120	Worst case gain from sensor noise to attitude Relative Performance Error with 120 s window
lin_H2_sens_2_T	Worst case H2 norm from sensor noise to commanded torque
lin_BW_cl	Closed loop bandwidth

Non-linear simulation analysis metrics

Metric	Description
sim_APE	APE value greater than 95% of the samples in a simulation
sim_AKE	AKE value greater than 95% of the samples in a simulation
sim_RPE_15	RPE with window 15 s greater than 95% of the samples in a simulation
sim_RPE_60	RPE with window 60 s greater than 95% of the samples in a simulation
sim_RPE_120	RPE with window 120 s greater than 95% of the samples in a simulation
sim_RPE_1000	RPE with window 1000 s greater than 99.7% of the samples in a simulation
sim_max_T	Maximum commanded torque in simulation
sim_std_T	Standard deviation of commanded torque in simulation
sim_t_slew	40 degree slew duration
sim_t_wol_tranq	Tranquilisation time after reaction wheel offloading

Co-design Implementation Summary: Direct Co-Design

- The **direct co-design** involves **optimising** the controller gains and structural design parameters **simultaneously** (monolithic MDO) via systune
- Linear Fractional Transform (LFT) used by MATLAB systune contains:
  - Optimisable parameters: **controller gains**
  - Optimisable parameters: **structural parameters**
  - System **uncertainties**
- **APRICOT** tool used in generation of LFT creates a **polynomial fit** from a number of FEM per appendage
  - Fitted LFT of flexible appendages **assembled** into full spacecraft LFT via SDT tool



FEM data

APRICOT

LFTs (polynomial fit)

SDT

LFT (assembled spacecraft)

Augmented plant (LFT)

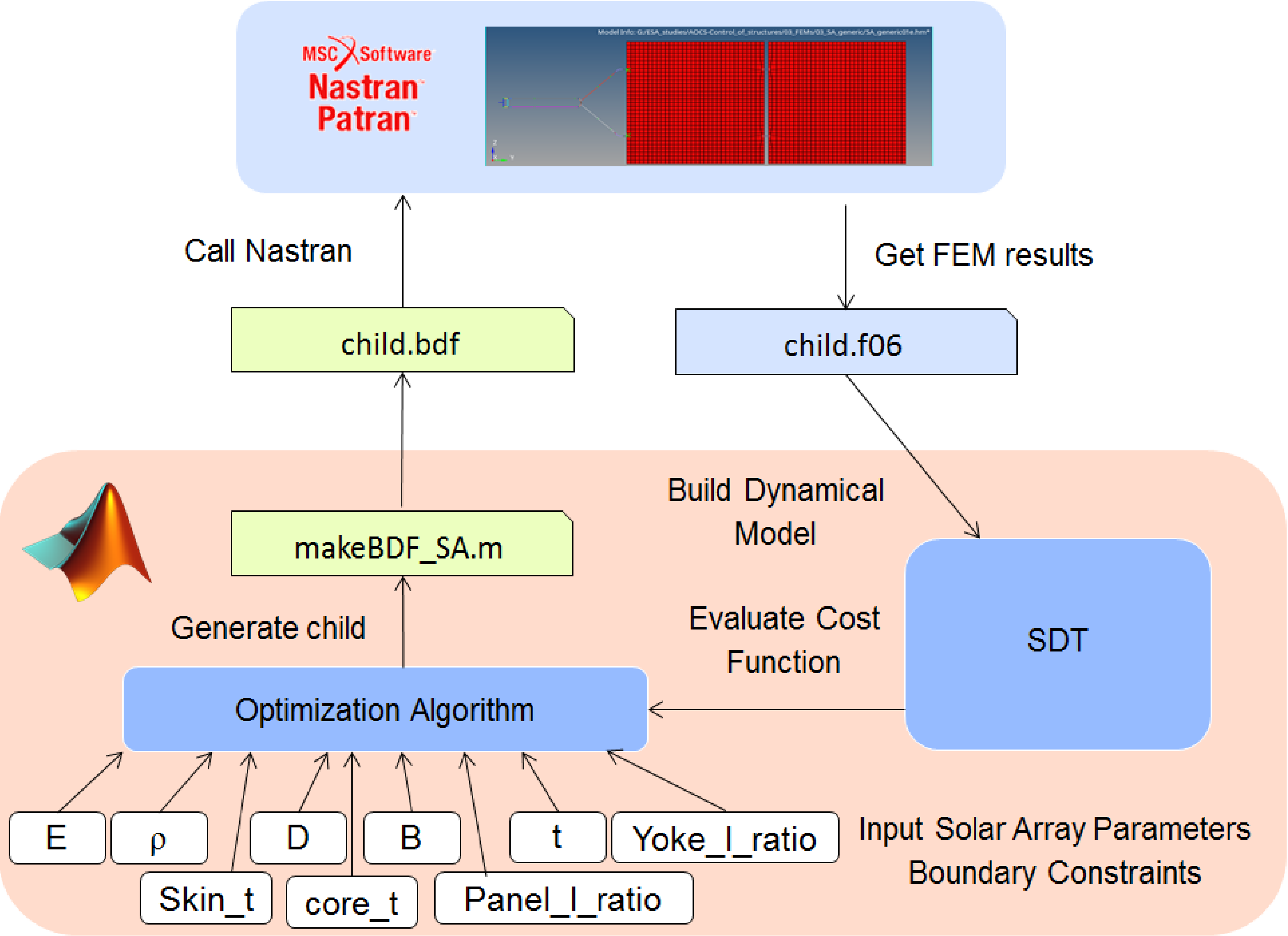
Synthesis LFT

systune control/structure optimisation

Optimal controller and structure

Co-design Implementation Summary: Iterative Co-Design

- The **iterative co-design** uses two nested optimisation loops:
  - Outer **<u>global</u> optimisation** loop (e.g. particle swarm) to optimise the structural parameters
  - Inner **<u>systune</u> optimisation** for the robust controller synthesis
- Rather than using the polynomial fitted LFT from APRICOT, iterative co-design runs **NASTRAN** at each iteration of the outer global optimisation loop
- NASTRAN run performed during each optimisation cost function evaluation → provides **M, C, K matrices** required for SDT to assemble the **full spacecraft plant** LFT with uncertainties



MSC Software Nastran Patran

Call Nastran

Get FEM results

child.bdf

child.f06

Build Dynamical Model

makeBDF_SA.m

SDT

Generate child

Evaluate Cost Function

Optimization Algorithm

E

ρ

D

B

t

Yoke_l_ratio

Skin_t

core_t

Panel_l_ratio

Input Solar Array Parameters Boundary Constraints

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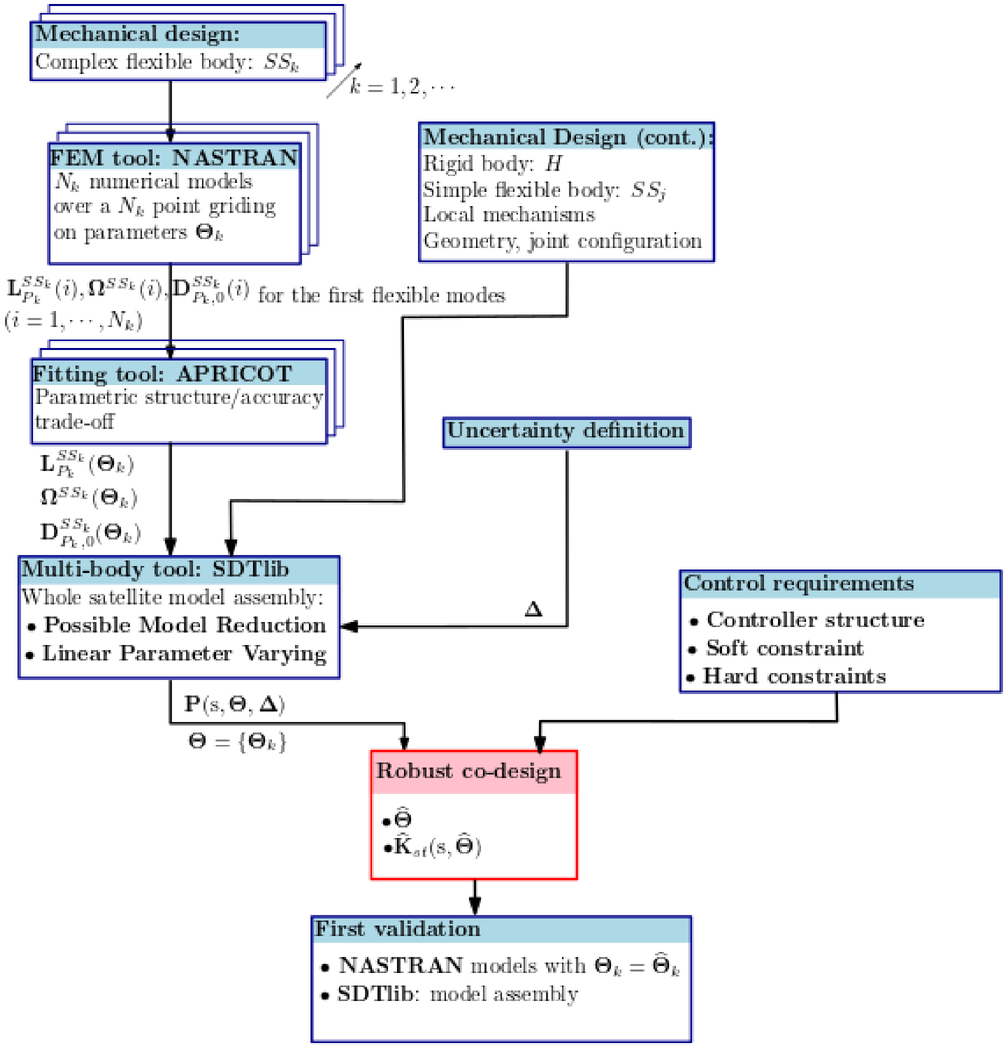
Physical (FEM) vs Analytical Modelling Methods Trade-off

Modelling Problem	Adapted Modelling Solution	Adapted Tool
Need of detailed description of the sub-structure or particular properties of the materials (such as the anisotropy of sandwich solar panels) are considered as design parameters of the co-design process	Finite Element (FE)	Interface Simulink/NASTRAN available in SDTlib
Take into account simple mechanical properties, like the length or the cross-section properties of a homogenous beam, or it is possible to easily replace non-isotropic material properties with equivalent isotropic analytical models of beams and plates	Analytical	Set of analytical models available in SDTlib: beams, plates, mechanisms (joints, reaction wheels, solar array drive mechanisms, etc.), simplified dynamics (sloshing effects)
Modelling of parametric uncertainties	Analytical	In all STDlib features, parametric uncertainties can be taken into account (included models obtained by FEM sub-systems) in order to build minimal Linear Fractional Representation (LFR) models
Simulation of non-linear rigid dynamics	Non-causal approaches	Simscape allows multi-physical modelling. Time simulation is appreciable when rigid dynamics is considered
Simulation of linear time invariant (LTI) or Linear parameter-varying (LPV) flexible dynamics	FE/Analytical	Linearization of SDTlib model in form of LTI/LPV systems

Optimization Methods – Direct vs Iterative

DIRECT



Mechanical design:
Complex flexible body: SS_k

$k = 1, 2, \cdots$

FEM tool: NASTRAN
N_k numerical models
over a N_k point griding
on parameters $\mathbf{\Theta}_k$

Mechanical Design (cont.):
Rigid body: H
Simple flexible body: SS_j
Local mechanisms
Geometry, joint configuration

$\mathbf{L}^{SS_k}_{P_k}(i), \mathbf{\Omega}^{SS_k}(i), \mathbf{D}^{SS_k}_{P_k,0}(i)$ for the first flexible modes
$(i = 1, \cdots, N_k)$

Fitting tool: APRICOT
Parametric structure/accuracy
trade-off

$\mathbf{L}^{SS_k}_{P_k}(\mathbf{\Theta}_k)$
$\mathbf{\Omega}^{SS_k}(\mathbf{\Theta}_k)$
$\mathbf{D}^{SS_k}_{P_k,0}(\mathbf{\Theta}_k)$

Uncertainty definition

$\mathbf{\Delta}$

Multi-body tool: SDTlib
Whole satellite model assembly:
- **Possible Model Reduction**
- **Linear Parameter Varying**

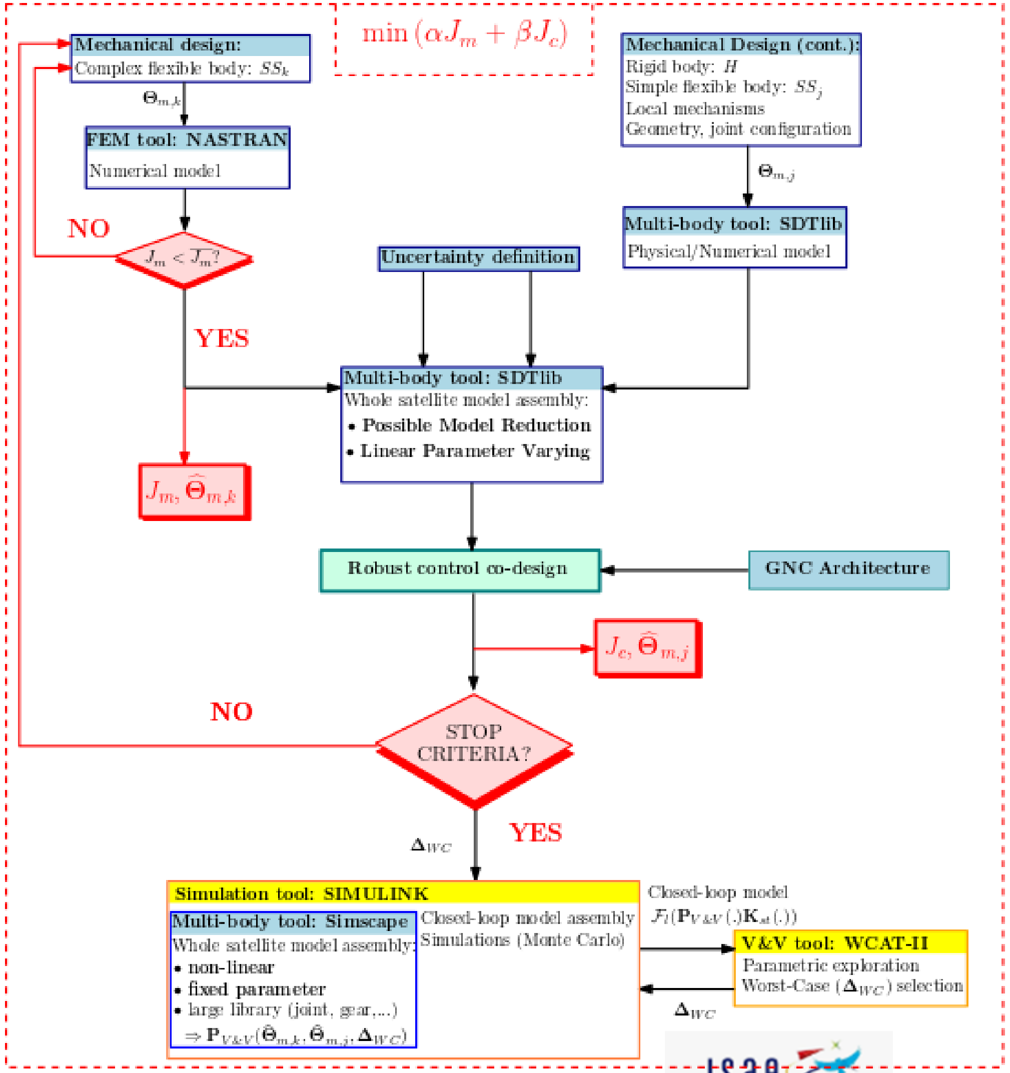
Control requirements
- **Controller structure**
- **Soft constraint**
- **Hard constraints**

$\mathbf{P}(s, \mathbf{\Theta}, \mathbf{\Delta})$
$\mathbf{\Theta} = \{\mathbf{\Theta}_k\}$

Robust co-design
- $\widehat{\mathbf{\Theta}}$
- $\widehat{\mathbf{K}}_{st}(s, \widehat{\mathbf{\Theta}})$

First validation
- **NASTRAN** models with $\mathbf{\Theta}_k = \widehat{\mathbf{\Theta}}_k$
- **SDTlib**: model assembly

ITERATIVE



$\min\left(\alpha J_m + \beta J_c\right)$

Mechanical design:
Complex flexible body: SS_k

$\mathbf{\Theta}_{m,k}$

FEM tool: NASTRAN
Numerical model

NO

$J_m < \bar{J}_m$?

YES

$J_m, \widehat{\mathbf{\Theta}}_{m,k}$

Mechanical Design (cont.):
Rigid body: H
Simple flexible body: SS_j
Local mechanisms
Geometry, joint configuration

$\mathbf{\Theta}_{m,j}$

Multi-body tool: SDTlib
Physical/Numerical model

Uncertainty definition

Multi-body tool: SDTlib
Whole satellite model assembly:
- **Possible Model Reduction**
- **Linear Parameter Varying**

Robust control co-design

GNC Architecture

$J_c, \widehat{\mathbf{\Theta}}_{m,j}$

NO

STOP
CRITERIA?

YES

$\mathbf{\Delta}_{WC}$

Simulation tool: SIMULINK

Multi-body tool: Simscape
Whole satellite model assembly:
- **non-linear**
- **fixed parameter**
- large library (joint, gear,...)

$\Rightarrow \mathbf{P}_{V\&V}(\widehat{\mathbf{\Theta}}_{m,k}, \widehat{\mathbf{\Theta}}_{m,j}, \mathbf{\Delta}_{WC})$

Closed-loop model assembly
Simulations (Monte Carlo)

Closed-loop model
$\mathcal{F}_l(\mathbf{P}_{V\&V}(.)\mathbf{K}_{st}(.))$

V&V tool: WCAT-II
Parametric exploration
Worst-Case ($\mathbf{\Delta}_{WC}$) selection

$\mathbf{\Delta}_{WC}$

Optimization Methods Trade-off

	PRO	CONS
Direct Co-Design	• Structure and Control design parameters at the same optimization level • "Fast" control re-design (only one control synthesis needed)	• Long preliminary generation of a family of models + APRICOT • Limited amount of design parameters (synthesis/analysis algorithms sensitivity to number of uncertain repetitions)
Iterative Co-Design	• Large number of structure design parameters possible • Higher possibility to not fall into local optimal solutions	• Structure and Control design parameters not at the same optimization level • Not fast control re-design (n control design needed)

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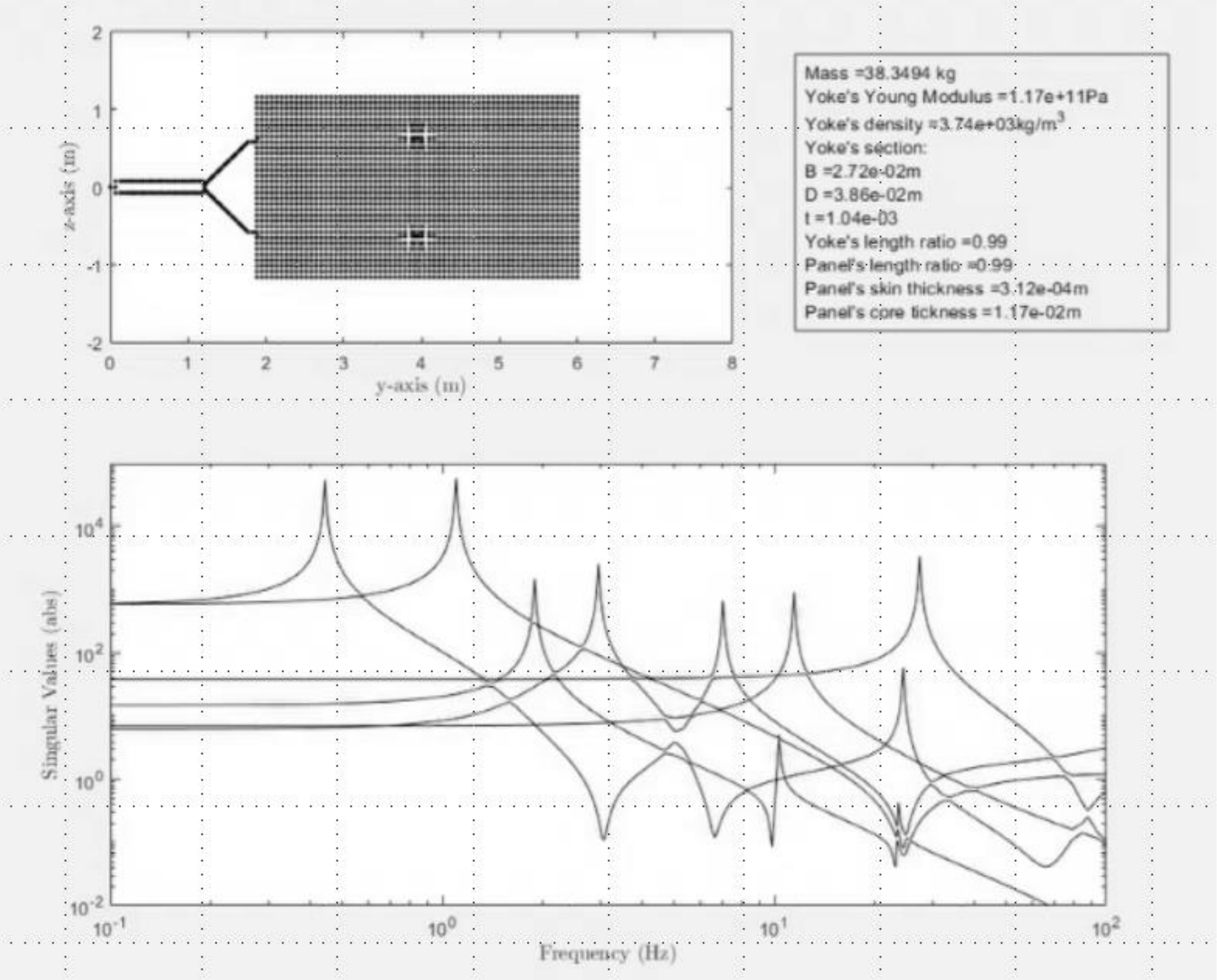
Preliminary Implementation: Building Blocks & Cross-Validation

