Executive Summary Report

DRL: ESR

DTI EXPORT CONTROL RATING: Not Listed
Rated by: P. Matakidis

Prepared by:	*Mark Watt* *D. Alazard / F. Sanfedino*	Mark Watt Digitally signed by: Mark Watt DN: CN = Mark Watt email = mark.watt@airbus.com C = GB O = Airbus DS OU = Airbus DS Date: 2022.12.13 17:16:17 Z	*Airbus Study Team* *ISAE-SUPAERO Study Team*
Checked by:	*Mark Watt*	Mark Watt Digitally signed by: Mark Watt DN: CN = Mark Watt email = mark.watt@airbus.com C = GB O = Airbus DS OU = Airbus DS Date: 2022.12.13 17:18:51 Z	*Study Technical Lead*
Approved by:	*Panos Matakidis*	P. Matakidis Digitally signed by: P. Matakidis DN: CN = P. Matakidis email = panos.matakidis@airbus.com C = GB O = Science Future Programmes Department OU = TSEAT2 Date: 2022.12.13 10:38:17 Z	*Study Manager*
Authorised by:	*Panos Matakidis*	P. Matakidis Digitally signed by: P. Matakidis DN: CN = P. Matakidis email = panos.matakidis@airbus.com C = GB O = Science Future Programmes Department OU = TSEAT2 Date: 2022.12.13 10:38:33 Z	*Study Manager*

CONTENTS

TABLES

FIGURES

1 INTRODUCTION

This document presents a high-level executive summary of the Control/Structure Co-Design for Planetary Spacecraft with Large Flexible Appendages study. A co-design in this context involves simultaneously optimising the controller and structure whilst meeting all performance and stability metrics.

A summary of the two main methods of performing a control/structure co-design will be presented: the Direct Co-design and the Iterative Co-design. Finally, a summary of the V&V activity performed at the end of the study will be presented.

APPLICABLE AND REFERENCE DOCUMENTS

1.1 Applicable Documents

The following documents are applicable and are referred to as [AD xx] in the text:

Number	Title	Document Number	Issue
AD-01	Control Structure Co-design for Planetary Spacecraft with Large Flexible Appendages, Statement Of Work	ESA-TECSAG-SOW-018989	1.0 (5/06/2020)

1.2 Reference Documents

The following documents are referenced for supporting information and are referred to as [RD xx] in the text:

Number	Title	Document Number	Issue
RD-01	TN01 TN-01 Problem Formulation	S&P-SP-ADSS-1000968538	3.0
RD-02	TN02 State of the Art of Inter Disciplinary Merged Design	S&P-DD-ADSS-1000968539	2.0
RD-03	TN03 Requirements Definition for Control and Structure	S&P-SP-ADSS-1000968540	3.0
RD-04	TN04 Physical Modelling and Finite Element Methods Trade-off	S&P-SP-ADSS-1000968541	2.0
RD-05	TN05 Design of Control and Structural Elements	S&P-DD-ADSS-1000968542	3.0
RD-06	TN06 GNC Architecture, Models and Uncertainty Models	S&P-MDL-ADSS-1000968543	2.0
RD-07	TN07 Co-Design Tools	S&P-DD-ADSS-1000968544	2.0
RD-08	TN-08 Metrics for Control, Structure and Optimisation	S&P-MX-ADSS-1000968548	1.1
RD-09	TN09 TN-09 Design of Control and Structural Elements	S&P-DD-ADSS-1000968549	1.1
RD-10	TN10 GNC and Structures Validation and Verification	S&P-VCD-ADSS-1000968551	3.0
RD-11	TN11 GNC and Structures Validation and Verification	S&P-RP-ADSS-1000968552	1.1
RD-12	Final Report	S&P-RP-ADSS-1000968561	1.0

2 ACRONYMS

Acronym	Meaning
AOCS	Attitude and Orbit Control System
APE	Absolute Performance Error
RPE	Relative Performance Error
SAR	Synthetic Aperture Radar
V&V	Validation and Verification
SDT	Satellite Dynamics Toolkit
LFT	Linear Fractional Transformation
CoM	Center of Mass

Acronym	Meaning
USS	Uncertain State Space
AKE	Absolute Knowledge Error

3 OVERVIEW OF ACTIVITIES

The study activities can be broadly split into the following phases:

1. Co-design synthesis and analysis activity
2. Validation and verification (V&V) activity

Both activities will be described in the following sections.

3.1 Co-design activity

Two methods of co-design are performed in this study:

- Direct co-design
- Iterative co-design.

The direct co-design involves optimising the controller gains and structural design parameters simultaneously via the MATLAB tool systune. An LFT is used by systune that contains the optimisable parameters of the controller gains and the structural parameters as well as the system uncertainties. The APRICOT tool is used in the generation of this LFT which creates a polynomial fit from a number of FEM which is then assembled into the full spacecraft LFT via the SDT tool.

The iterative co-design uses an outer global optimisation loop (e.g. particle swarm) to optimise the structural parameters and an inner systune optimisation for the robust controller synthesis. Rather than using the polynomial fitted LFT from APRICOT, the iterative co-design runs NASTRAN at each iteration of the outer global optimisation loop to provide the inputs required for SDT to assemble the full spacecraft.

The aforementioned tools are as follows. The systune tool is a Matlab function which tunes fixed-structure control systems subject to both soft and hard design goals and is compatible with robust design techniques. APRICOT (Approximation of Polynomial and Rational-type for Indeterminate Coefficients via Optimization Tools) is a function in the SMAC toolbox of the SMART library (ONERA) which allows numerical data to be converted into polynomial or rational expressions (used for fitting the LFT). SDT (Satellite Dynamics Toolbox) is a tool developed by ISAE SUPAERO used to compute the linear dynamics model of satellites with multiple flexible appendages.

Table 3-1 summarizes the associated TN and SW associated to each task.

Task	Description	TN	SW
FEM modelling	NASTRAN/MATLAB interface	TN4/Sect. 7	SW1/AUTOMATIC_MODEL_GENRATION
Mechanical Design	Physical model of simple-shaped flexible bodies	TN4/Sect 7	SW1/BEAMS SW1/PLATES
Fitting via APRICOT	Parametric model interpolation with LFT model	TN9/Sect 5.1	SW4_DirectCoDesignFinal
Linear multi-body dynamics modelling	Spacecraft assembly (linear and parameterized model)	TN9/Sect 5.2	SW4_DirectCoDesignFinal
Non-linear multi-body dynamics modelling	Spacecraft assembly (non-linear model)	TN4/sect 7	SW1/ENVISION_final
SDTlib to Simscape comparison	Cross-checking and model validation	TN4/sect7	SW1/COMPLEX_FLEXIBLE_BODIES
Robust co-design	Robust control: systune/muysn comparison	TN2/Appendix. TN9/Sect. 4	SW2_Optimal_Robust_Control

Task	Description	TN	SW
	Robust co-design on EnVision Benchmark: • Direct approach • Indirect approach	TN9/Sect 5 TN8/sect. 7	SW4_DirectCoDesignFinal SW4_DirectCoDesignFinal SW4_IndirectCoDesignFinal

Table 3-1: TN and SW per study task

Note that a significant aspect of this study was to perform a detailed trade-off of the tools and methods for various stages of the co-design process. For further details on this refer to the Final Report [RD-12].