- **Analytical Modelling**
  - Cross-validation between SDTlib and Simscape:
    - Beams, joints, local stiffness, rigid bodies, mechanisms (RW)
  - Expertise gained on Simscape/Multibody

- **Physical Modelling of complex structures**
  - Checking of NASTRAN/SDTlib interface
  - NASTRAN/Simscape interface
  - Expertise gained in Reduced Order Flexible Solid (ROFS) block
  - Cross-Validation NASTRAN/SDTlib/Simscape

- **Uncertainty Modelling**
  - Inclusion of parametric uncertainties in SDTlib models
  - Building of a family of possible plant with APRICOT

SDTlib/NASTRAN Interface

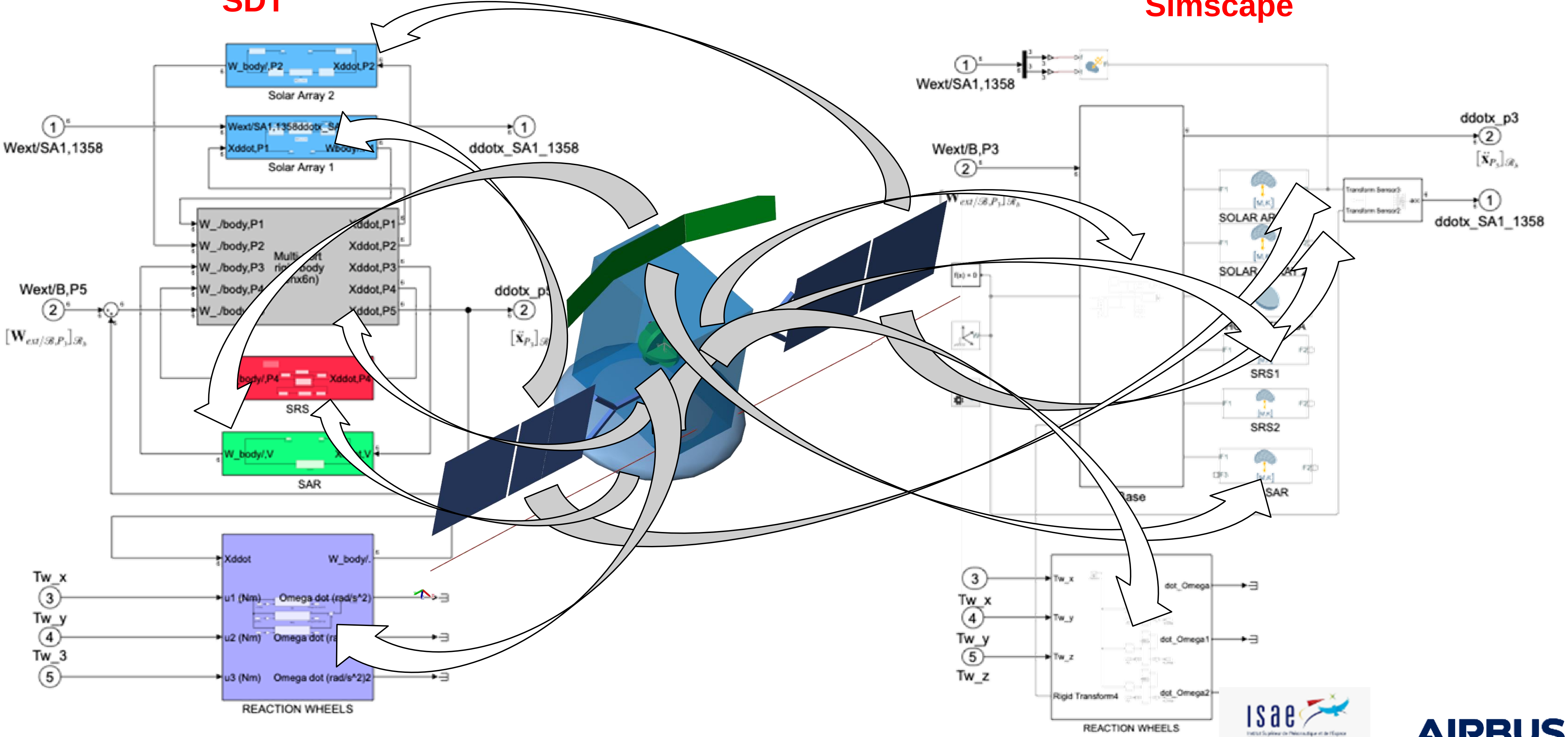


Mass =38.3494 kg
Yoke's Young Modulus =1.17e+11Pa
Yoke's density =3.74e+03kg/m^3
Yoke's section:
B =2.72e-02m
D =3.86e-02m
t =1.04e-03
Yoke's length ratio =0.99
Panel's length ratio =0.99
Panel's skin thickness =3.12e-04m
Panel's core tickness =1.17e-02m

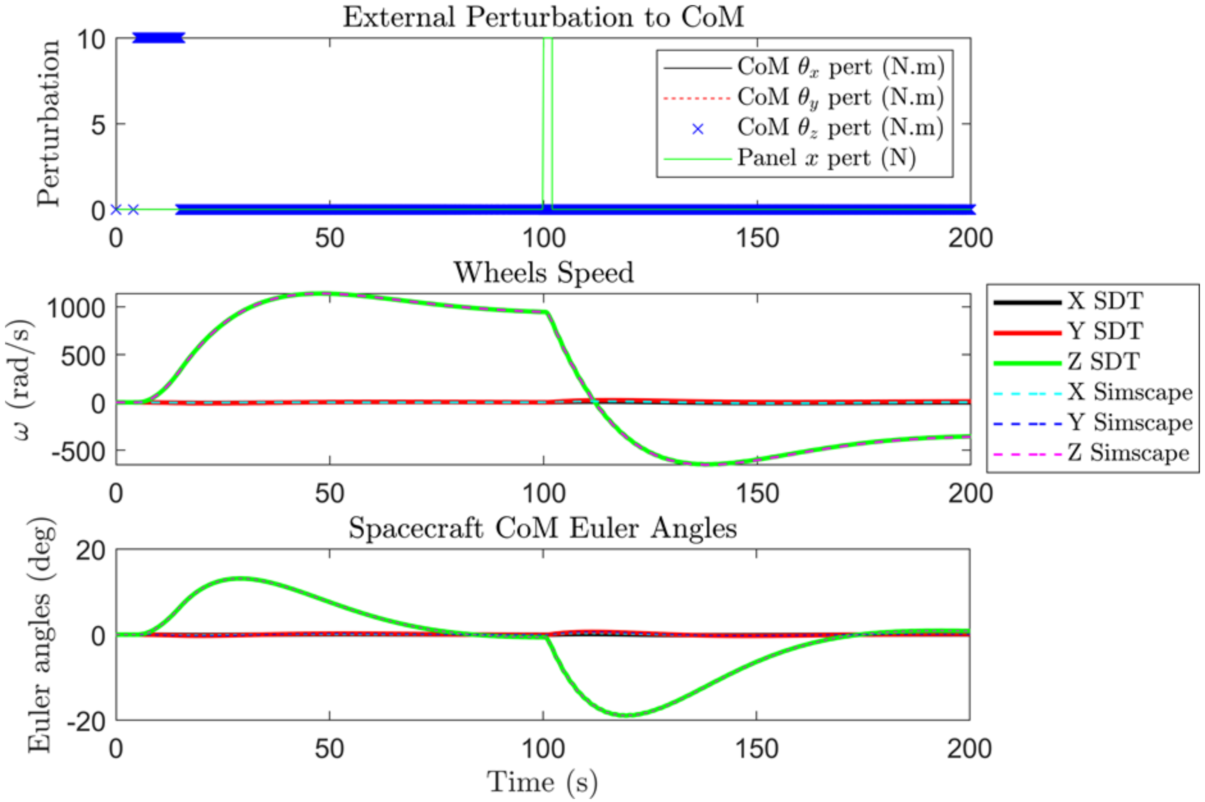
ENVISION BENCHMARK – SDTlib/Simscape Frequency domain Validation

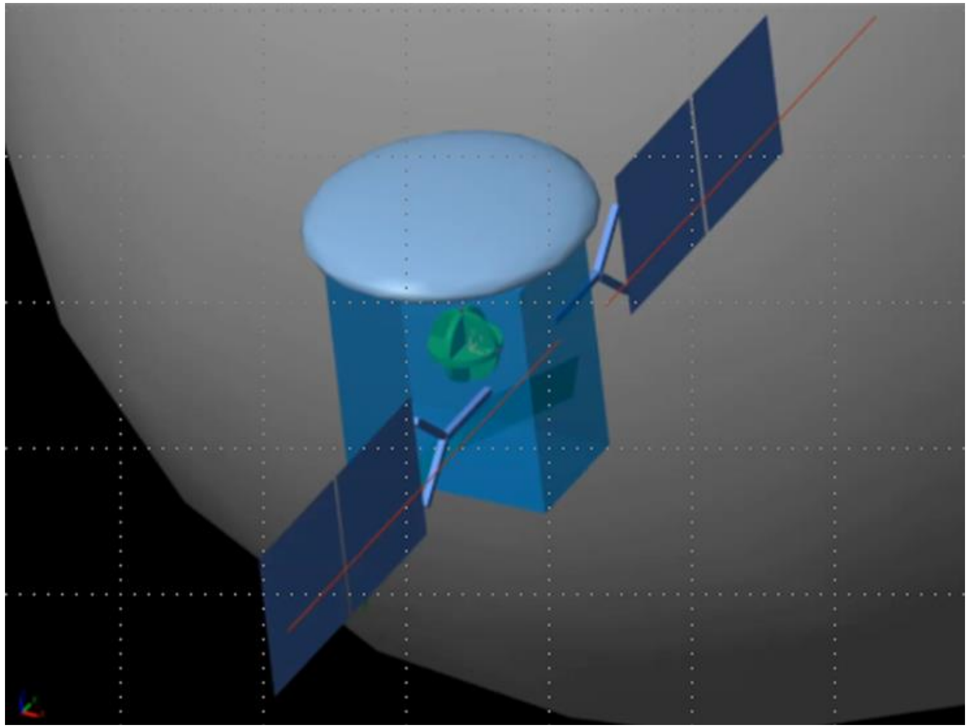
SDT

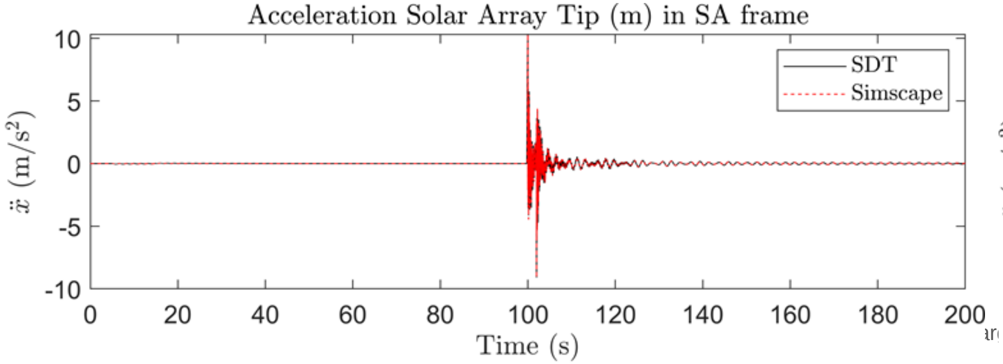
Simscape

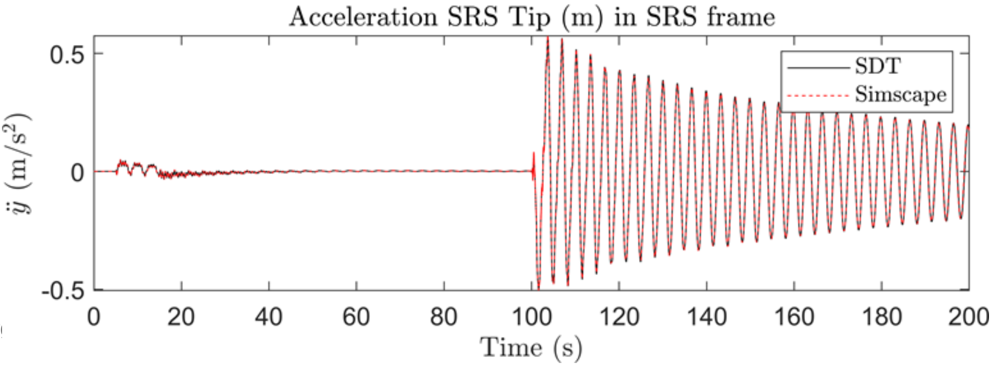


ENVISION BENCHMARK – SDTlib/Simscape Time domain Validation



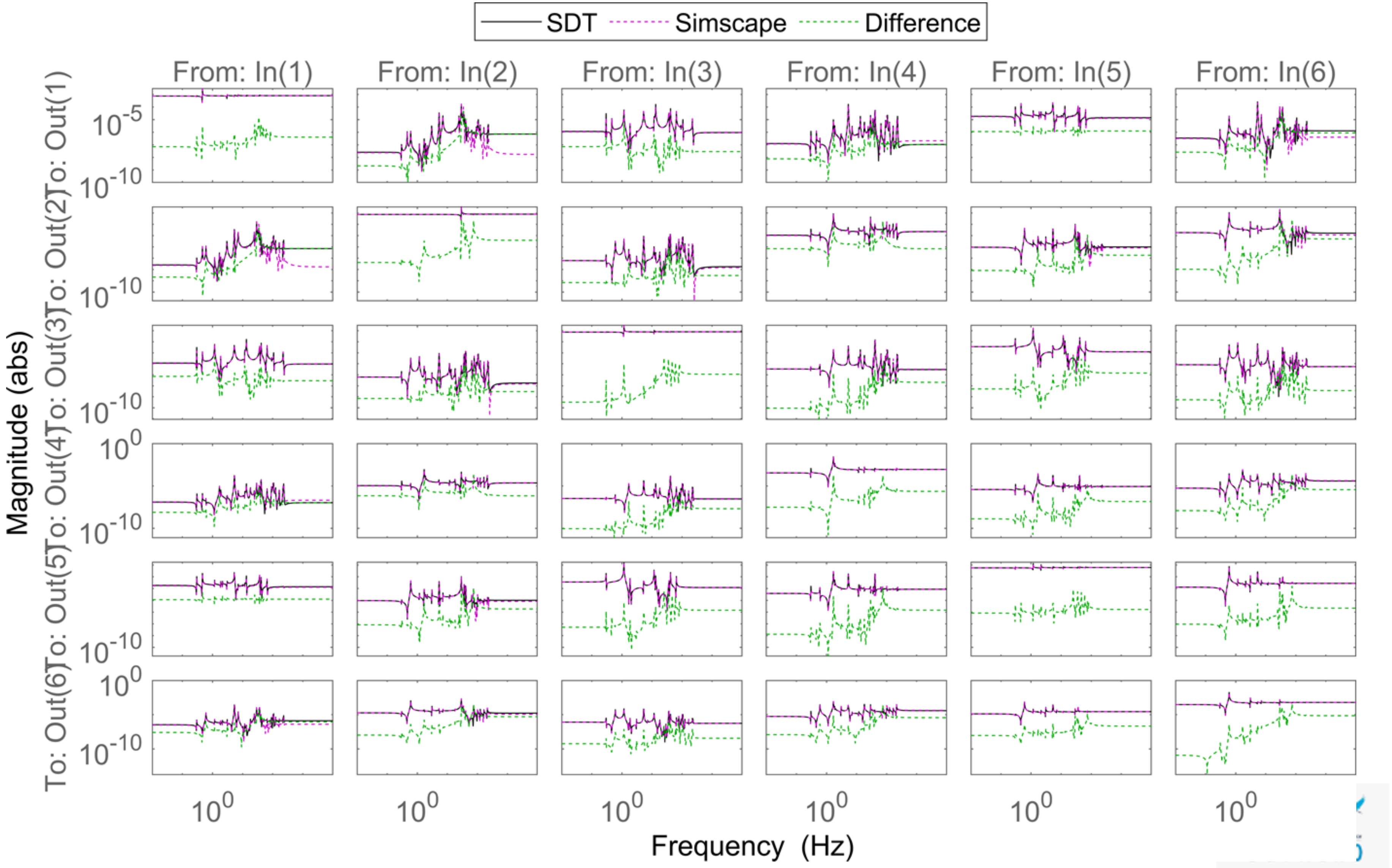






Simulation Time (s)	
Simscape	46.98
SDT	13.41

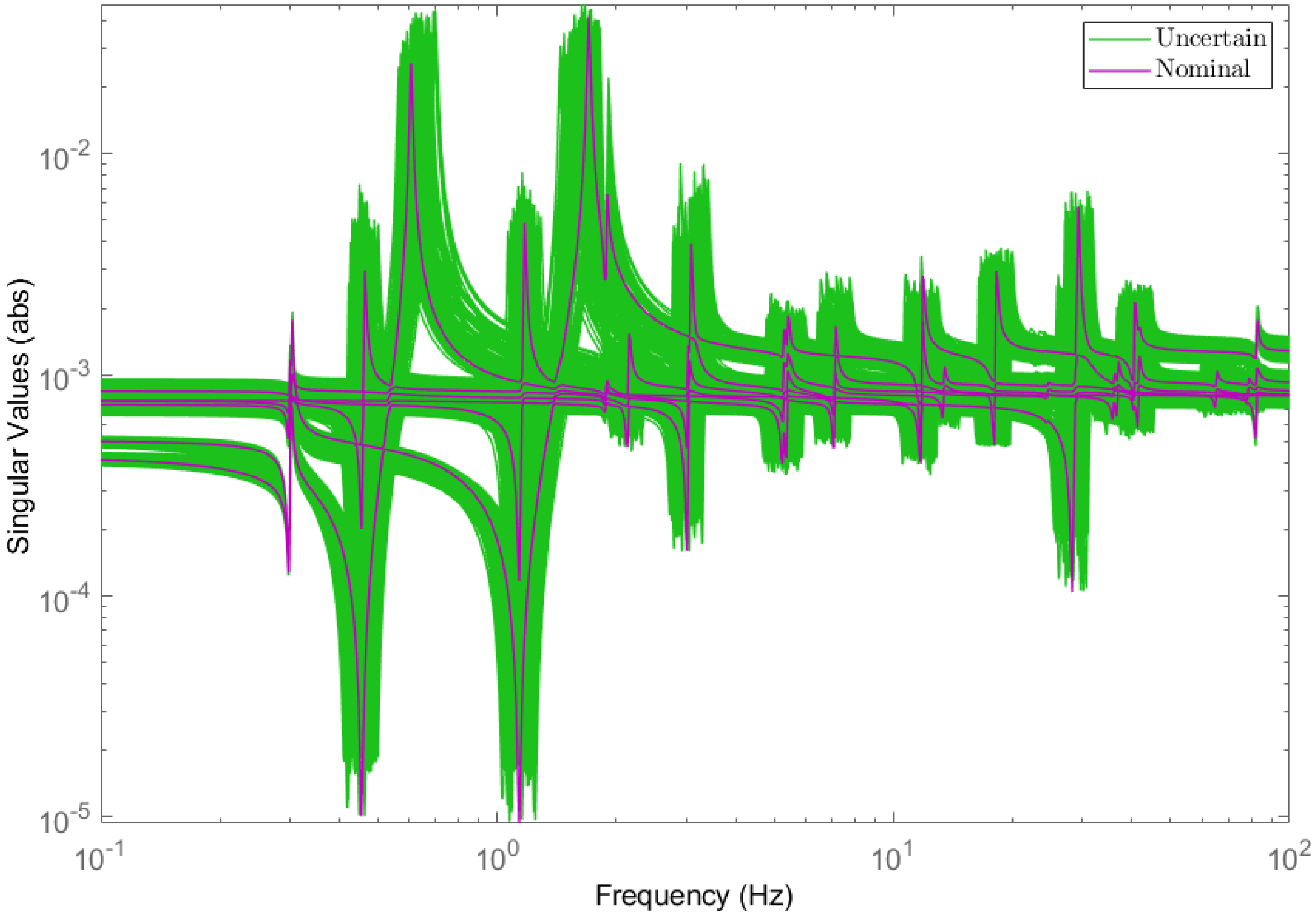
ENVISION BENCHMARK – SDTlib/Simscape Frequency domain Validation



ENVISION BENCHMARK – Uncertain Plant with SDTlib

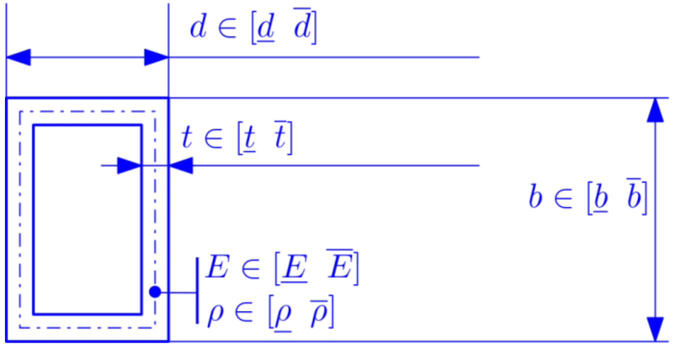
PLANT COMPLEXITY:

- 100 states
- 14 uncertain parameters
- 56 uncertainty repetitions



Implementation of the direct co-design: **FEM model parametric fitting with Apricot.**

Study case: 100 models of the solar panel with 10 flexible modes computed from Nastran on a grid randomly scattered in the varying parametric space $\mathfrak{D}_{\boldsymbol{\theta}}$ with $\boldsymbol{\theta} = [E \quad \rho \quad b \quad d \quad t]^T$ (yoke tunable parameters).



3 NASTRAN parameters ($\mathrm{diag}(\boldsymbol{\omega}), \mathbf{L}_P, \mathbf{D}_{P,0}$) to be approximated by an LFT in order to build the model with the SDTLIB.