3.2 V&V activity

The Validation and Verification (V&V) of the co-design controllers is summarised below. The following analysis campaigns were performed:

- Linear analysis (mu-analysis/worst-case gain)
  - Robust performance analysis (mu-analysis)
  - Robust stability analysis (mu-analysis)
  - Maximum bandwidth analysis
  - H2 norm analysis
- Non-linear simulations
  - Monte Carlo simulation campaign
  - Worst-case analysis (differential Evolution)

The following controllers were tested:

- Direct co-design controller
- Iterative co-design controller
- Classical controller (Non-linear Monte Carlo simulations only)

3.3 Reference scenario: 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, to understand how and why Venus and Earth evolved so differently. Perched at the inner edge of the habitable zone, Venus may once have had abundant liquid water and been able to sustain life, before developing the runaway greenhouse warming which rendered it uninhabitable today; thus providing a natural laboratory for understanding planetary conditions for life.

The EnVision mission was chosen due to its fine pointing requirements and its number of large flexible appendages. The EnVision appendages are the SRS dipole antennae, the Synthetic Aperture Radar (SAR) and two large solar arrays.

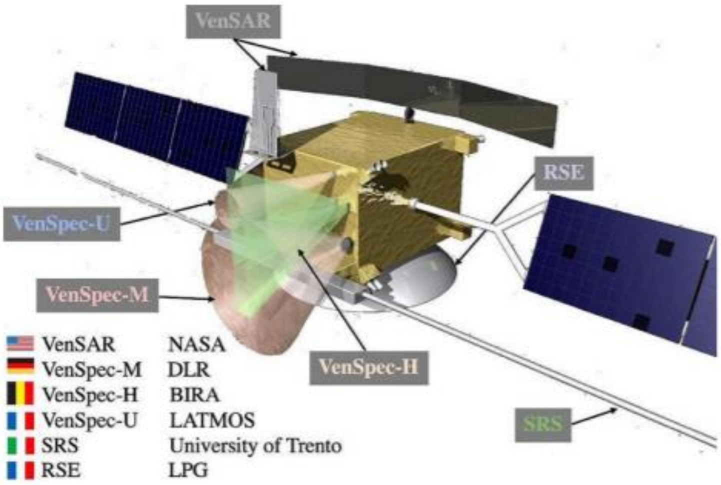


Figure 3-1: EnVision spacecraft

4 CO-DESIGN IMPLEMENTATION DEFINITION

Figure 4-1**Error! Reference source not found.** and Figure 4-2 schematically presents the constitutive tools and process flowchart for the direct co-design and the iterative co-design respectively. During this study, all fundamental elements have been tested and validated on both academic and industrial scenarios by gradually increasing the problem complexity, in order to define the possible limits and alternatives of the proposed algorithms.

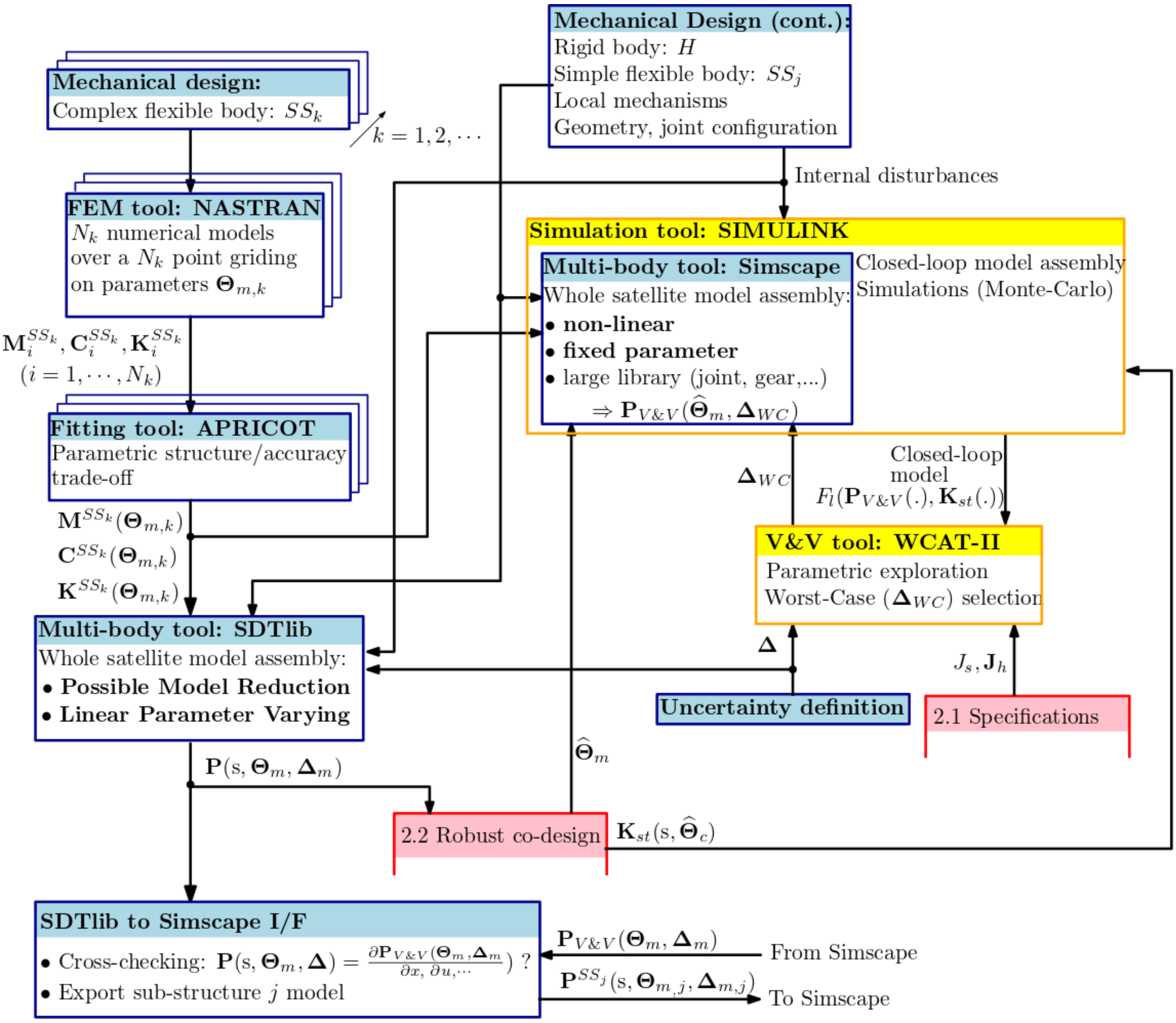