Procedure:

- Harmonize the +- sign in the modal participation factor $\mathbf{L}_p$ provided by NASTRAN,
- Normalize the varying parameters: $\boldsymbol{\theta} \longrightarrow \tilde{\boldsymbol{\theta}}$
- Chose a polynomial structure with **physical sense** monomials:$\tilde{\rho}\tilde{d}\tilde{b}\tilde{t}$, $\tilde{E}\tilde{d}\tilde{t}^3, \tilde{E}\tilde{d}\tilde{b}^3$,… Thus a 5-th order polynomial with $\tilde{\rho}, \tilde{E}, \tilde{b}, \tilde{d}, \tilde{t}$ till order 1,1,3,3,3

	size	n_E	n_ρ	n_b	n_d	n_t	GRE
$\mathrm{diag}(\boldsymbol{\omega})$	10x10	10	20	120	90	30	$1.3\ 10^{-14}$
$\mathbf{L}_p$	10x6	10	20	104	54	18	$8.3\ 10^{-16}$
$\mathbf{D}_{p,0}$	6x6	32	64	327	189	63	$9.2\ 10^{-16}$
$\boldsymbol{D}_{P_1}^{A_1}(s, \bar{\boldsymbol{\theta}})$	6x6x20	72	144	775	477	159	??

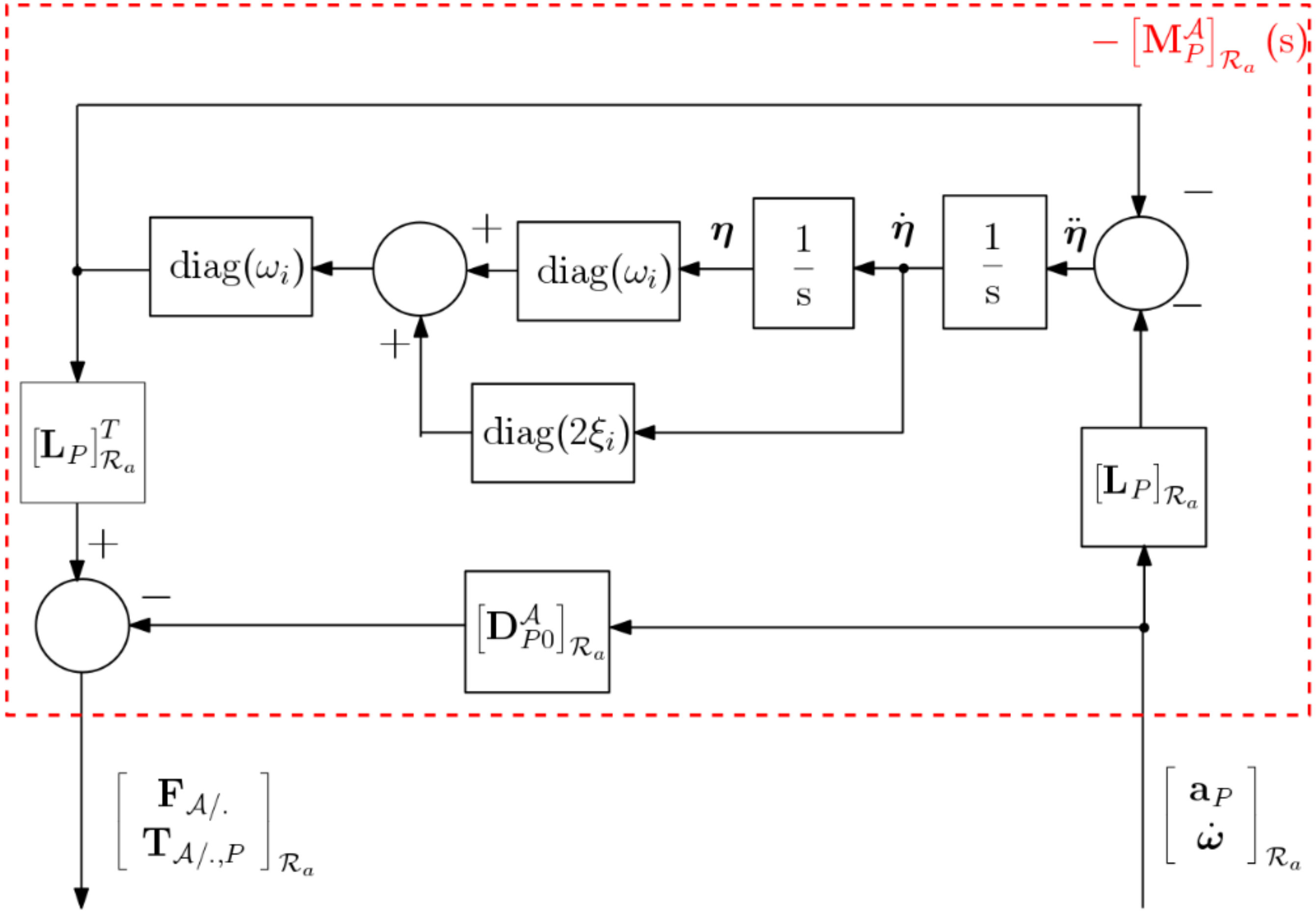
Implementation of the direct co-desi with Apricot.

Study case: 100 models of the solar panel with 10 flexible m
varying parametric space $\mathfrak{D}_{\boldsymbol{\theta}}$ with $\boldsymbol{\theta} = [E \quad \rho \quad b \quad d \quad t]^T$ (yoke

3 NASTRAN parameters $(\mathrm{diag}(\boldsymbol{\omega}), \mathbf{L}_P, \mathbf{D}_{P,0})$ to be approxima
the model with the SDTLIB. Ex: $\mathbf{L}_P(\boldsymbol{\theta}) = lft(\mathbf{M}, \mathrm{diag}(E\mathbf{I}_{n_E}, \rho\mathbf{I},$

Procedure:

- Harmonize the +- sign in the modal participation factor $\mathbf{L}_p$
- Normalize the varying parameters: $\boldsymbol{\theta} \longrightarrow \tilde{\boldsymbol{\theta}}$
- Chose a polynomial structure with **physical sense** monoi
  $\tilde{\rho}, \tilde{E}, \tilde{b}, \tilde{d}, \tilde{t}$ till order 1,1,3,3,3



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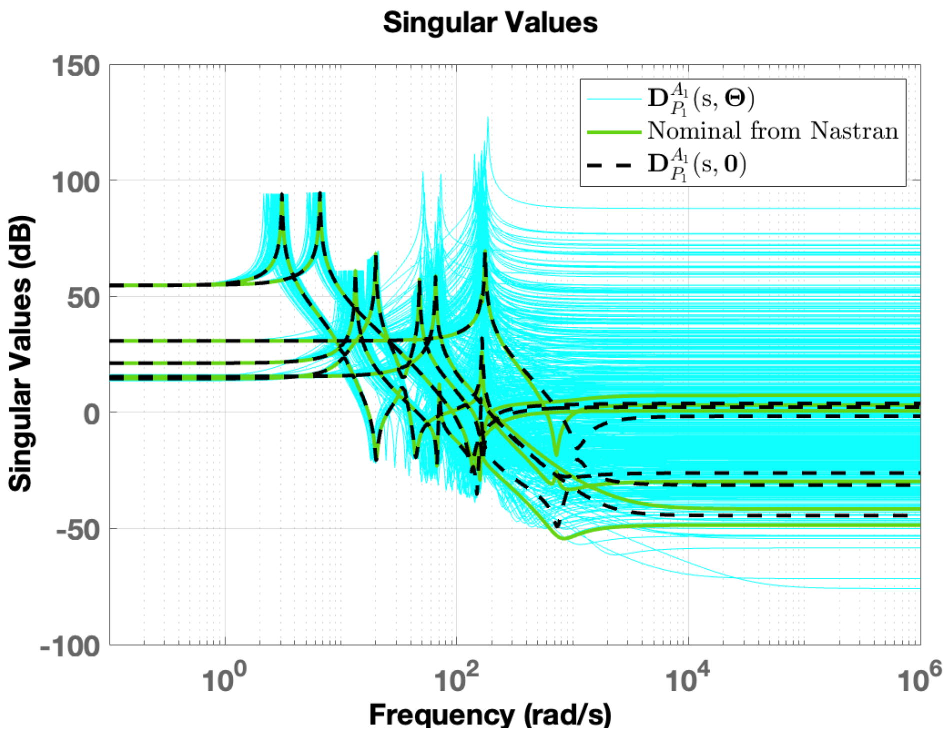
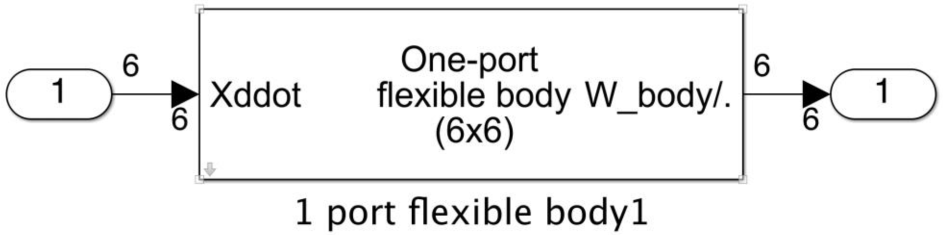
$\boldsymbol{D}_{P_1}^{A_1}(s, \overline{\boldsymbol{\theta}})$	6x6x20	72	144	775	477	159	??

AIRBUS

Implementation of the direct co-design: **FEM model parametric fitting with Apricot.**

- Validation of the approximated LFT model of the SA by the comparison of the nominal model provided by NASTRAN and $\boldsymbol{D}_{P_1}^{A_1}(s, \mathbf{0})$:





$$[\mathbf{D}_{P_1}^{\mathscr{A}_1}]_{\mathscr{R}_{a_1}}(s)$$

OK but a huge LFT !!

➔ Limitation for SYSTUNE and future μ- analyses.

➔ Need to work with:

- **less accurate LFT,**
- **lower number of tunable parameters,**
- **with a greater impact on the total mass.**

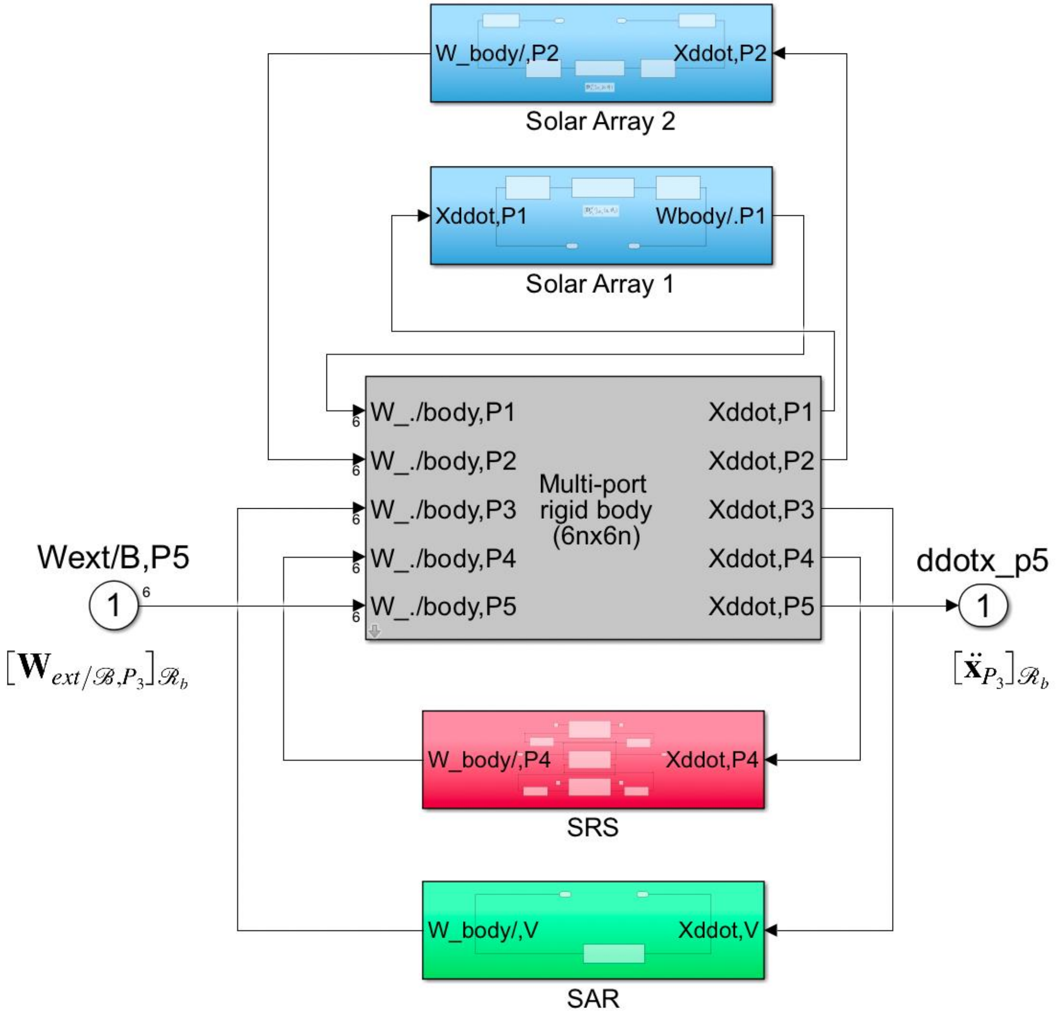
Implementation of the direct co-design: **Spacecraft assembly with the SDTlib**

The EnVision-based benchmark for co-design assessment considers:

- The main body (MB) with uncertainties on the mass (m_{MB}) and the 3 terms of the diagonal of the inertia matrix at the CoM: $(I_{x,MP}, I_{y,MB}, I_{z,MP})$,
- The 2 symmetrical solar arrays (SA) in any angular configuration $\theta \in [-\pi,\ \pi]$ modelled with APRICOT with 4 flexible modes, uncertainties on the frequencies of the first 2 flexible modes and 1 sizing parameter: the core thickness t_{SA},
- The SAR (V) modelled with APRICOT with 4 flexible modes, uncertainties on the frequencies of the first 2 flexible modes and 1 sizing parameter: the core thickness $t_{V,}$
- The 2 booms (SRS) of the SRS modelled using the SDTlib analytical model of a beam with 2 sizing parameters the radius r_{SRS} and the thickness t_{SRS} of the tube cross section.

Tunable parameters: $\boldsymbol{\Theta} = \{t_{SA}, t_V, r_{SRS}, t_{SRS}\}$,

Uncertain parameters: $\Delta = \{\theta, \omega_{1,SA}, \omega_{2,SA}, \omega_{1,V}, \omega_{2,,V}, m_{MB}, I_{x,MP}, I_{y,MB}, I_{z,MP}\}$

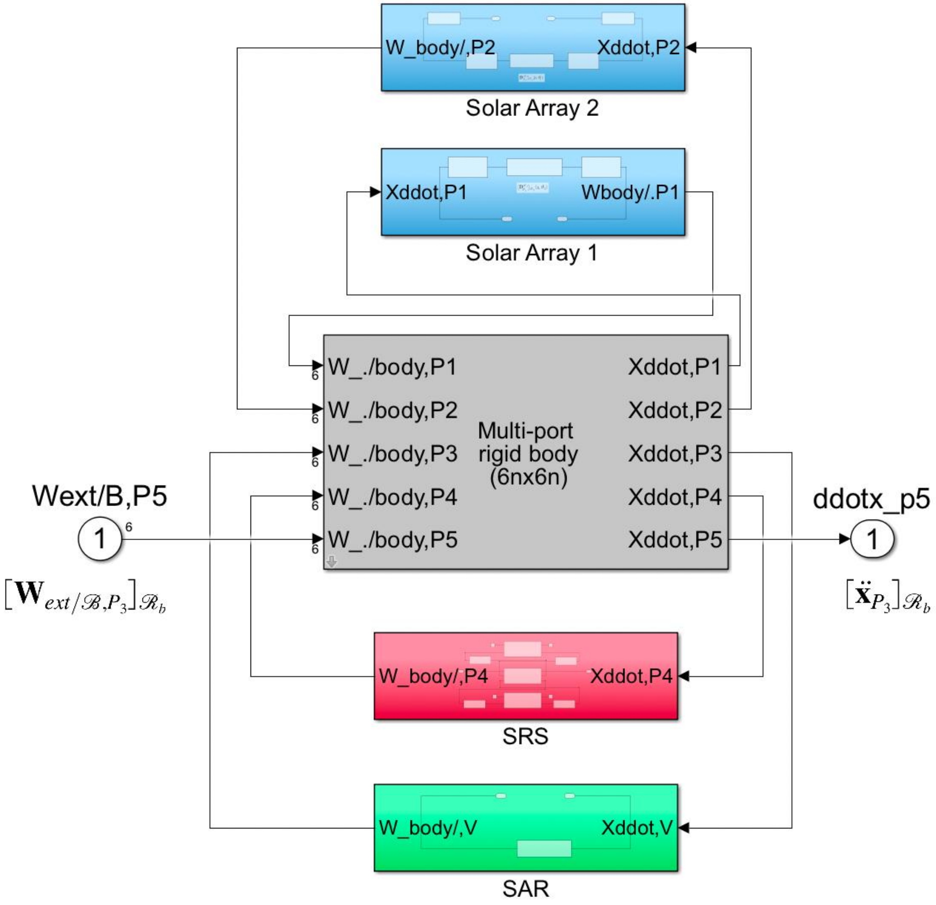


Implementation of the direct co-design: **Spacecraft assembly with the SDTlib**

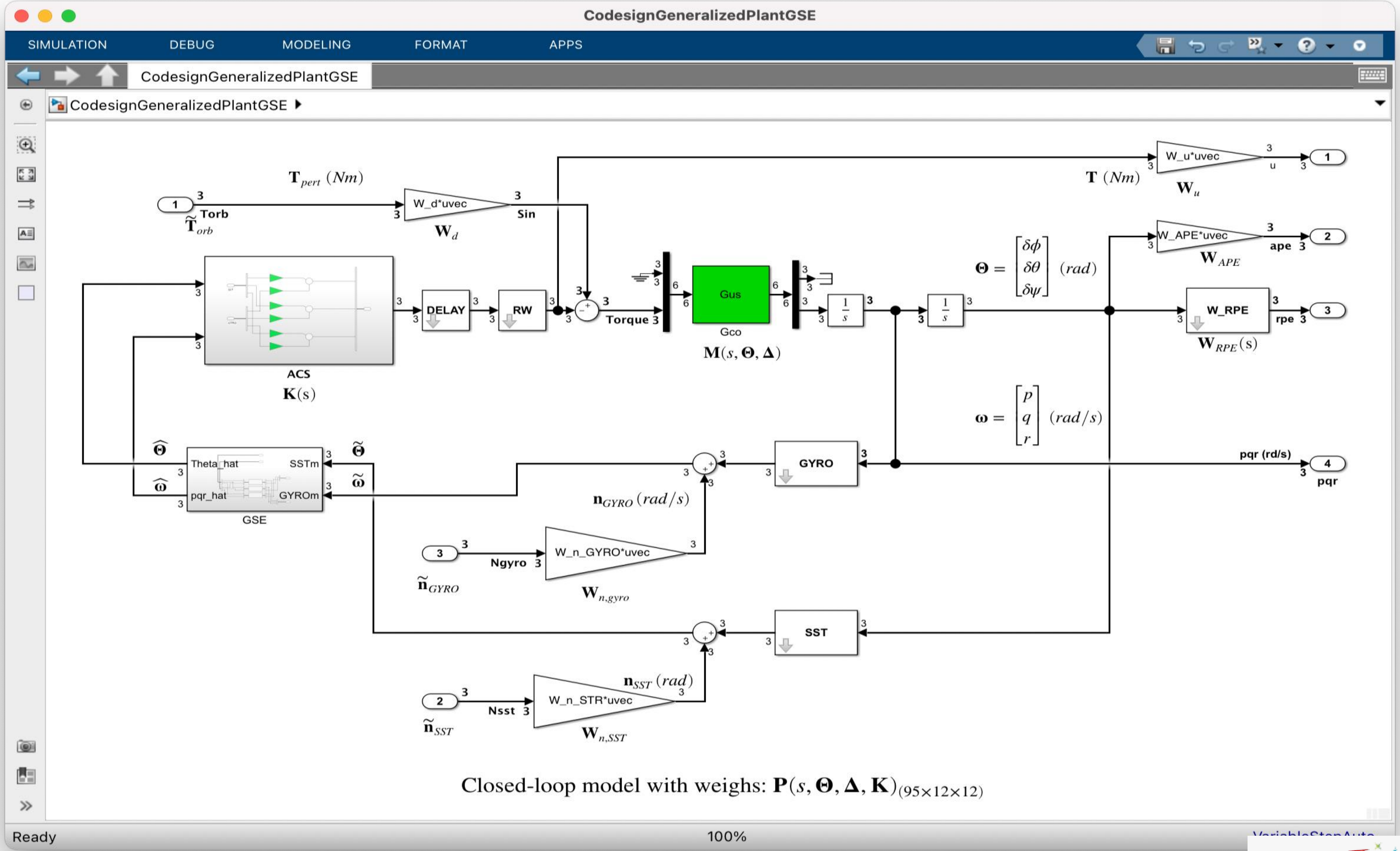
Parametric details on the model of Benchmark : $\mathbf{M}(s,\boldsymbol{\Theta},\Delta)$

```
Guco =

  Generalized continuous-time state-space model with 6 outputs, 6 inputs, 68 states,
  and the following blocks:
    CTSAt: Tunable 1x1 gain, 56 occurrences.
    CTVt: Tunable 1x1 gain, 51 occurrences.
    I_xx_CB: Uncertain real, nominal = 1.05e+03, variability = [-15,15]%, 1 occurrences
    I_yy_CB: Uncertain real, nominal = 1.52e+03, variability = [-15,15]%, 1 occurrences
    I_zz_CB: Uncertain real, nominal = 1.54e+03, variability = [-15,15]%, 1 occurrences
    Mass_CB: Uncertain real, nominal = 1.17e+03, variability = [-15,15]%, 3 occurrences
    RSRSt: Tunable 1x1 gain, 213 occurrences.
    TSRSt: Tunable 1x1 gain, 232 occurrences.
    dW1SAun: Uncertain real, nominal = 1, variability = [-25,25]%, 4 occurrences
    dW1Vun: Uncertain real, nominal = 1, variability = [-25,25]%, 2 occurrences
    dW2SAun: Uncertain real, nominal = 1, variability = [-25,25]%, 4 occurrences
    dW2Vun: Uncertain real, nominal = 1, variability = [-25,25]%, 2 occurrences
    tan_Theta_div4: Uncertain real, nominal = 0, range = [-1,1], 16 occurrences
```