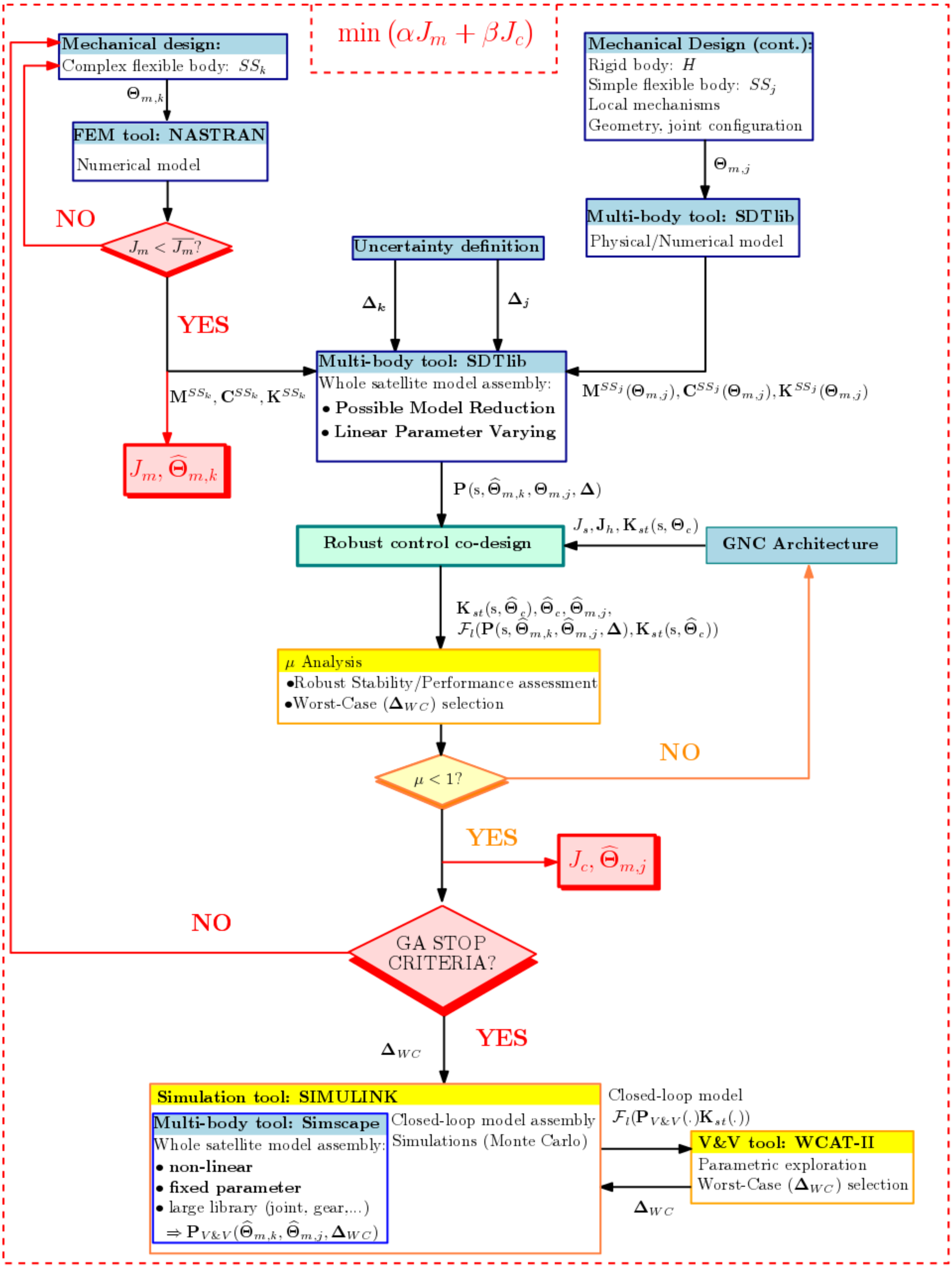