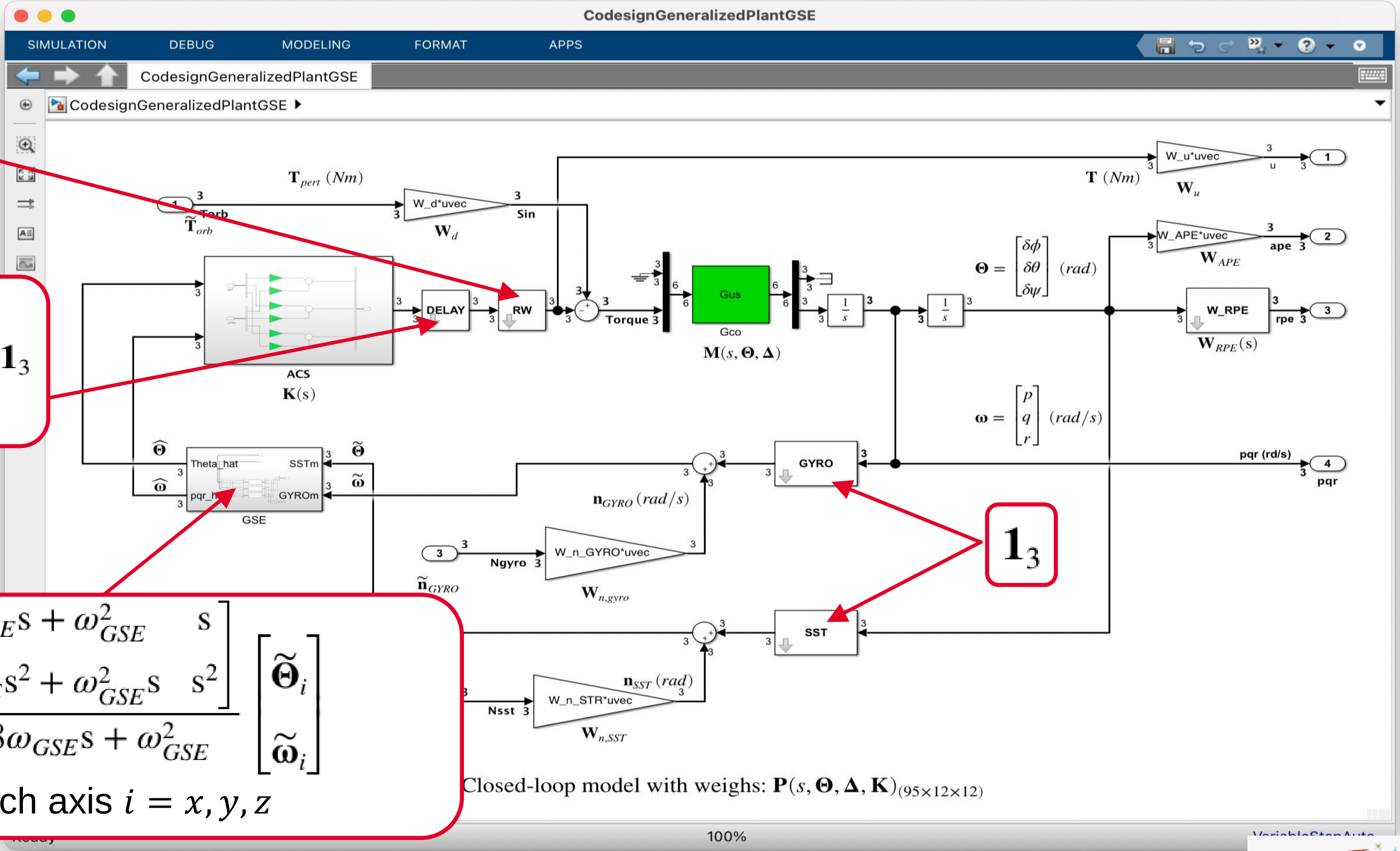


Co-design problem: **control requirements**



Closed-loop model with weighs: $\mathbf{P}(s, \mathbf{\Theta}, \mathbf{\Delta}, \mathbf{K})_{(95\times12\times12)}$

Co-design problem: **control requirements**



Closed-loop model with weighs: $\mathbf{P}(s,\mathbf{\Theta},\mathbf{\Delta},\mathbf{K})_{(95\times12\times12)}$

$$\frac{\omega_{act}}{s+\omega_{act}}$$

$$\frac{T_d^2 s^2 - 6T_d s + 12}{T_d^2 s^2 + 6T_d s + 12}\,1_3$$

$$1_3$$

$$\begin{bmatrix}\hat{\mathbf{\Theta}}_i\\ \hat{\mathbf{\omega}}_i\end{bmatrix} = \frac{\begin{bmatrix}1.8\omega_{GSE}s+\omega_{GSE}^2 & s\\ 1.8\omega_{GSE}s^2+\omega_{GSE}^2 s & s^2\end{bmatrix}}{s^2+1.8\omega_{GSE}s+\omega_{GSE}^2}\begin{bmatrix}\tilde{\mathbf{\Theta}}_i\\ \tilde{\mathbf{\omega}}_i\end{bmatrix}$$

on each axis $i = x, y, z$

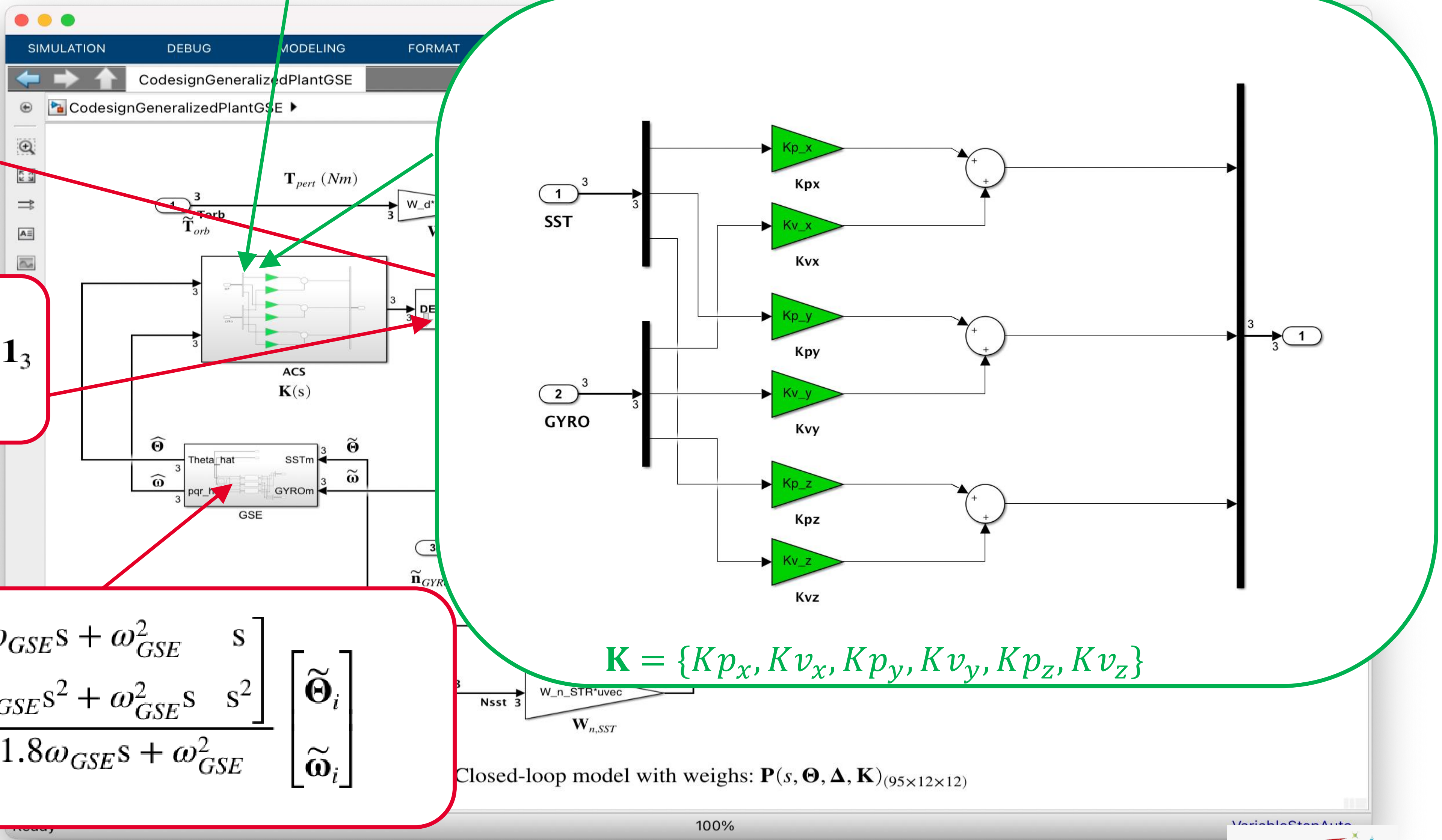
Co-design problem:

3 single axis PD controllers

$$\frac{\omega_{act}}{s+\omega_{act}}$$

$$\frac{T_d^2 s^2 - 6T_d s + 12}{T_d^2 s^2 + 6T_d s + 12}\mathbf{1}_3$$

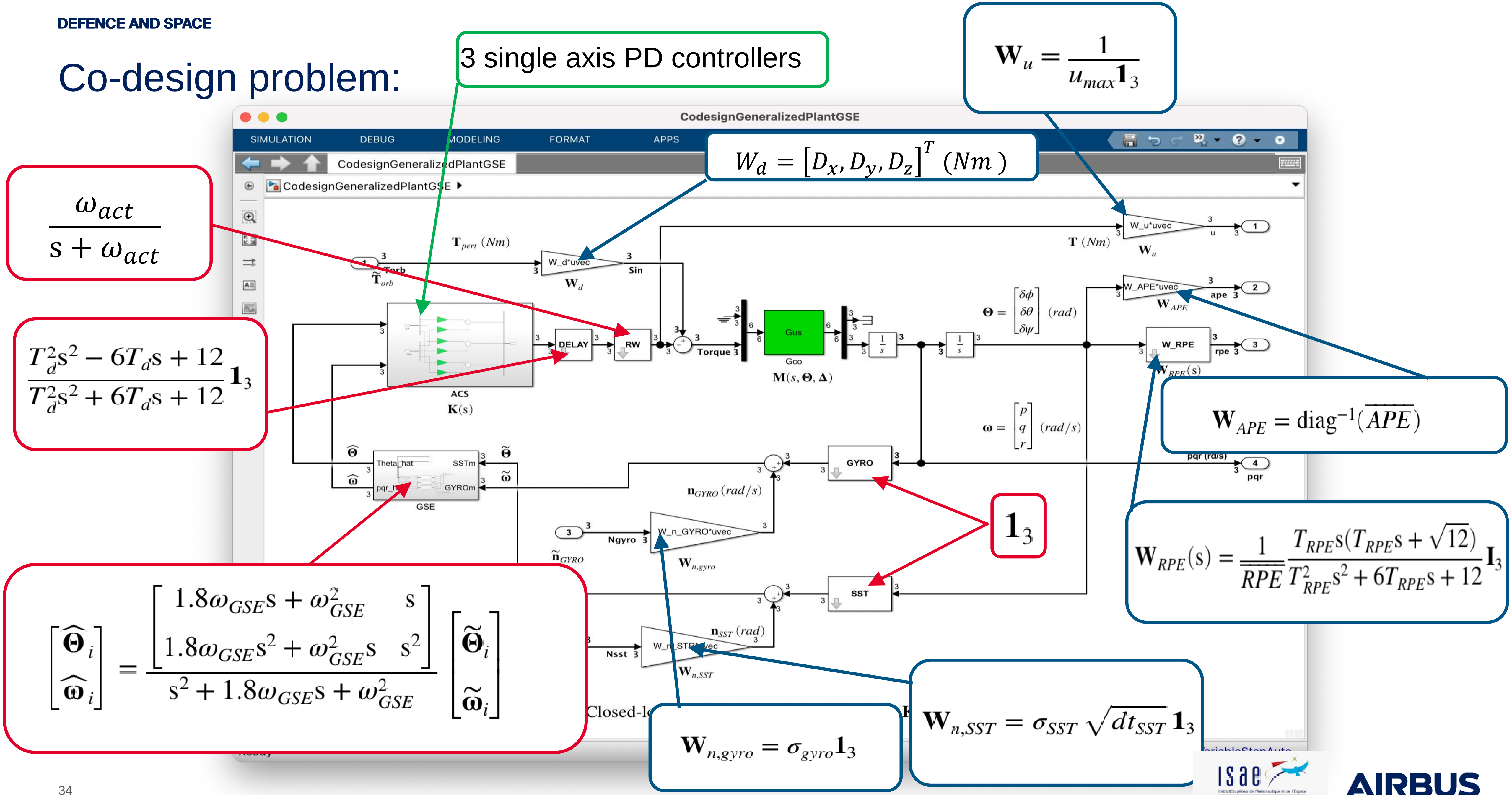
$$\begin{bmatrix}\widehat{\boldsymbol{\Theta}}_i \\ \widehat{\boldsymbol{\omega}}_i\end{bmatrix} = \frac{\begin{bmatrix}1.8\omega_{GSE}s+\omega_{GSE}^2 & s \\ 1.8\omega_{GSE}s^2+\omega_{GSE}^2 s & s^2\end{bmatrix}}{s^2+1.8\omega_{GSE}s+\omega_{GSE}^2}\begin{bmatrix}\tilde{\boldsymbol{\Theta}}_i \\ \tilde{\boldsymbol{\omega}}_i\end{bmatrix}$$



$\mathbf{K} = \{Kp_x, Kv_x, Kp_y, Kv_y, Kp_z, Kv_z\}$

Closed-loop model with weighs: $\mathbf{P}(s, \boldsymbol{\Theta}, \boldsymbol{\Delta}, \mathbf{K})_{(95\times12\times12)}$

Co-design problem:



3 single axis PD controllers

$$\mathbf{W}_u = \frac{1}{u_{max}\mathbf{1}_3}$$

$$W_d = [D_x, D_y, D_z]^T \ (Nm)$$

$$\frac{\omega_{act}}{s+\omega_{act}}$$

$$\frac{T_d^2 s^2 - 6T_d s + 12}{T_d^2 s^2 + 6T_d s + 12}\mathbf{1}_3$$

$$\mathbf{W}_{APE} = \mathrm{diag}^{-1}(\overline{APE})$$

$$\mathbf{1}_3$$

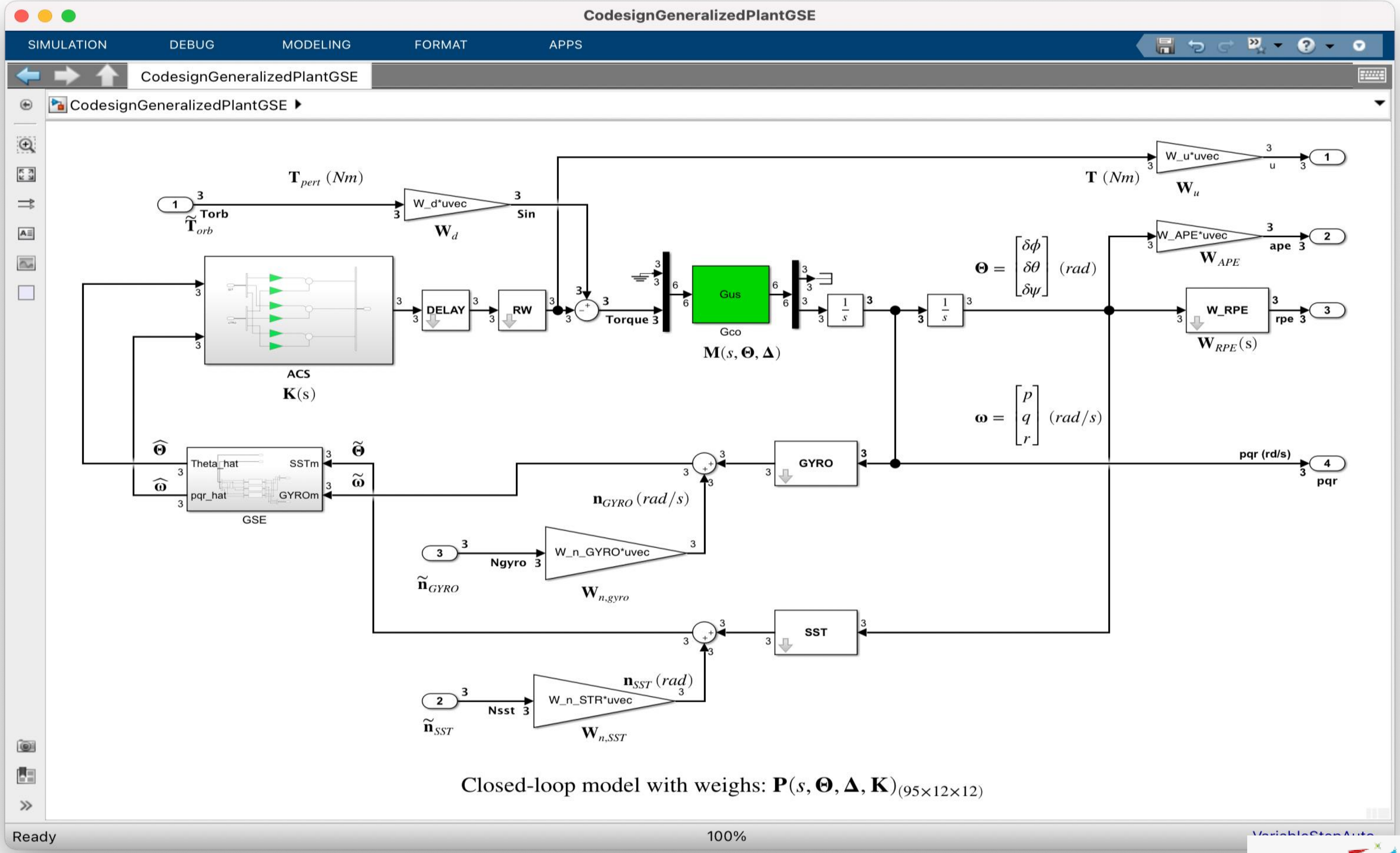
$$\mathbf{W}_{RPE}(s) = \frac{1}{\overline{RPE}}\frac{T_{RPE}s(T_{RPE}s+\sqrt{12})}{T_{RPE}^2 s^2 + 6T_{RPE}s + 12}\mathbf{1}_3$$

$$\begin{bmatrix}\widehat{\boldsymbol{\Theta}}_i \\ \widehat{\boldsymbol{\omega}}_i\end{bmatrix} = \frac{\begin{bmatrix}1.8\omega_{GSE}s + \omega_{GSE}^2 & s \\ 1.8\omega_{GSE}s^2 + \omega_{GSE}^2 s & s^2\end{bmatrix}}{s^2 + 1.8\omega_{GSE}s + \omega_{GSE}^2}\begin{bmatrix}\widetilde{\boldsymbol{\Theta}}_i \\ \widetilde{\boldsymbol{\omega}}_i\end{bmatrix}$$

$$\mathbf{W}_{n,gyro} = \sigma_{gyro}\mathbf{1}_3$$

$$\mathbf{W}_{n,SST} = \sigma_{SST}\sqrt{dt_{SST}}\,\mathbf{1}_3$$

Co-design problem: **control requirements**



Closed-loop model with weighs: $\mathbf{P}(s, \mathbf{\Theta}, \mathbf{\Delta}, \mathbf{K})_{(95\times12\times12)}$

Co-design problem: **control requirements**

- **The optimization problem (without literal expression the mass)**

$$\min_{\boldsymbol{\Theta},\mathbf{K}}\ \max_{\boldsymbol{\Delta}}\ \bar{\sigma}\left(\left[\mathbf{M}_{F_x\to\ddot{x}}(j\omega,\boldsymbol{\Theta},\boldsymbol{\Delta})\right]^{-1}\right)\quad \forall\omega\in[0,\ 0.0001]$$

- **Such that:**

1. **HC1:** $\max_{\boldsymbol{\Delta}}\left\|\mathbf{P}_{\mathrm{Torb}\to\mathrm{ape}}(\mathrm{s},\boldsymbol{\Theta},\boldsymbol{\Delta},\mathbf{K})\right\|_\infty\leq 1$ **(perf APE)**
2. **HC2:** $\max_{\boldsymbol{\Delta}}\left\|\mathbf{P}_{\mathrm{Torb}\to\mathrm{rpe}}(\mathrm{s},\boldsymbol{\Theta},\boldsymbol{\Delta},\mathbf{K})\right\|_\infty\leq 1$ **(perf RPE)**
3. **HC3:** $\max_{\boldsymbol{\Delta}}\left\|\mathbf{P}_{\mathrm{Torb}\to\mathrm{u}}(\mathrm{s},\boldsymbol{\Theta},\boldsymbol{\Delta},\mathbf{K})\right\|_\infty\leq 1$ **(control signal limitations)**
4. **HC4:** $\max_{\boldsymbol{\Delta}}\left\|\mathbf{P}_{\mathrm{Sin}\to\mathrm{Torque}}(\mathrm{s},\boldsymbol{\Theta},\boldsymbol{\Delta},\mathbf{K})\right\|_\infty\leq 1.5$ **(disc margin)**
5. **HC4:** $\max_{\boldsymbol{\Delta}}\left\|\mathbf{P}_{\begin{bmatrix}\mathrm{Nsst}\\ \mathrm{Ngyro}\end{bmatrix}\to\begin{bmatrix}\mathrm{APE}\\ \mathrm{RPE}\end{bmatrix}}(\mathrm{s},\boldsymbol{\Theta},\boldsymbol{\Delta},\mathbf{K})\right\|_2\leq 1$ **(variance on RPE and APE from sensor (SST and GYRO) noises)**

Co-design problem: **control requirements**

- **The optimization problem (without literal expression the mass)**

$$\min_{\mathbf{\Theta},\mathbf{K}}\max_{\mathbf{\Delta}}\bar{\sigma}\left(\left[\mathbf{M}_{F_x\to\ddot{x}}(j\omega,\mathbf{\Theta},\mathbf{\Delta})\right]^{-1}\right)\quad\forall\omega\in[0,\ \ 0.0001]$$

- **Such that:**

1. **HC1:** $\max_{\mathbf{\Delta}}\left\|\mathbf{P}_{\text{Torb}\to\text{ape}}(s,\mathbf{\Theta},\mathbf{\Delta},\mathbf{K})\right\|_{\infty}\leq 1$ **(perf APE)**
2. **HC2:** $\max_{\mathbf{\Delta}}\left\|\mathbf{P}_{\text{Torb}\to\text{rpe}}(s,\mathbf{\Theta},\mathbf{\Delta},\mathbf{K})\right\|_{\infty}\leq 1$ **(perf RPE)**
3. **HC3:** $\max_{\mathbf{\Delta}}\left\|\mathbf{P}_{\text{Torb}\to\text{u}}(s,\mathbf{\Theta},\mathbf{\Delta},\mathbf{K})\right\|_{\infty}\leq 1$ **(control signal limitation**
4. **HC4:** $\max_{\mathbf{\Delta}}\left\|\mathbf{P}_{\text{Sin}\to\text{Torque}}(s,\mathbf{\Theta},\mathbf{\Delta},\mathbf{K})\right\|_{\infty}\leq 1.5$ **(disc margin)**
5. **HC4:** $\max_{\mathbf{\Delta}}\left\|\mathbf{P}_{\begin{bmatrix}\text{Nsst}\\\text{Ngyro}\end{bmatrix}\to\begin{bmatrix}\text{APE}\\\text{RPE}\end{bmatrix}}(s,\mathbf{\Theta},\mathbf{\Delta},\mathbf{K})\right\|_{2}\leq 1$ **(variance on RPE and APE from sensor (SST and GYRO) noises**)

Such a robust co-design problem is solved thanks to

- the ***slTuner*** interface directly applied on the SIMULINK file of the closed-loop system
- ***Systune*** with 1 soft constraint and 5 hard constraints

- Study context & concluded summary
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- Approach, modelling & optimisation methods trade-off
- Implementation
- **Results – Direct Co-design (10’)**
- Validation & verification
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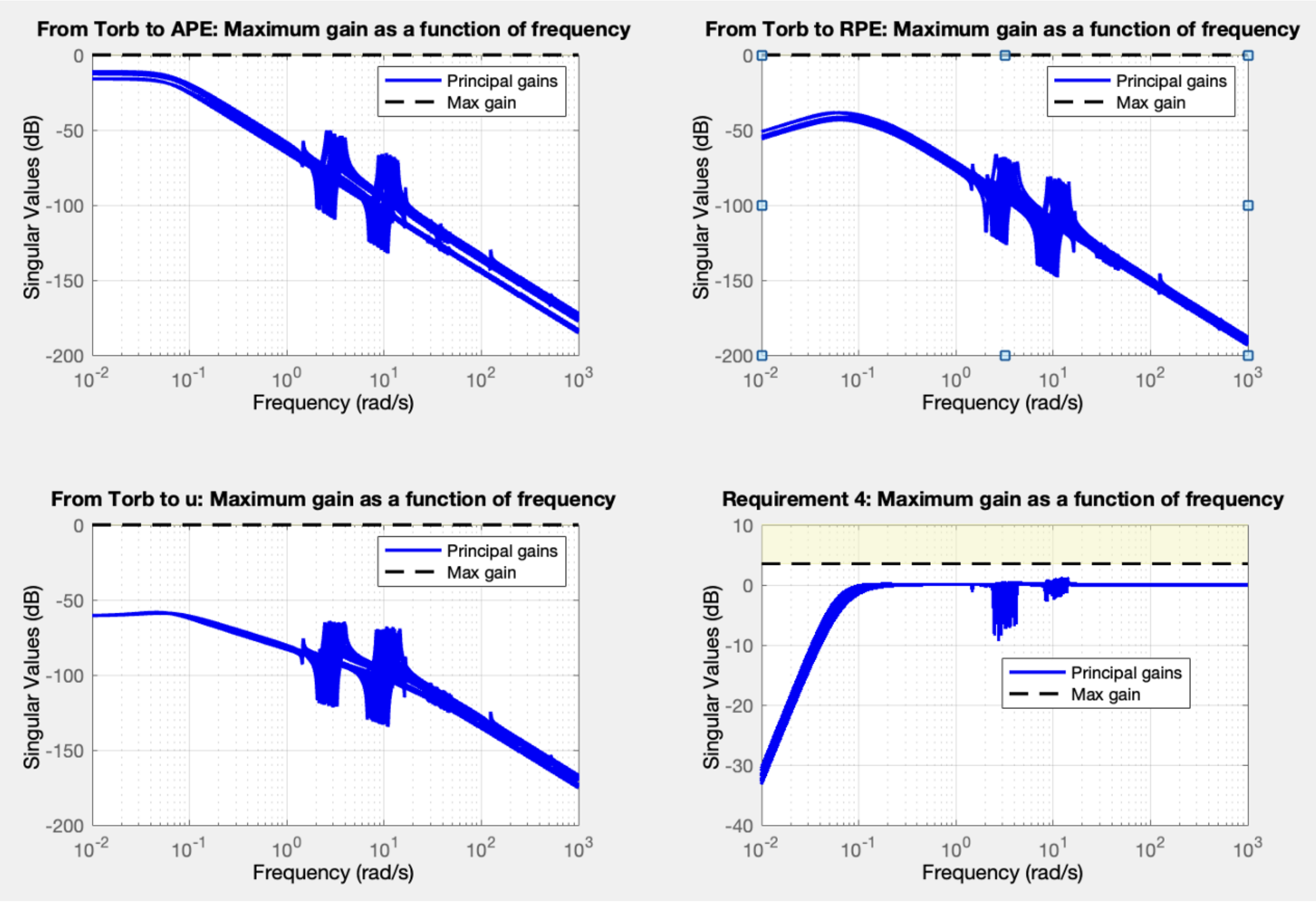
Direct codesign: **Results**

- The problem is not so challenging : 21 Kgs are saved (w.r.t. the nominal conf.).
- **All the mech. parameters are tuned to their lower bounds**.
- Hard constraints are not saturated.



Direct codesign: **Results**

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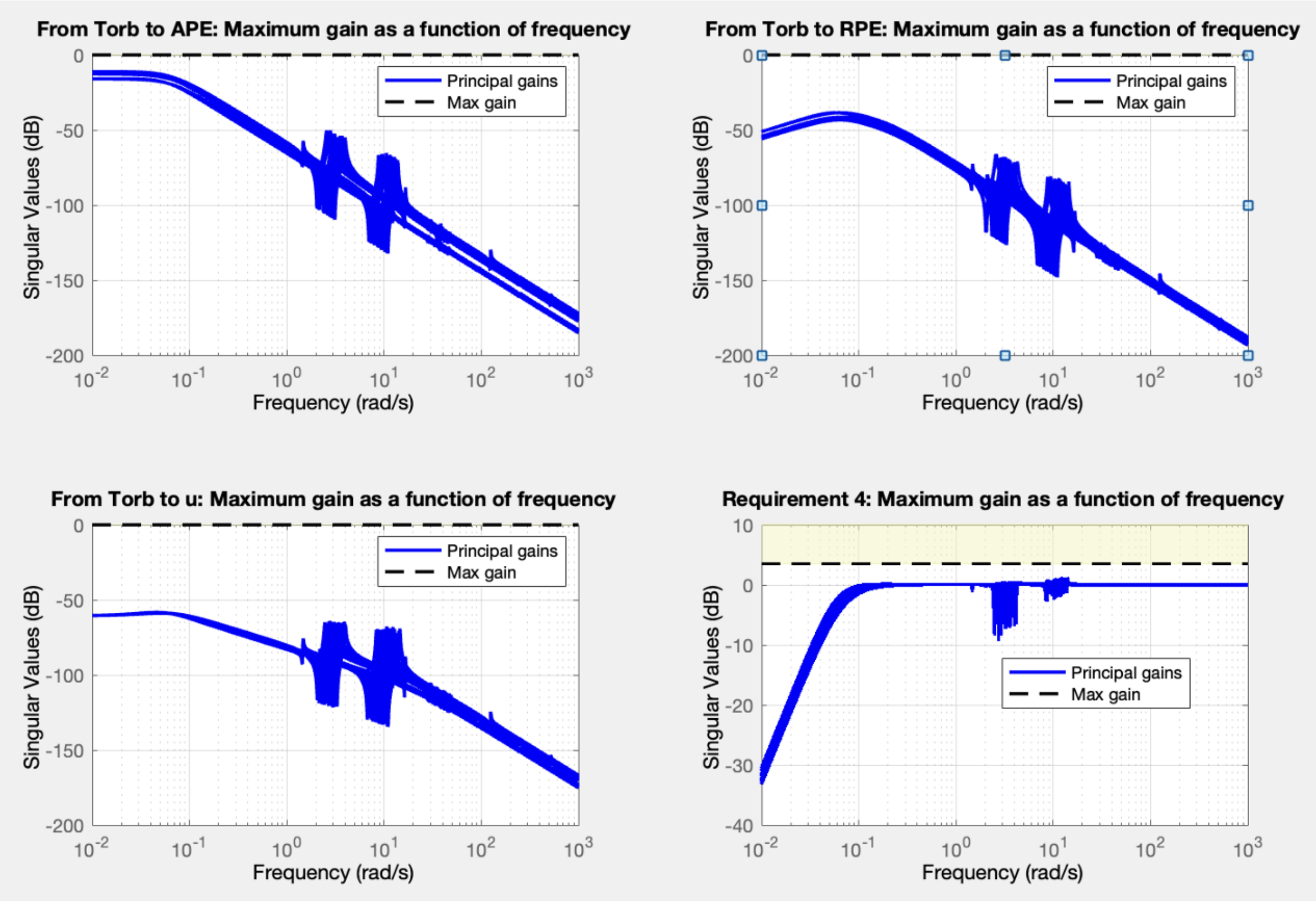


The same responses are obtained on the validation model built from the NASTRAN models of the SAs and the SAR with the optimal mechanical configurations (with all the flexible modes)

Direct codesign: **Additional results**

Several design problems are also considered:

Problem I (robust co-design) $\min_{\boldsymbol{\Theta},\mathbf{K}} \max_{\boldsymbol{\Delta}} \overline{\boldsymbol{\sigma}}\left(\left[M_{\mathbf{F_x}\to\ddot{x}}(\mathrm{j}\omega, \boldsymbol{\Theta}, \boldsymbol{\Delta})\right]^{-\mathbf{1}}\right)\ \forall\, \omega \in [0,\ 0.0001]$

such that:

1. HC1 (perf APE): $\max_{\boldsymbol{\Delta}} \left\|\mathbf{P}_{\mathbf{Torb}\to\mathbf{ape}}(s, \boldsymbol{\Theta}, \boldsymbol{\Delta}, \mathbf{K})\right\|_{\infty} / \boldsymbol{\gamma}_{\mathbf{1}} < \mathbf{1}.$
2. HC2 (perf RPE): $\max_{\boldsymbol{\Delta}} \left\|\mathbf{P}_{\mathbf{Torb}\to\mathbf{rpe}}(s, \boldsymbol{\Theta}, \boldsymbol{\Delta}, \mathbf{K})\right\|_{\infty} / \boldsymbol{\gamma}_{\mathbf{2}} < \mathbf{1},$
3. HC3 (control limitation): $\max_{\boldsymbol{\Delta}} \|\mathbf{P}_{\mathbf{Torb}\to\mathbf{u}}(s, \boldsymbol{\Theta}, \boldsymbol{\Delta}, \mathbf{K})\|_{\infty} / \boldsymbol{\gamma}_{\mathbf{3}} < \mathbf{1},$
4. HC4 (disc margin) : $\max_{\boldsymbol{\Delta}} \left\|\mathbf{P}_{\mathbf{Sin}\to\mathbf{Torque}}(s, \boldsymbol{\Theta}, \boldsymbol{\Delta}, \mathbf{K})\right\|_{\infty} / \boldsymbol{\gamma}_{\mathbf{4}} < \mathbf{1},$
5. HC5 (variance): $\max_{\boldsymbol{\Delta}} \left\|\mathbf{P}_{\begin{bmatrix}\mathbf{Nsst}\\ \mathbf{Ngyro}\end{bmatrix}\to\begin{bmatrix}\mathbf{APE}\\ \mathbf{RPE}\end{bmatrix}}(s, \boldsymbol{\Theta}, \boldsymbol{\Delta}, \mathbf{K})\right\|_{\infty} < \mathbf{1}$

The previous co-design problem is characterized by : $\gamma_1 = 1, \gamma_2 = 1, \gamma_3 = 1, \gamma_4 = 1.5.$

➔ **objective: playing with the γ_i to highlight trade-offs**

Direct codesign: **Additional results**

Several design problems are also considered:

Problem II (robust co-design): $\min_{\Theta,K} \max_{\Delta} \left\| P_{Torb \rightarrow ape}(s, \Theta, \Delta, K) \right\|_{\infty} / \gamma_1$

such that:

1. HC2 (perf RPE): $\max_{\Delta} \left\| P_{Torb \rightarrow rpe}(s, \Theta, \Delta, K) \right\|_{\infty} / \gamma_2 < 1,$
2. HC3 (control limitation): $\max_{\Delta} \| P_{Torb \rightarrow u}(s, \Theta, \Delta, K) \|_{\infty} / \gamma_3 < 1,$
3. HC4 (disc margin) : $\max_{\Delta} \left\| P_{Sin \rightarrow Torque}(s, \Theta, \Delta, K) \right\|_{\infty} / \gamma_4 < 1,$
4. HC5 (variance): $\max_{\Delta} \left\| P_{\begin{bmatrix} Nsst \\ Ngyro \end{bmatrix} \rightarrow \begin{bmatrix} APE \\ RPE \end{bmatrix}}(s, \Theta, \Delta, K) \right\|_{\infty} < 1.$

The APE is now a soft constraint (the mass is no more minimized)

Direct codesign: **Additional results**

Several design problems are also considered:

Problem III (robust design): $\min_{\boldsymbol{\Theta},\mathbf{K}} \max_{\boldsymbol{\Delta}} \left\| \mathbf{P}_{\mathbf{Torb}\to\mathbf{ape}}(s, \boldsymbol{\Theta}_{\mathbf{g}}, \boldsymbol{\Delta}, \mathbf{K}) \right\|_{\infty} / \boldsymbol{\gamma}_{\mathbf{1}}$

such that:

1. HC2 (perf RPE): $\max_{\boldsymbol{\Delta}} \left\| \mathbf{P}_{\mathbf{Torb}\to\mathbf{rpe}}(s, \boldsymbol{\Theta}_{\mathbf{g}}, \boldsymbol{\Delta}, \mathbf{K}) \right\|_{\infty} / \boldsymbol{\gamma}_{\mathbf{2}} < \mathbf{1},$
2. HC3 (control limitation): $\max_{\boldsymbol{\Delta}} \left\| \mathbf{P}_{\mathbf{Torb}\to\mathbf{u}}(s, \boldsymbol{\Theta}_{\mathbf{g}}, \boldsymbol{\Delta}, \mathbf{K}) \right\|_{\infty} / \boldsymbol{\gamma}_{\mathbf{3}} < \mathbf{1},$
3. HC4 (disc margin) : $\max_{\boldsymbol{\Delta}} \left\| \mathbf{P}_{\mathbf{Sin}\to\mathbf{Torque}}(s, \boldsymbol{\Theta}_{\mathbf{g}}, \boldsymbol{\Delta}, \mathbf{K}) \right\|_{\infty} / \boldsymbol{\gamma}_{\mathbf{4}} < \mathbf{1},$
4. HC5 (variance): $\max_{\boldsymbol{\Delta}} \left\| \mathbf{P}_{\begin{bmatrix}\mathbf{Nsst}\\ \mathbf{Ngyro}\end{bmatrix}\to\begin{bmatrix}\mathbf{APE}\\ \mathbf{RPE}\end{bmatrix}}(s, \boldsymbol{\Theta}_{\mathbf{g}}, \boldsymbol{\Delta}, \mathbf{K}) \right\|_{\infty} < \mathbf{1}.$

where $\boldsymbol{\Theta}_{\mathbf{g}}$ is a given mechanical configuration:

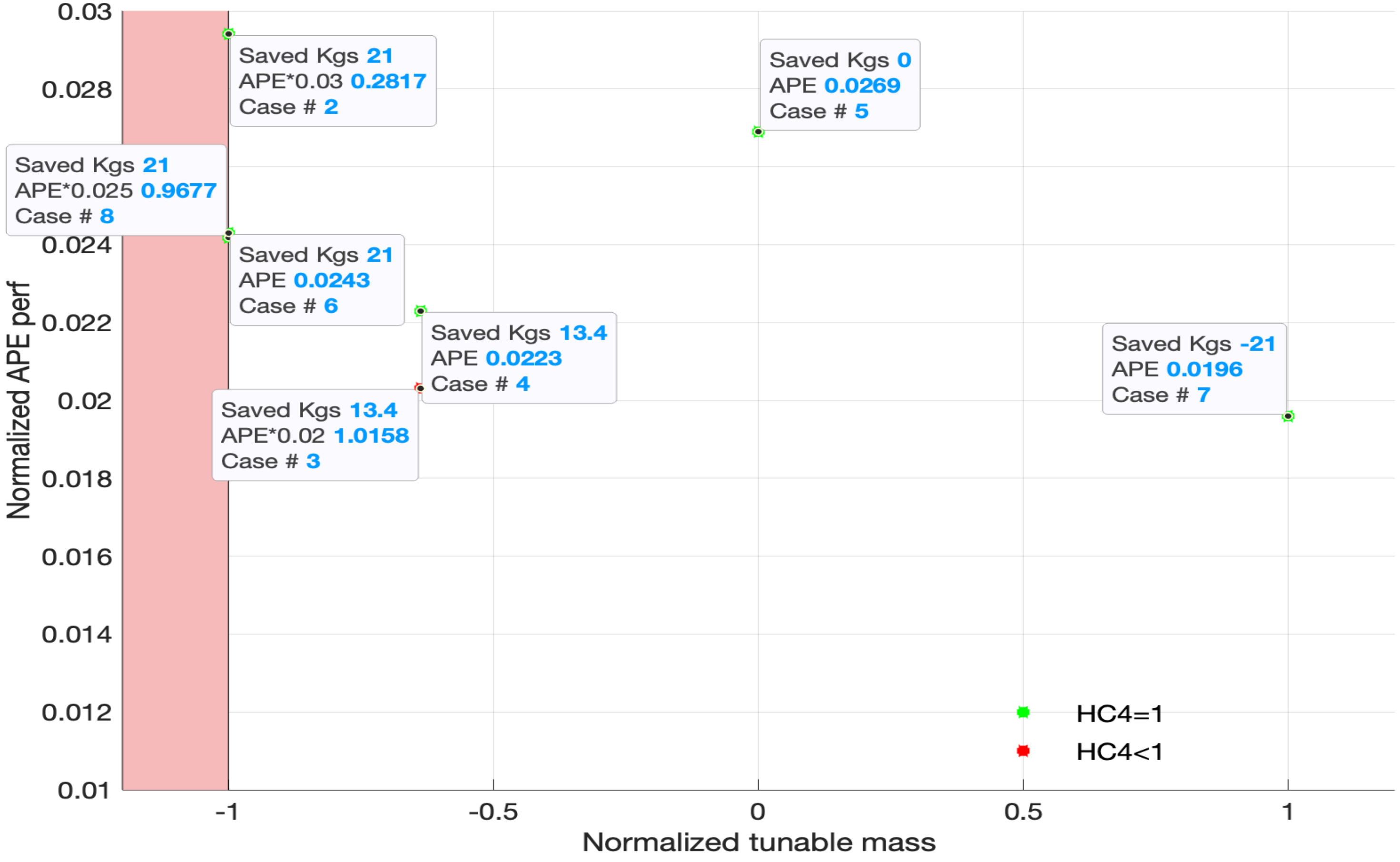
- $\boldsymbol{\Theta}_{\mathbf{g}} = \boldsymbol{\Theta}_{\mathbf{0}}$**:** (nominal) all mechanical parameters are tuned on the median value,
- $\boldsymbol{\Theta}_{\mathbf{g}} = \overline{\boldsymbol{\Theta}}$**:** all mechanical parameters are tuned to their upper bounds,
- $\boldsymbol{\Theta}_{\mathbf{g}} = \underline{\boldsymbol{\Theta}}$**:** all mechanical parameters are tuned to their lower bounds,

Direct codesign: **Additional results**

Case #	Description	HC1 (APE)	HC2 (RPE)	HC3 (Umax)	HC4 (Disc margin)	HC5 (noise reject)	Saved mass (Kg)	δt_{SA}	δt_V	δt_{SRS}	δr_{SRS}
1	The nominal co-design Problem	0.2817	0.0119	0.0012	0.7640	0.0408	21	-1	-1	-1	-1
2	The nominal co-design Problem I $\gamma_1 = 0.03, \gamma_2 = 1, \gamma_3 = 1, \gamma_4 = 1.5.$	0.9804	0.0054	0.0016	0.9735	0.0522	21	-1	-1	-1	-1
3	The co-design problem I with $\gamma_1 = 0.02, \gamma_2 = 1, \gamma_3 = 1, \gamma_4 = 1.5.$	1.0158	0.0036	0.0017	1.0158	0.0523	13.4	-1	1	-1	-1
4	The co-design problem II with $\gamma_1 = 1, \gamma_2 = 1, \gamma_3 = 1, \gamma_4 = 1.5.$	0.0223	0.0036	0.0016	0.9991	0.0521	13,4	-1	1	-1	-1
5	The control design problem III with $\gamma_1 = 1, \gamma_2 = 1, \gamma_3 = 1, \gamma_4 = 1.5.$ and $\boldsymbol{\Theta}_g = \boldsymbol{\Theta}_0$	0.0269	0.0042	0.0016	0.9993	0.0525	0	0	0	0	0
6	The control design problem III with $\gamma_1 = 1, \gamma_2 = 1, \gamma_3 = 1, \gamma_4 = 1.5.$ and $\boldsymbol{\Theta}_g = \underline{\boldsymbol{\Theta}}$:	0.0243	0.0037	0.0016	0.9989	0.0523	21	-1	-1	-1	-1
7	The control design problem III with $\gamma_1 = 1 , \gamma_2 = 1, \gamma_3 = 1, \gamma_4 = 1.5.$ and $\boldsymbol{\Theta}_g = \overline{\boldsymbol{\Theta}}$	0.0196	0.0030	0.0016	0.9999	0.0523	-21	1	1	1	1

Direct codesign: **Additional results**

Pareto front between the normalized APE and the normalized saved mass ….