Figure 4-1: Constitutive tools and process flowchart for the direct co-design



$\Theta_{m,k}$: mechanical parameters for complex flexible bodies (FEM model)
$\Theta_{m,j}$: mechanical parameters for simple flexible bodies (physical model)
Θ_c : structured controller parameters
$\mathbf{\Delta}$: parametric and complex uncertainies; varying mechanism parameters (i.e. solar panel angular configuration)

Figure 4-2: Constitutive tools and process flowchart for the iterative co-design

The generalised closed-loop co-design problem is shown in Figure 4-3 showing the input/output weights and various linear elements in the closed-loop.

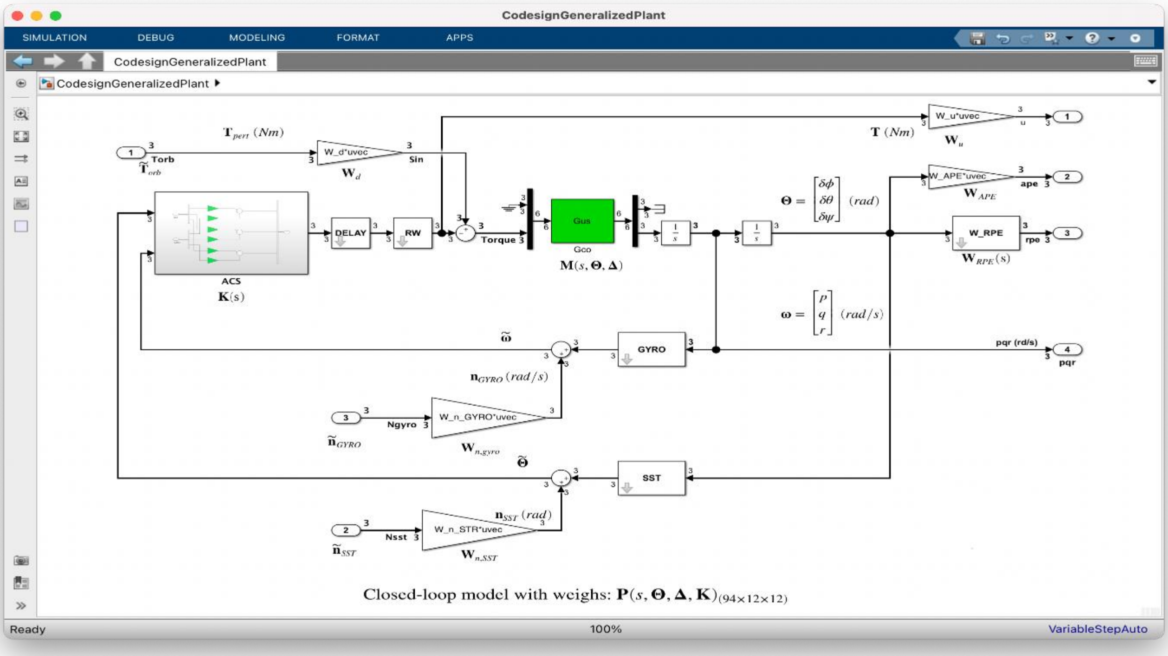


Figure 4-3: The generalized closed-loop co-design problem

Note that the use of APRICOT in the direct co-design restricts the number of uncertain parameters that can be included in the LFT. APRICOT can fail to find a solution when too many uncertain parameters are present. Therefore, the iterative co-design (which runs NASTRAN, rather than relying on APRICOT) allows for a greater number of uncertainties and therefore provides a greater scope for the optimisation at the synthesis stage.

5 DIRECT CO-DESIGN

5.1 General procedure

The dynamic model of the benchmark is first computed using:

- APRICOT to find an LFT fitting the collection of NASTRAN models sampled in the parametric space for:
    - the 6×6 dynamic model of the solar array: $\mathbf{D}^{SA}(s, \delta t_{SA}) = F_l(\mathbf{P}^{SA}(s), \delta t_{SA}\mathbf{I}_{60})$.
      Note that this fitting is performed on the mechanical parameters of the flexible bodies (frequencies, modal participation factors, mass, inertia, geometry) before the assembly of the model. Thus it is possible to add the 25 % of uncertainty on the flexible mode frequencies. The 2 solar array are assumed to be identical.
    - the 6×6 dynamic model of the SAR: $\mathbf{D}^{VENSAR}(s, \delta t_{SA}) = F_l(\mathbf{P}^{VENSAR}(s), \delta t_{VENSAR}\mathbf{I}_{116})$.
- the boom analytical model of the SDTlib for the 6×6 dynamic model of each part of the SRS: $\mathbf{D}^{SRS}(s, \delta t_{SA}) = F_l(F_l(\mathbf{P}^{SRS}(s), \delta r_{srs}\mathbf{I}_{110}), \delta t_{srs}\mathbf{I}_{130})$.
  The 2 booms of the SRS are assumed to be identical.
- the parametrized 6×6 twice DCM of the SDTlib: $\mathbf{DCM}(\theta) = F_l(\mathbf{P}^{DCM}, \tan(\frac{\theta}{4})\mathbf{I}_8)$ on each of input and output of the 2 solar arrays.