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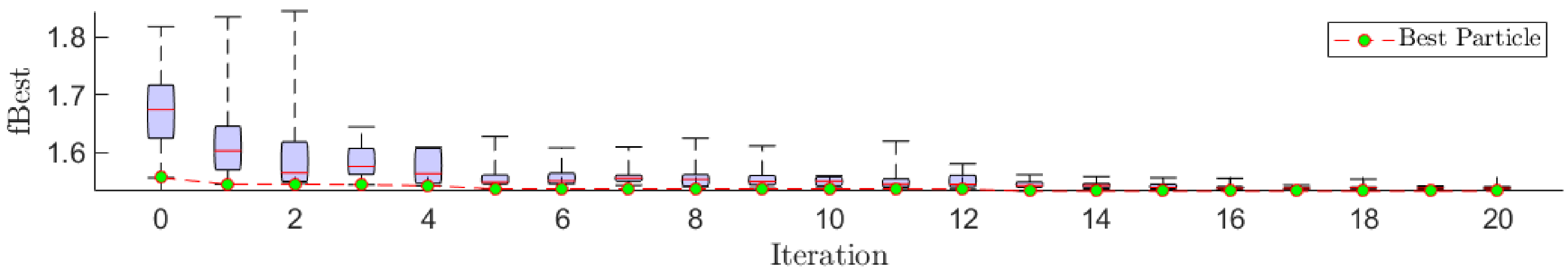
Iterative Co-design

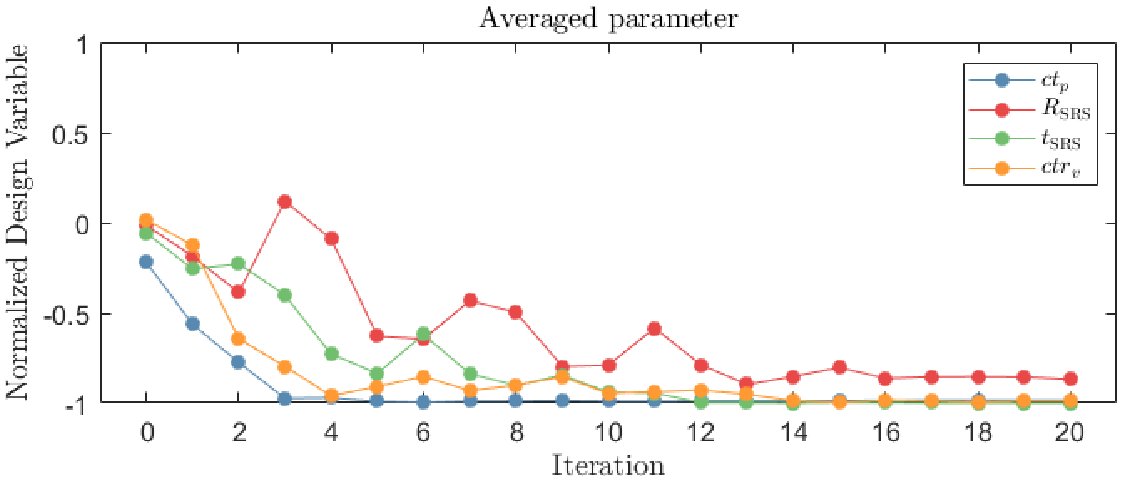
Total computational time	48963.37 s ≈ 13.6 hours
Minimum value of the nominal spacecraft total mass	1256.71 kg
Percentage of the saved mass w.r.t. the maximum expected mass without considering mass of the central rigid body m_cb (saved mass on the flexible appendages): (m_max – m_best)/(m_max-m_cb)	33.11 %
Mass reduction obtained w.r.t. the maximum expected nominal mass	41.43 kg
Optimal mass index	0.6689
Optimal control index	0.9206

Flexible Appendage	**Min Mass (kg)**	**Max Mass (kg)**	**Opt Mass (kg)**	**Saved Mass w.r.t. Max mass (kg)**	**% Saved Mass w.r.t. Max mass**
Solar Arrays	2 x 24.184	2 x 39.851	2 x 24.309	2 x 15.542	39 %
SRS	2 x 0.94421	2 x 2.3854	2 x 0.9797	2 x 1.4057	58.929 %
SAR	33.109	40.669	33.132	7.5370	18.534 %

Iterative Co-design

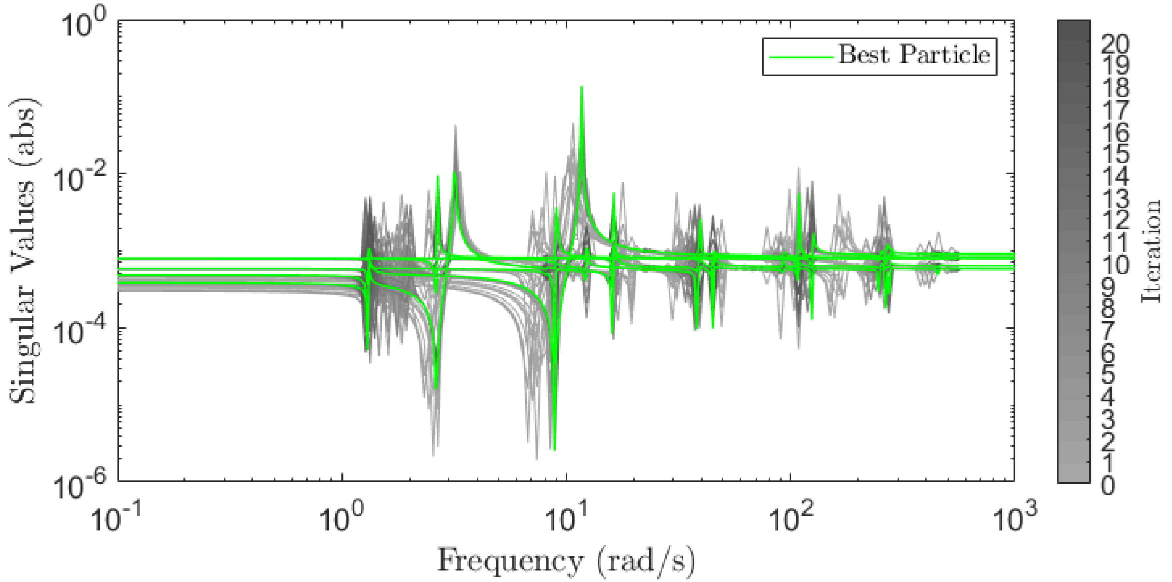
Evolution of the cost function during Particle Swarm's iterations



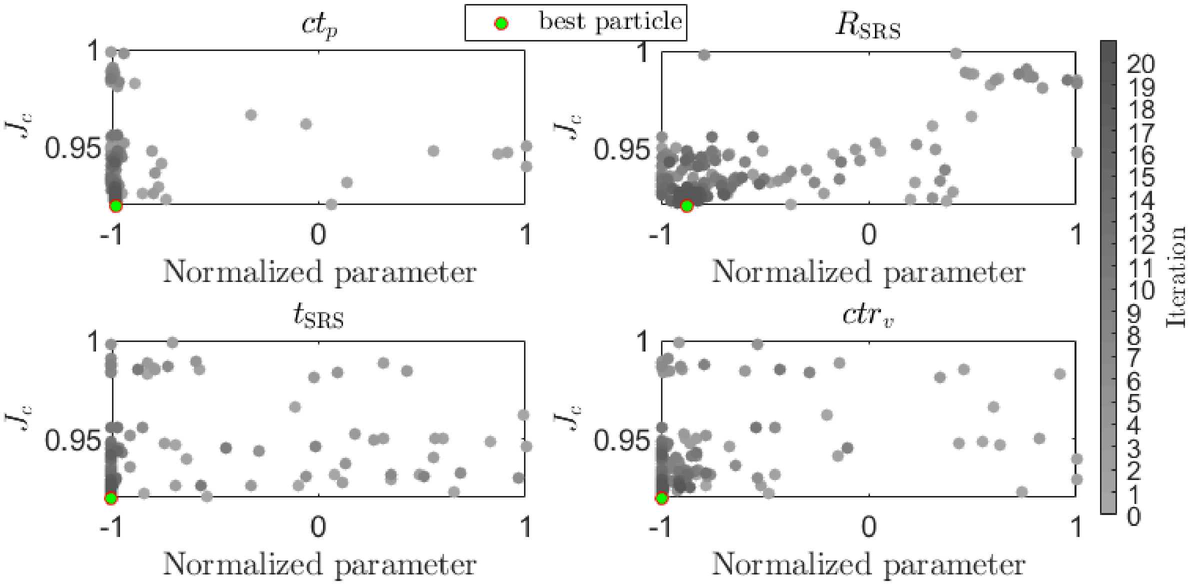


Parameter	Symbol	Unit	Min Value	Max Value	Best Particle
Panel's core thickness	ct_p	m	0.01	0.035	0.010222
SRS outer radius	R_{SRS}	m	0.0125	0.02	0.01297
SRS wall thickness	t_{SRS}	m	3.8e-4	6e-4	3.8e-4
SAR core thickness ratio	ctr_v	abs	0.5	1.5	0.50297

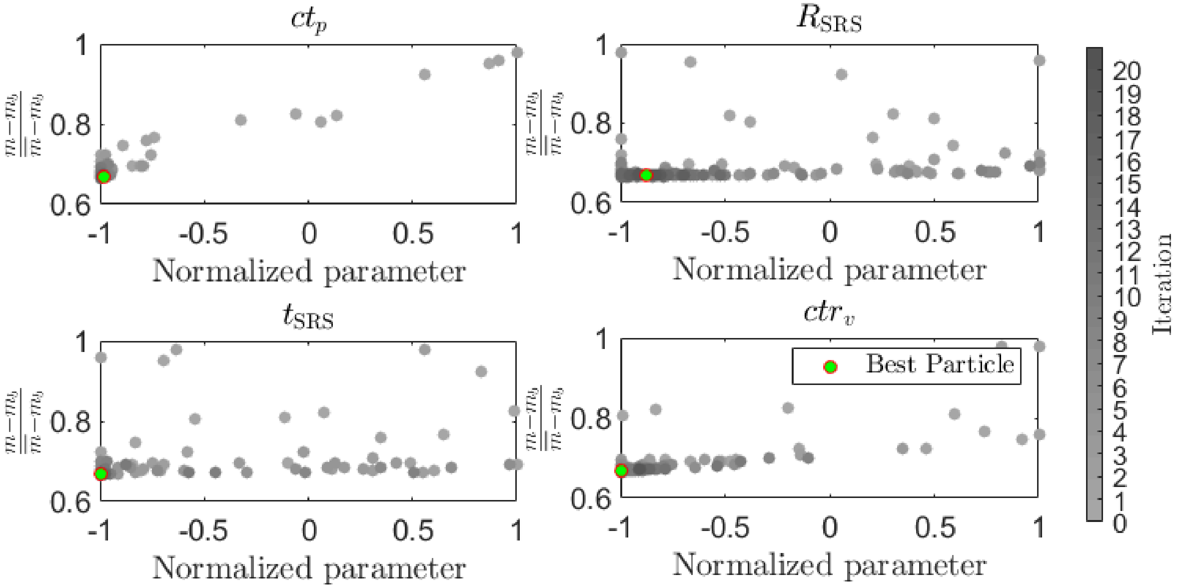
Iterative Co-design



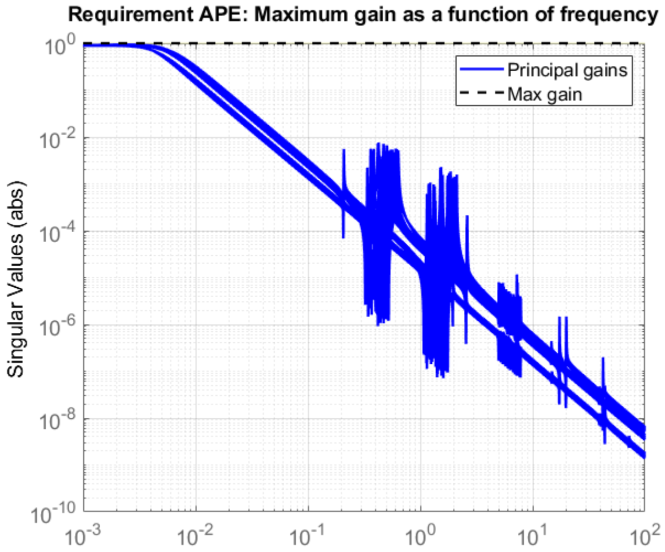
Control Index vs Design Parameters

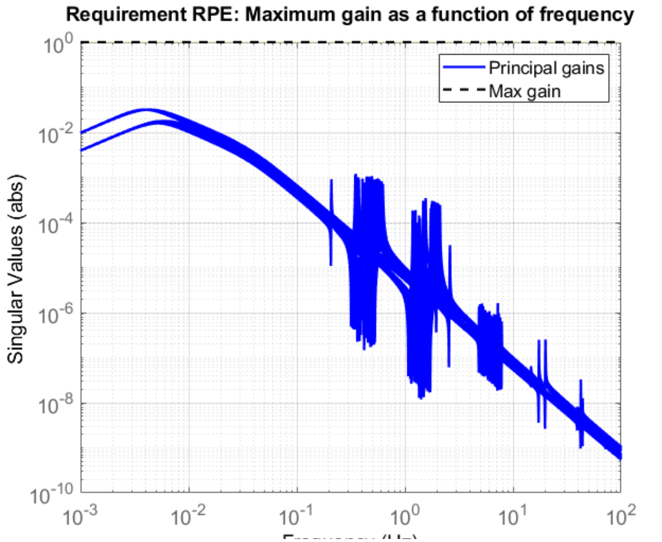


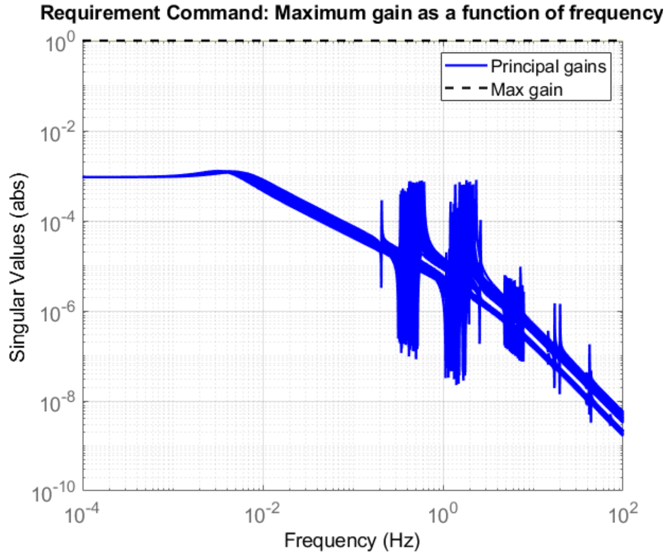
Mass Index vs Design Parameters

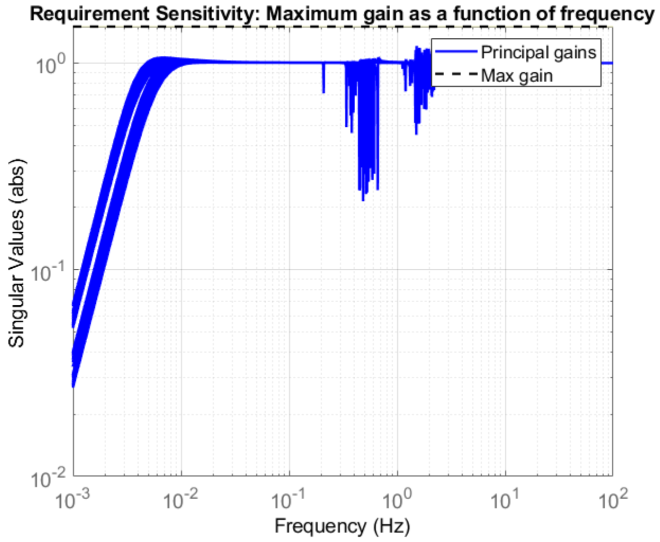


Iterative Co-design


Requirement APE: Maximum gain as a function of frequency


Requirement RPE: Maximum gain as a function of frequency


Requirement Command: Maximum gain as a function of frequency


Requirement Sensitivity: Maximum gain as a function of frequency

Requirement	Worst-Case
APE	0.920620
RPE	0.031945
Command	0.001248
Sensitivity	0.873935
Noise Variance	0.032255

Iterative Co-design – Dealing with several design parameters and exogenous structural constraints

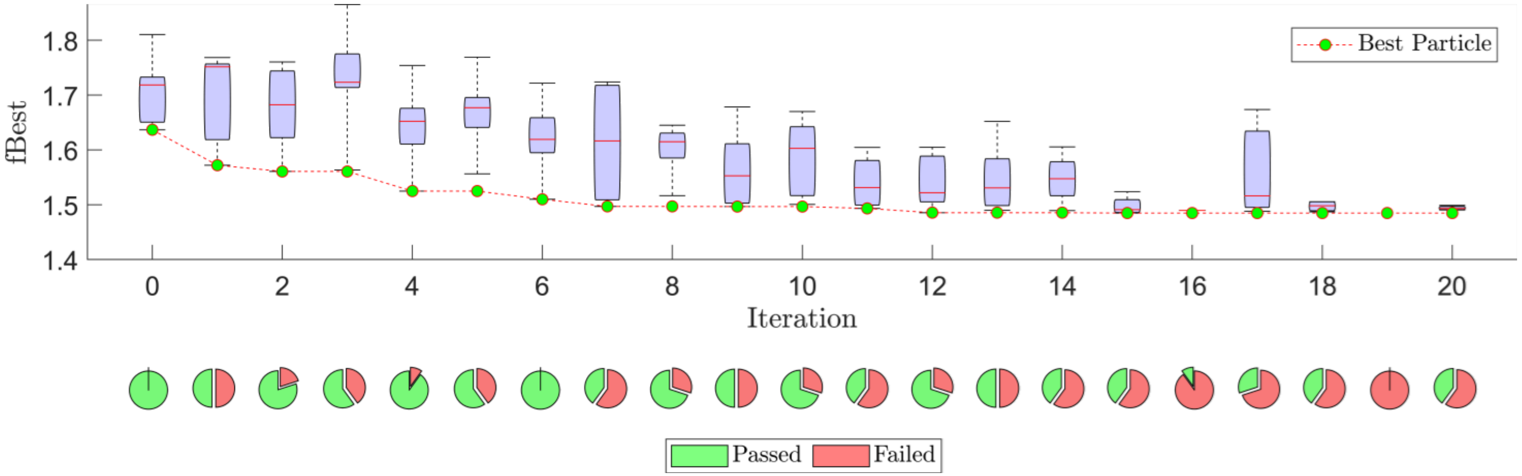
Parameter	Symbol	Unit	Min Value	Max Value	Best Particle
Yoke's Young's Modulus	E_y	Pa	1.1e11	1.23e11	**1e11**
Yoke's density	ρ_y	kg/m^3	2180	4500	**3753.2**
Yoke's section width	B_y	m	0.015	0.05	**0.0296**
Yoke's section height	D_y	m	0.015	0.05	**0.0164**
Yoke's section thickness	t_y	m	0.001	0.002	**0.002**
Panel's skin thickness	st_p	m	2e-4	4e-4	**2.08e-4**
Panel's core thickness	ct_p	m	0.01	0.035	**0.01**
Yoke's length ratio	lr_y	abs	0.42	1	**0.42**
Panel's length ratio	lr_p	abs	0.75	1.333	**1.040**
SRS outer radius	R_{SRS}	m	0.0125	0.02	**0.0132**
SRS wall thickness	t_{SRS}	m	3.8e-4	6e-4	**4.04e-4**
SAR core thickness ratio	ctr_v	abs	0.5	1.5	**0.5**

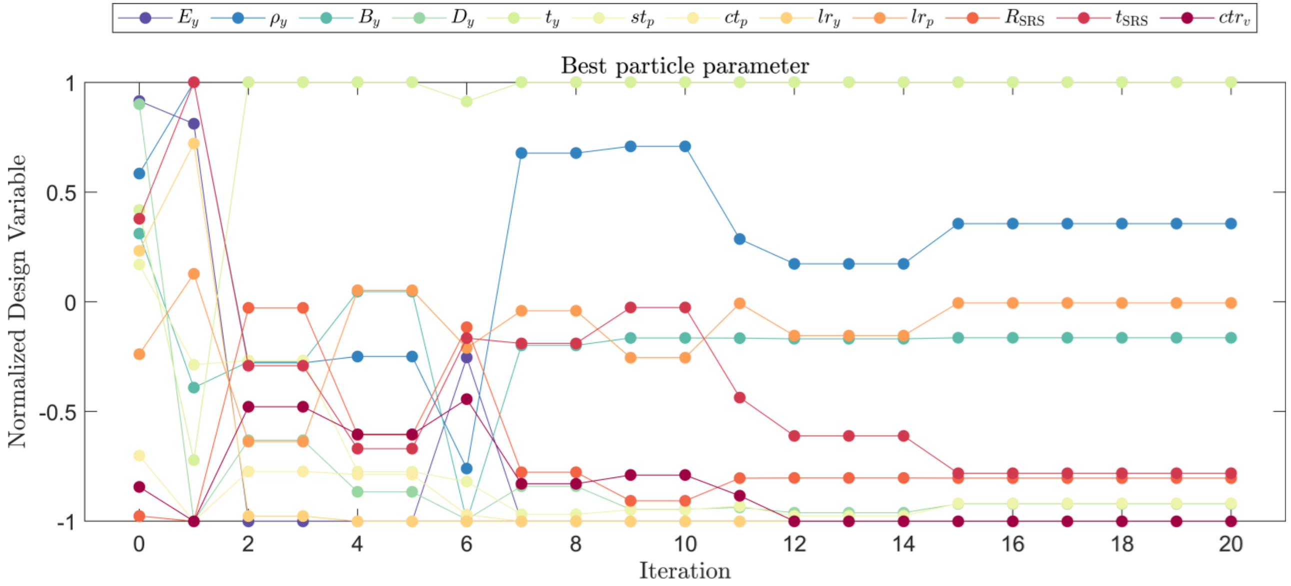
Iterative Co-design – Dealing with several design parameters and exogenous structural constraints