The model of the whole system can then be assembled using the function ***ulinearize*** applied to the SIMULINK file. The whole LFT can be simplified using the general function ***simplify*** and normalized parameters can be substituted for the physical ones. Then the 4 uncertain physical parameters $\boldsymbol{\Theta} = [t_{SA},\, t_{VENSAR},\, r_{SRS},\, t_{SRS}]^T$ must be transformed into tunable parameters thanks to the function ***myusubs***.

The closed-loop model $\mathbf{P}(s, \boldsymbol{\Theta}, \boldsymbol{\Delta}, \mathbf{K})$ for the co-design is handled thanks to the slTuner interface.

The total mass $m(\boldsymbol{\Theta}, \boldsymbol{\Delta})$ to be optimized (as a soft constraint) in the general co-design problem is evaluated from the dcgain (or the low frequency response) of the inverted transfer from the force to acceleration along the x-axis. Thus, it is not required to know a-priori the analytical expression of $m(\boldsymbol{\Theta}, \boldsymbol{\Delta})$. The requirements and the optimal co-design problem becomes:

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

such that:

1. $\max_{\boldsymbol{\Delta}} \|\mathbf{P}_{\mathrm{Torb}\to\mathrm{ape}}(\mathrm{s}, \boldsymbol{\Theta}, \boldsymbol{\Delta}, \mathbf{K})\|_\infty \leq 1$ (HC1 : APE performance),
2. $\max_{\boldsymbol{\Delta}} \|\mathbf{P}_{\mathrm{Torb}\to\mathrm{rpe}}(\mathrm{s}, \boldsymbol{\Theta}, \boldsymbol{\Delta}, \mathbf{K})\|_\infty \leq 1$ HC2 : (RPE performance),
3. $\max_{\boldsymbol{\Delta}} \|\mathbf{P}_{\mathrm{Torb}\to\mathrm{u}}(\mathrm{s}, \boldsymbol{\Theta}, \boldsymbol{\Delta}, \mathbf{K})\|_\infty \leq 1$ (HC3 : control signal limitation),
4. $\max_{\boldsymbol{\Delta}} \|\mathbf{P}_{\mathrm{Sin}\to\mathrm{Torque}}(\mathrm{s}, \boldsymbol{\Theta}, \boldsymbol{\Delta}, \mathbf{K})\|_\infty \leq 1.5$ (HC4 : disc margin),
5. $\max_{\boldsymbol{\Delta}} \|\mathbf{P}_{\begin{bmatrix}\mathrm{Nsst}\\ \mathrm{Ngyro}\end{bmatrix}\to\begin{bmatrix}\mathrm{APE}\\ \mathrm{RPE}\end{bmatrix}}(\mathrm{s}, \boldsymbol{\Theta}, \boldsymbol{\Delta}, \mathbf{K})\|_2 \leq 1$ (HC5: variance on RPE and APE from sensor (SST and GYRO) noises.

This problem is solved thanks to the function ***systune***.

Summary of the result: one can check that the first 4 hard constraints HC1 to HC4 (depicted in Figure 5-1) are not at all saturated and the 4 sizing parameters are tuned on their lower bound. The value of the HC5 is 0.0617. The saved mass is 21 Kgs. The 4 mechanical sizing parameters $\boldsymbol{\Theta} = [t_{SA},\, t_{VENSAR},\, r_{SRS},\, t_{SRS}]^T$ are all tuned to their lower bounds.