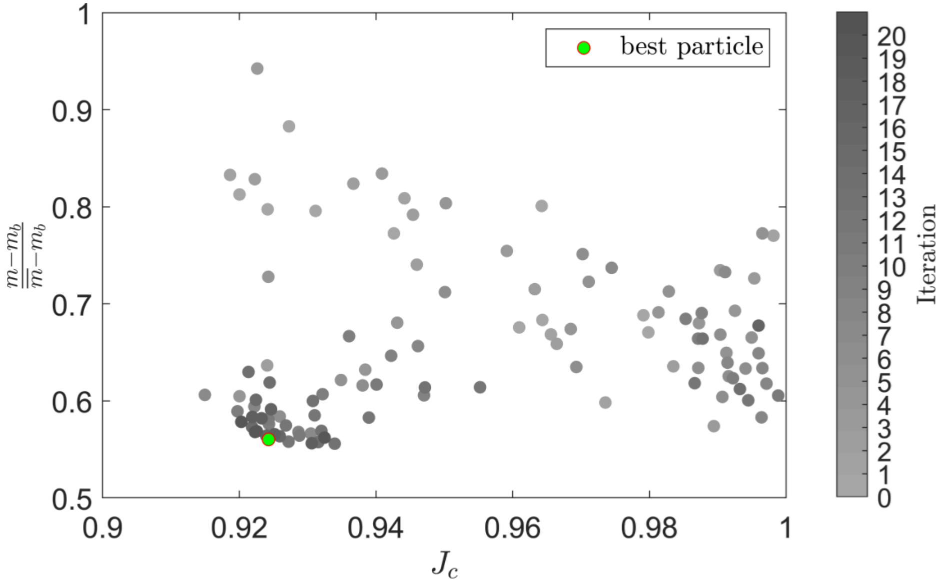
Total computational time	36251.98 s ≈ 10 hours
Minimum value of the nominal spacecraft total mass	1249.67 kg
Percentage of the saved mass w.r.t. the maximum expected mass without considering mass of the central rigid body m_cb (saved mass on the flexible appendages): (m_max – m_best)/(m_max-m_cb)	43.95 %
Mass reduction obtained w.r.t. the maximum expected nominal mass	60.13 kg
Optimal mass index	0.5605
Optimal control index	0.924266

Flexible Appendage	**Min Mass (kg)**	**Max Mass (kg)**	**Opt Mass (kg)**	**Saved Mass w.r.t. Max mass (kg)**	**% Saved Mass w.r.t. Max mass**
Solar Arrays	2 x 19.796	2 x 45.678	2 x 20.717	2 x 24.96	54.646 %
SRS	2 x 0.94421	2 x 2.3854	2 x 1.0631	2 x 1.3223	55.432 %
SAR	33.109	40.669	33.109	7.560	18.589 %

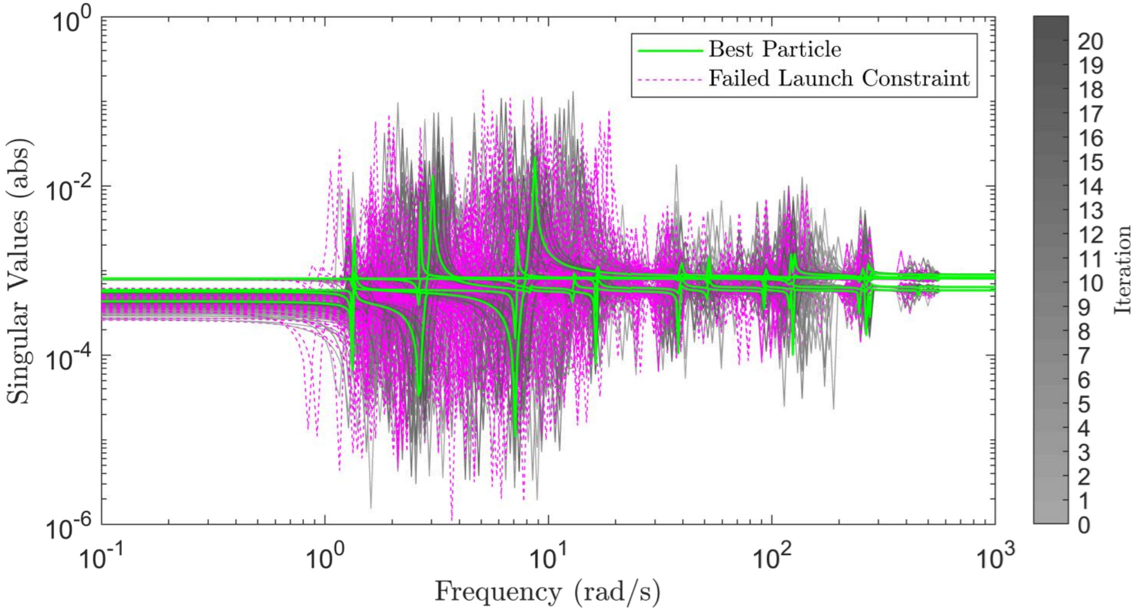
Iterative Co-design – Dealing with several design parameters and exogenous structural constraints

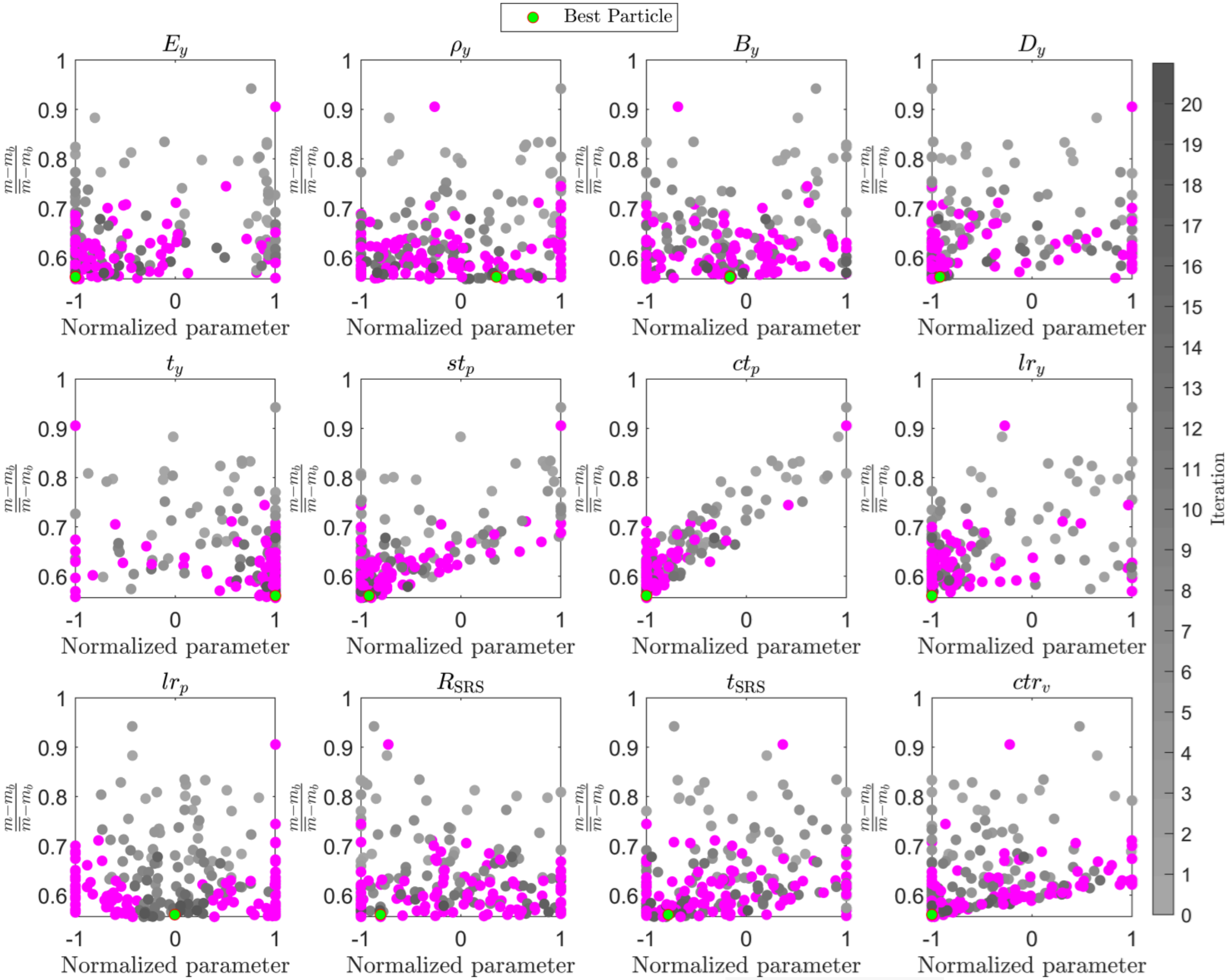




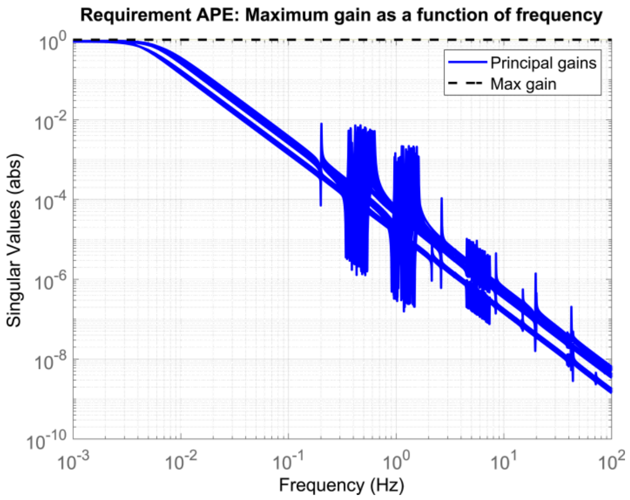


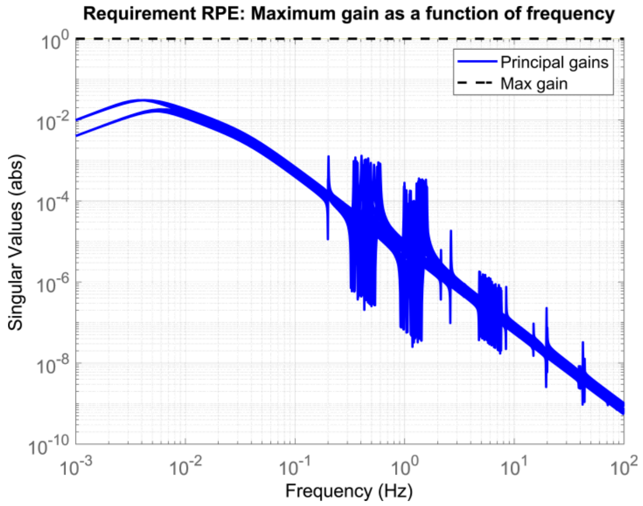
Iterative Co-design – Dealing with several design parameters and exogenous structural constraints

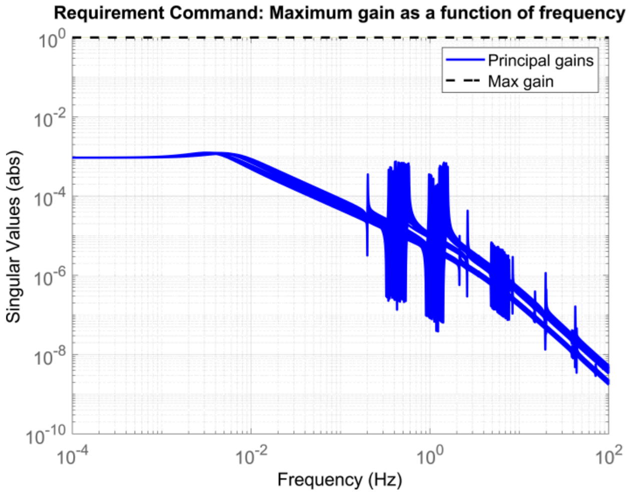


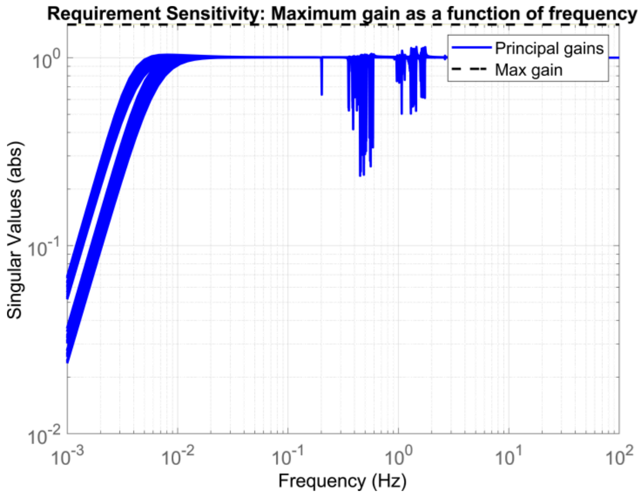


Iterative Co-design – Dealing with several design parameters and exogenous structural constraints









Requirement	**Optimal Value**
APE	0.924266
RPE	0.030560
Command	0.001222
Sensitivity	0.782743
Noise Variance	0.033027

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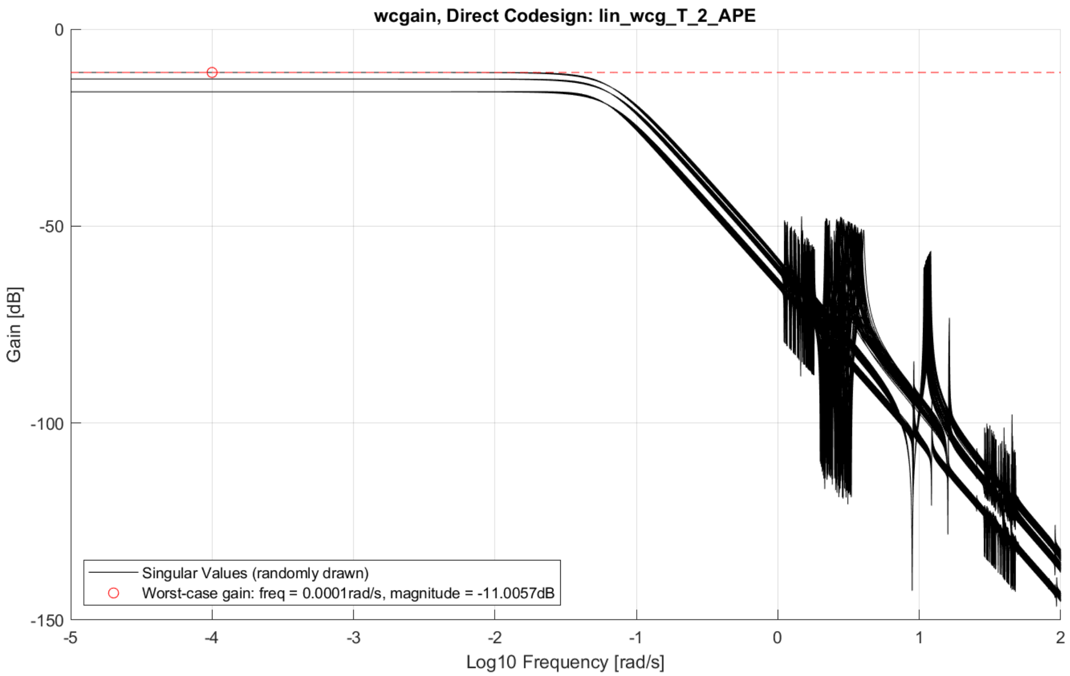
Validation & Verification Summary

- The V&V activity involved the following analyses:
  - **Linear analysis** (mu-analysis/worst-case gain)
  - **Non-linear** simulations
- The following controllers were tested:
  - **Direct co-design** controller
  - **Iterative co-design** controller
  - **Classical** controller (Non-linear Monte Carlo simulations only)
- The **linear analysis** comprised of the following analyses:
  - **Robust performance** analysis (mu-analysis)
  - **Robust stability** analysis (mu-analysis)
  - Maximum **bandwidth** analysis
  - **H2** norm analysis
- The **non-linear** simulator analysis comprised of the following analyses:
  - **Monte Carlo** analysis campaign
  - **Worst-case analysis** campaign
    - Differential evolution global optimisation

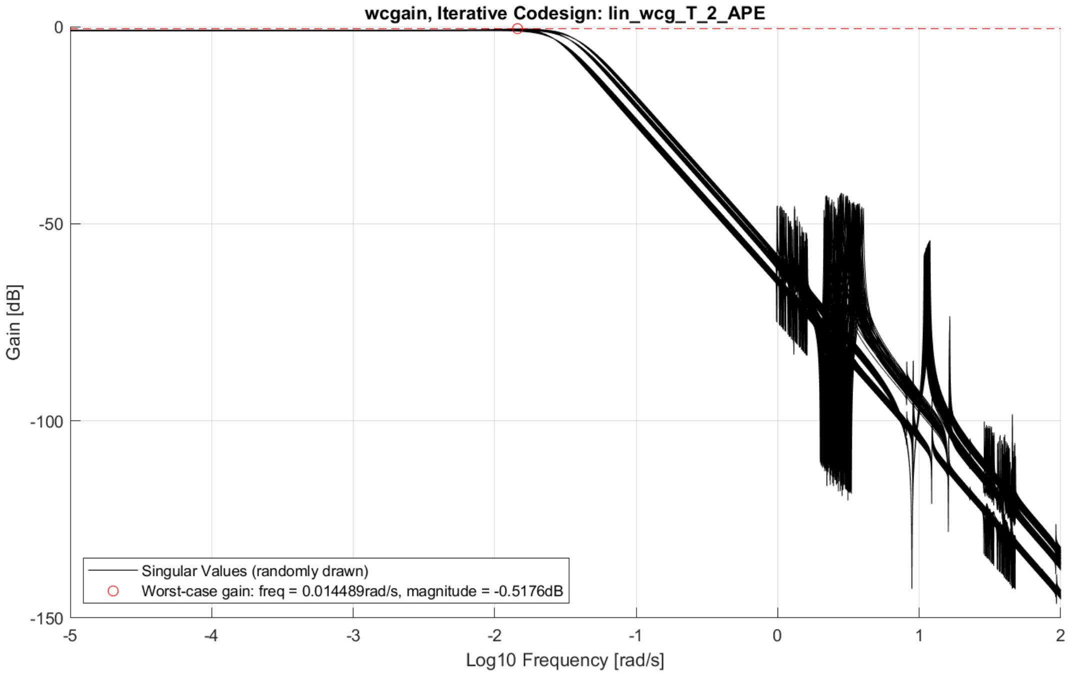
Linear Analysis: Robust Performance, direct co-design (worst-case gain)

- Robust performance is shown via the Matlab function **wcgain**
- Requires **upper bound < 0dB** for all transfers
- **Singular values** of 10 randomly drawn transfers (black)
- Wcgain **solution not possible** on full augmented plant, simplifications were necessary to find a solution:
  - **Truncation** of some flexible modes
  - **SA angle** run for discrete angles [0 30 60 90 120 150]deg



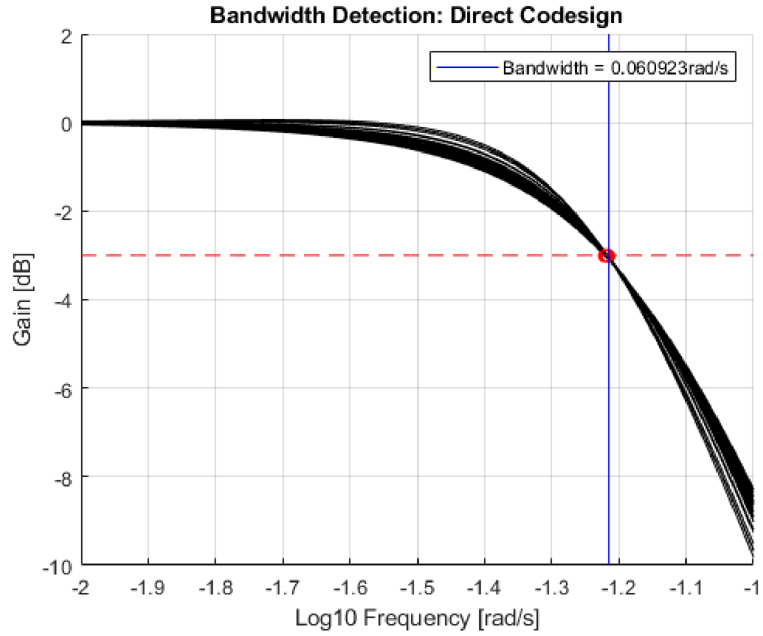
Linear Analysis: Robust Performance, iterative co-design (worst-case gain), Disturbance to APE

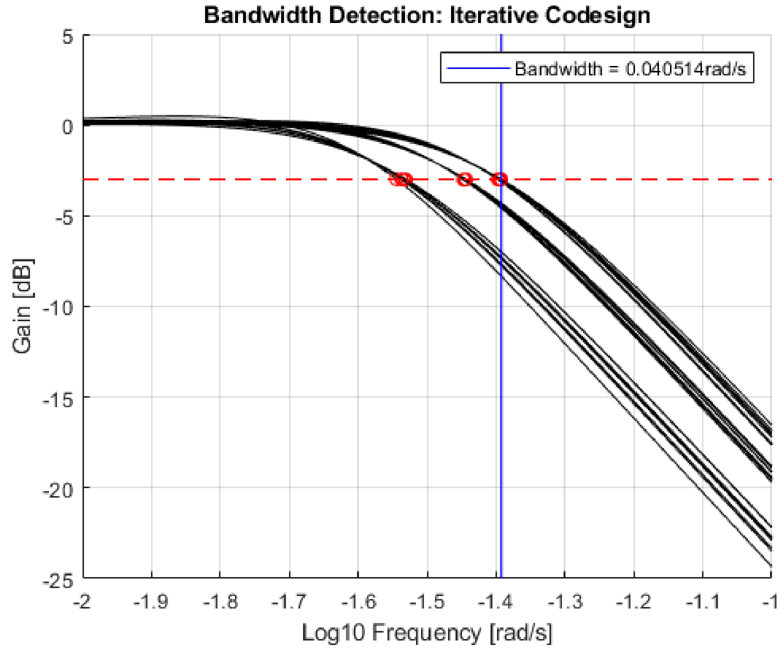
- Disturbance to APE transfer for the iterative co-design shows the **highest upper bound**, very close to 0dB
- Iterative co-design controller has **lower bandwidth** controller
- Greater margin needed on disturbance torque
- Other contributors to disturbance torque (**feedforward errors**) result in the y-axis APE exceeding the requirement as a result
- All other iterative co-design wcgain upper bound were more **comfortably below 0dB**



Additional linear Analysis: robust stability, bandwidth analysis, H2 norm

- Initial **robust stability** analysis did not find a solution on full LFT
  - Show **negative real parts of the**
  - **Successful** lower bounds > 1 found with reduced plant
    - Direct Co-design lower bound = **3.3202**
    - Indirect Co-design lower bound = **3.2230**
- **Maximum bandwidth** calculated empirically via randomly generated plants
  - **3dB drop** in gain wrt DC-gain of Td→APE transfer
  - **Lower bandwidth** of iterative co-design is observed
  - Maximum bandwidth is more than an **order of magnitude** lower than minimum **flexible mode frequency** (SRS, 1.8718rad/s) showing successful gain rejection
- **H2 norm** analysis performed using wcvariance function provided by SUPAERO
  - All upper bounds **< 0dB**

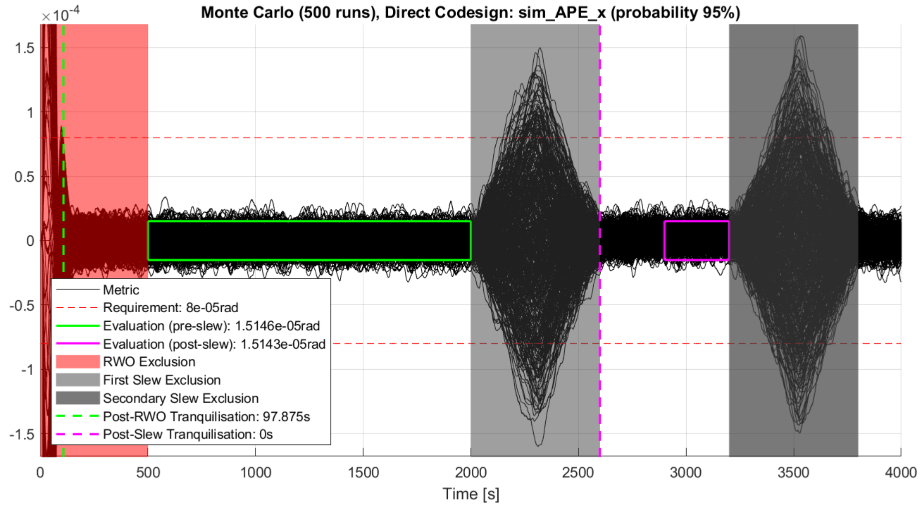

Bandwidth Detection: Direct Codesign


Bandwidth Detection: Iterative Codesign

Non-linear Simulations: simulator description

- Non-linear simulator developed in frame of the study, used for **Monte Carlo** and **worst-case analysis** optimisation
- **Two slews** present in the Monte Carlo simulations (40deg roll over 10 minutes)
  - Slew from nominal attitude to **SAR acquisition attitude**
  - Slew back to **nominal attitude**
- Slewing to SAR acq. attitude result in **increase in gravity gradient** torque
- **RWO** performed at start of simulation
  - **Thruster pulses** with closed loop RW control
  - This approach gives the most **aggressive** RWO dynamics
- Science requirements **not applicable** during RWO and slews
- **Feedforward** used:
  - **RW gyro-torque** feedforward
  - **Angular acceleration** feedforward
  - **Inertia gyro-torque** (from cross-products) feedforward
- **Tranquilisation** analysed
- Green and magenta boxes represent **statistical mixed interpretation** evaluation of all time-steps and over all simulations

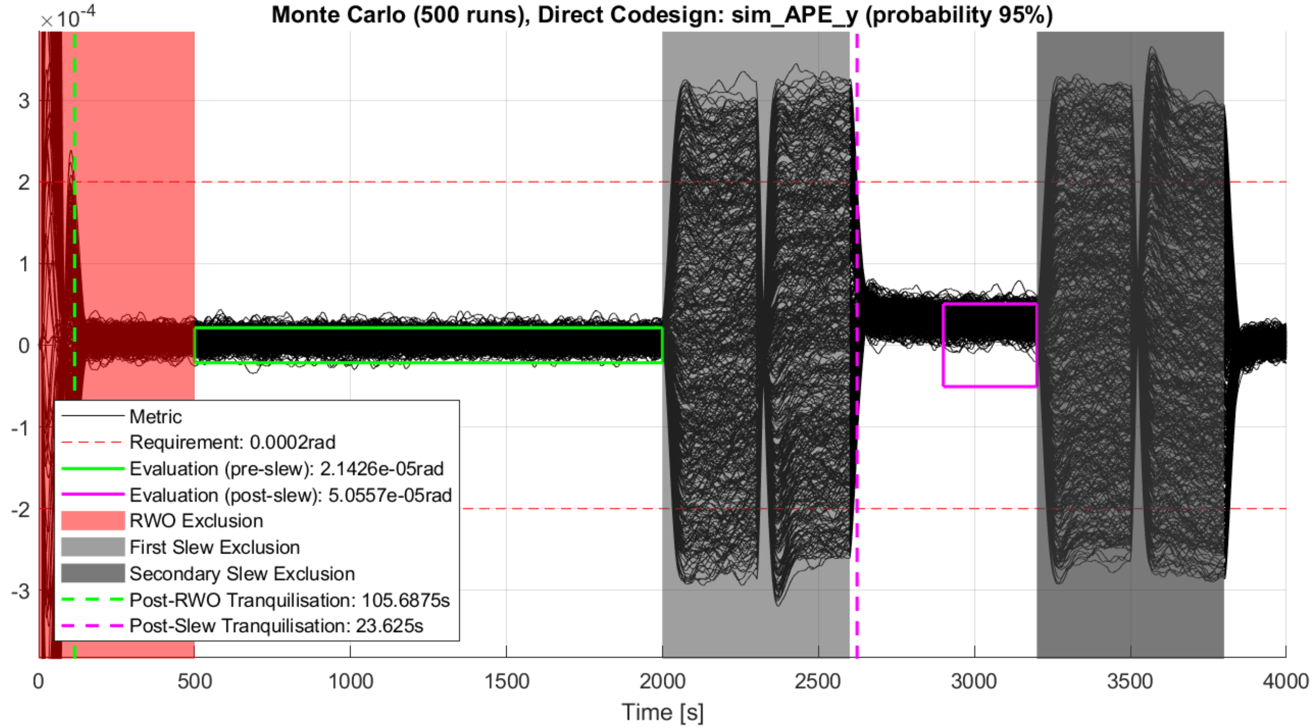
Example of Monte Carlo plot



Monte Carlo (500 runs), Direct Codesign: sim_APE_x (probability 95%)

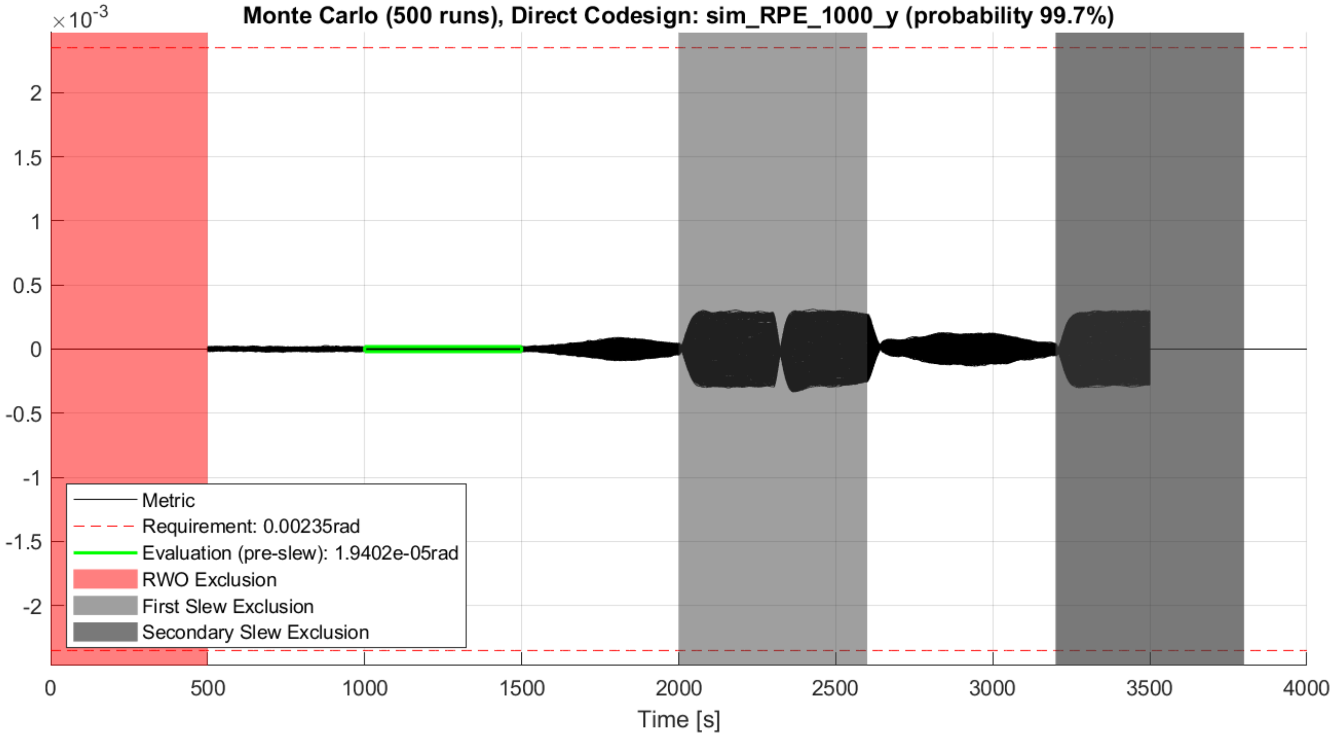
Non-linear Simulations, Monte Carlo, Direct Co-design: APE y-axis

- **Y-axis APE** is generally the **driving scenario**, although direct co-design controller is comfortably within requirements thanks to higher bandwidth



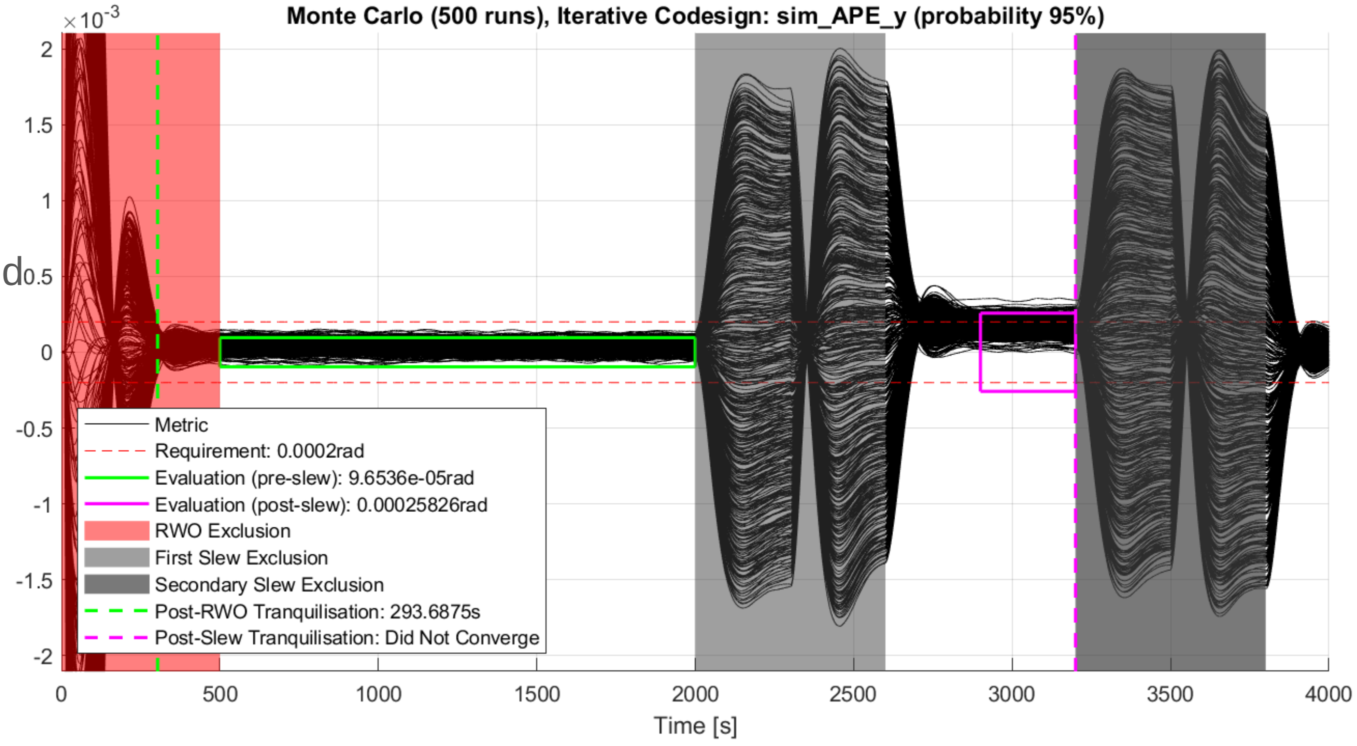
Non-linear Simulations, Monte Carlo, Direct Co-design: RPE y-axis (1000s)

- All **RPE** performances **comfortably within requirements**
- Y-axis with **1000s** window is the **most prominent**
- Statistical mixed interpretation evaluation **cannot be performed** between slew due to large window size, although compliance can be **easily observed** from the plot



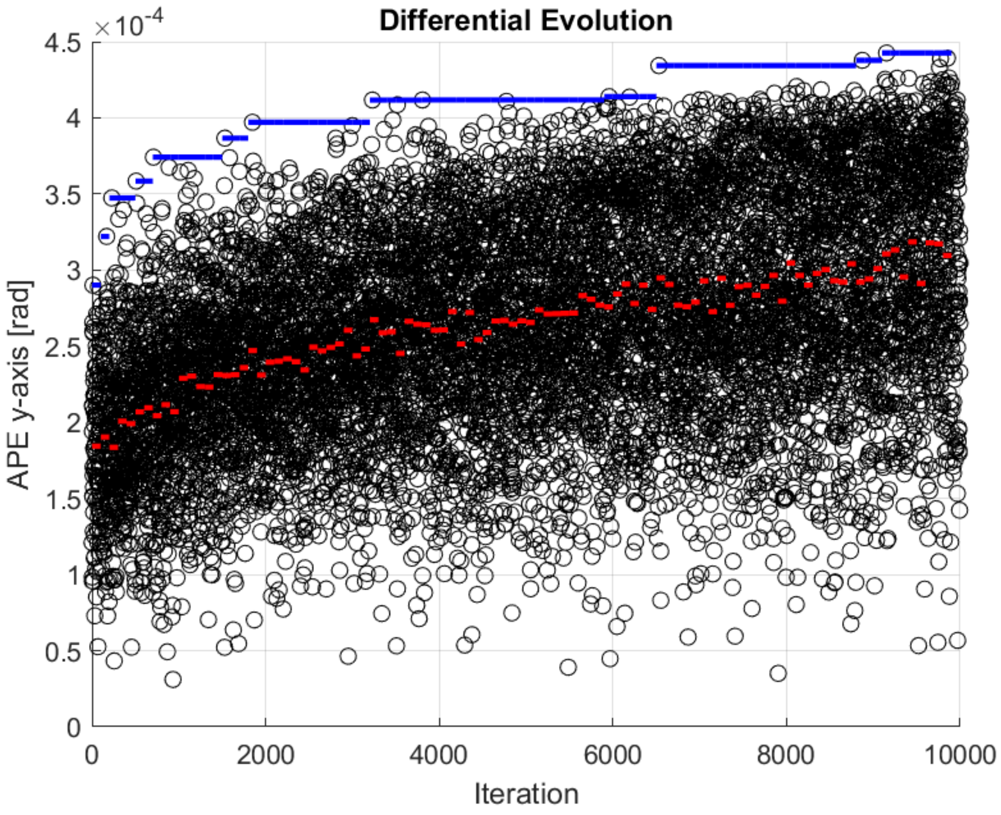
Non-linear Simulations, Monte Carlo, Indirect Co-design: APE y-axis

- **Only non-compliance** when at SAR acquisition attitude (after first slew), due contribution of errors in all three **feedforward** signals, could be avoided via:
  - Taking **sufficient margin** on values used in synthesis
  - **Predicting** the additional contributing factors and accounting for them in synthesis
- Re-running synthesis following V&V was not planned



Non-linear Simulations, Worst-Case Analysis, Indirect Co-design: APE y-axis Scenario 1

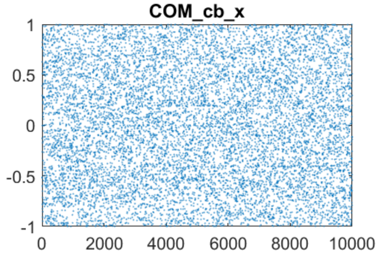
- Optimisation-based worst-case analysis was performed for **indirect co-design y-axis APE** (driver)
- **Differential Evolution** algorithm (global optimisation, evolutionary algorithm) via WCATII
- A dedicated, **shorter** (500s) simulation was used for the optimisation to reduce run time (many iterations needed)
  - RWO not performed
  - Slews not performed
  - Simulations starts in SAR acquisition attitude
- Worst-case found is considerably higher than the requirement (2e-4Nm); however, **this does not represent a statistical evaluation** and cannot be used directly to prove non-compliance
  - **Monte Carlo** must be used for **final validation**, although this result is useful in identifying worst-case



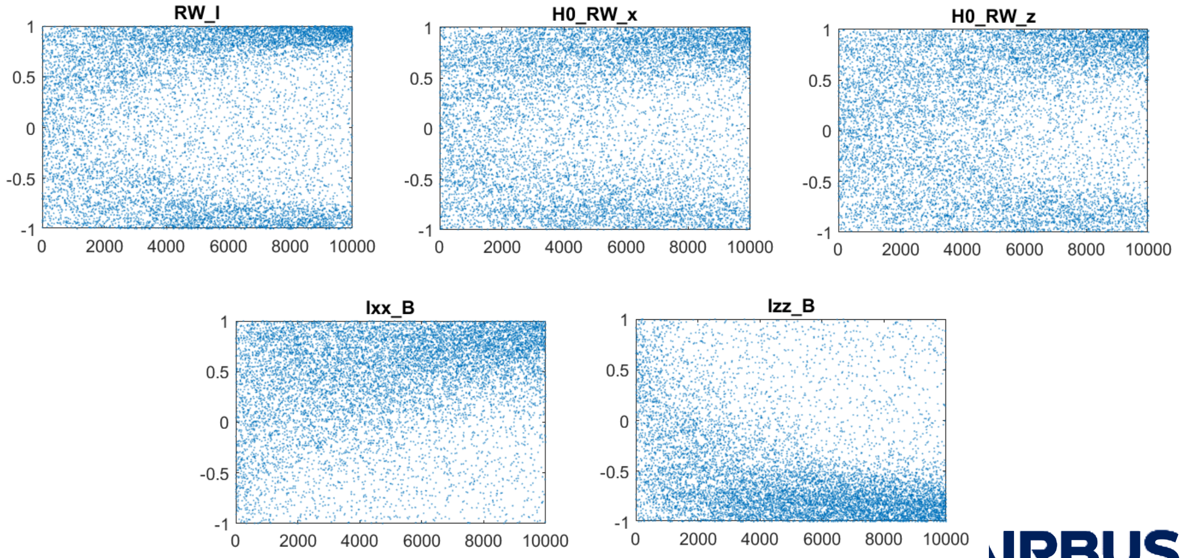
Non-linear Simulations, Worst-Case Analysis, Indirect Co-design: APE y-axis Scenario 1

- The **vast majority** of parameters are **non-converged**
- Three of the converged parameters can be explained: **RW inertia, RW z-momentum & RW z-momentum**
  - RW inertia uncertainty reduces accuracy of RW **gyro-torque** feedforward
  - This effect is worse when RW **momentum is maximised**
  - Y-axis momentum **does not contribute** to Y-axis feedforward torque
- Spacecraft Ixx and Izz inertias contribution is due to **largest cross-products** w.r.t. frame aligned with orbital velocity vector → larger inertia gyro torque **feedforward** error

Example of non-converged parameter



Converging parameters



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Conclusions (1)

- GNC design cycle was performed using an **integrated control-structures co-design** using the EnVision benchmark

- This activity involved **simultaneously optimising** the controller and key structural parameters in order to provide a solution which provides **minimal spacecraft mass** whilst simultaneously satisfying **AOCS requirements**

	Solar Array saved mass [kg]	**SRS saved mass [kg]**	**SAR saved mass [kg]**	**Total mass saving [kg]**
Direct co-design	31.3	3.24	7.56	42
Iterative co-design (4 parameters)	31.08	2.81	7.54	41.43
Iterative co-design (12 parameters)	49.92	2.64	7.56	60.12

- Integrated modelling, design and verification **framework** was developed which is generic and can also be applied to other missions

- Framework was developed via a number of **study cases** during study

- Additionally, a high fidelity end-to-end non-linear simulation environment was developed to be tested via a **V&V process** consisting of linear analysis, non-linear simulator-based Monte Carlo and worst-case analysis in order to validate against the **requirements** of the EnVision mission

Conclusions (2)

- **Areas for further development** identified during the study are as follows:
  - Adoption of a more **challenging scenario** to better explore the pareto front of the optimisation, such as:
    - Using **relaxed range limits** for the optimised structural design parameters such that the optimal structural parameters would not lie on the limits
    - Using more **demanding pointing requirements**, and therefore allowing divergence from the EnVision requirements. This could result in the local minima not being at the extreme limits of the structural parameters
  - The use of **analytical models of thin plates**, thereby removing the need to use NASTRAN for structures such as the SAR and solar arrays → potentially, the iterative co-design process could **avoid the use of NASTRAN** in-the-loop completely
  - Incorporation of **launch constraints test in the direct co-design** in order to have a fair comparison between direct and iterative co-design. In the study, the launch constraints were only accounted for in the iterative co-design
  - Use of **multicore software architecture** to reduce synthesis/V&V runtime
  - Modelling of **appendage deflection** in the co-design synthesis and analysis, thereby ensuring that **boresight** accuracy requirements are met

Open discussion & questions

Thank you

Back-up Slides