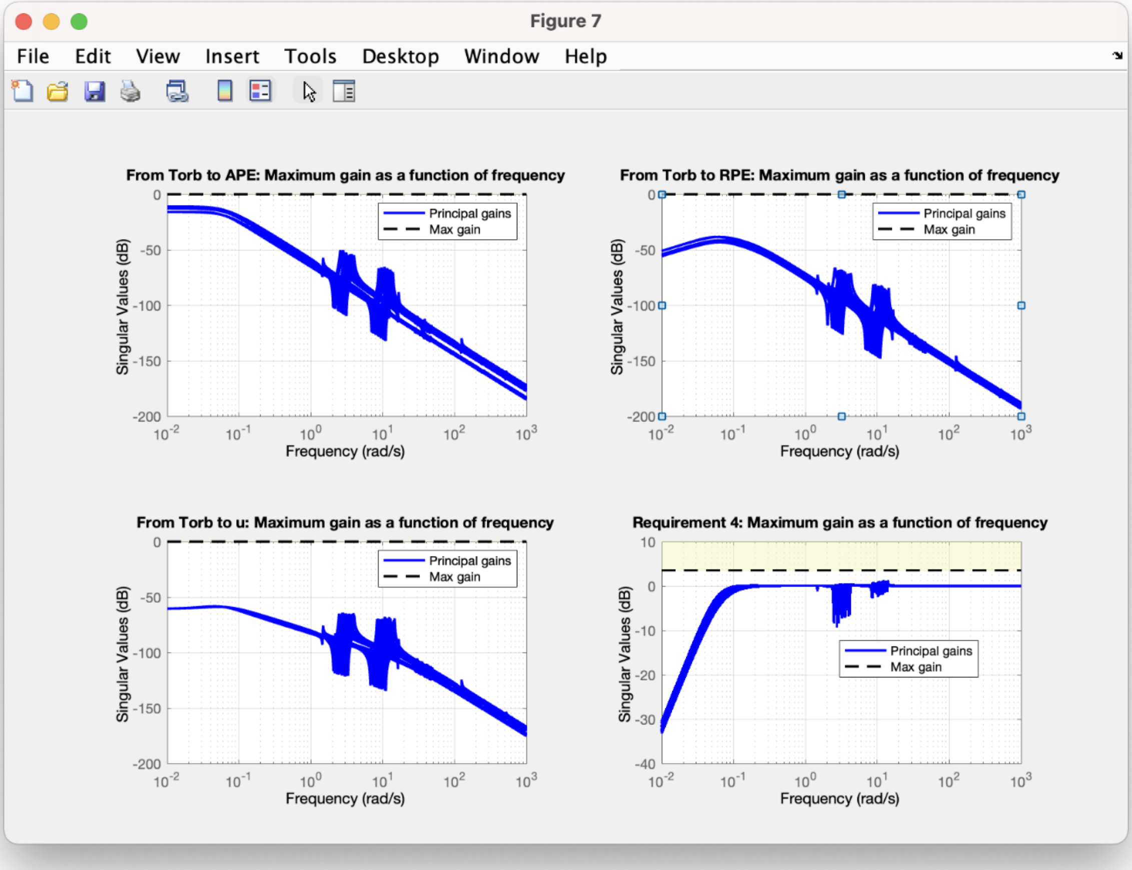


Figure 5-1 Frequency-domain responses of the hard constraints.

5.2 Direct co-design conclusions

This co-design on a simpler LFR of the parametric model leads to the conclusion that the approach based on APRICOT and systune is quite efficient. Additionally, interactivity with the user is very good due to a reasonable computation time. The call to systune takes approximately 3 minutes on this nominal co-design and approximately 1 hour for the most challenging co-design scenarios. Note that the RandomStart option was not used in the runs of systune in order to minimize the computation time.

Such an approach must be restricted to "reasonable" sizes of the LFR of the parametric model and a few sizing parameters (APRICOT restriction). Note that this problem is not at all challenging since all mechanical parameters are tuned to their lower bounds and the margins on all the hard constraints are sufficiently high.

In order to raise some more challenging co-design problems, the APE requirement has been hardened. In this case, the co-design finds a minimal mass solution while saturating the 2 hard constraints on the APE requirement and disc margin requirement. Balancing between hard and soft constraints for the APE requirement allows us to roughly investigate the Pareto front between the normalized APE and the normalized saved mass as depicted in Figure 5-2.

With the exception of the robust control design for the nominal mechanical configuration (case # 5), all the points saturating the disc margin requirements (green points) seem to belong to a convex Pareto front.

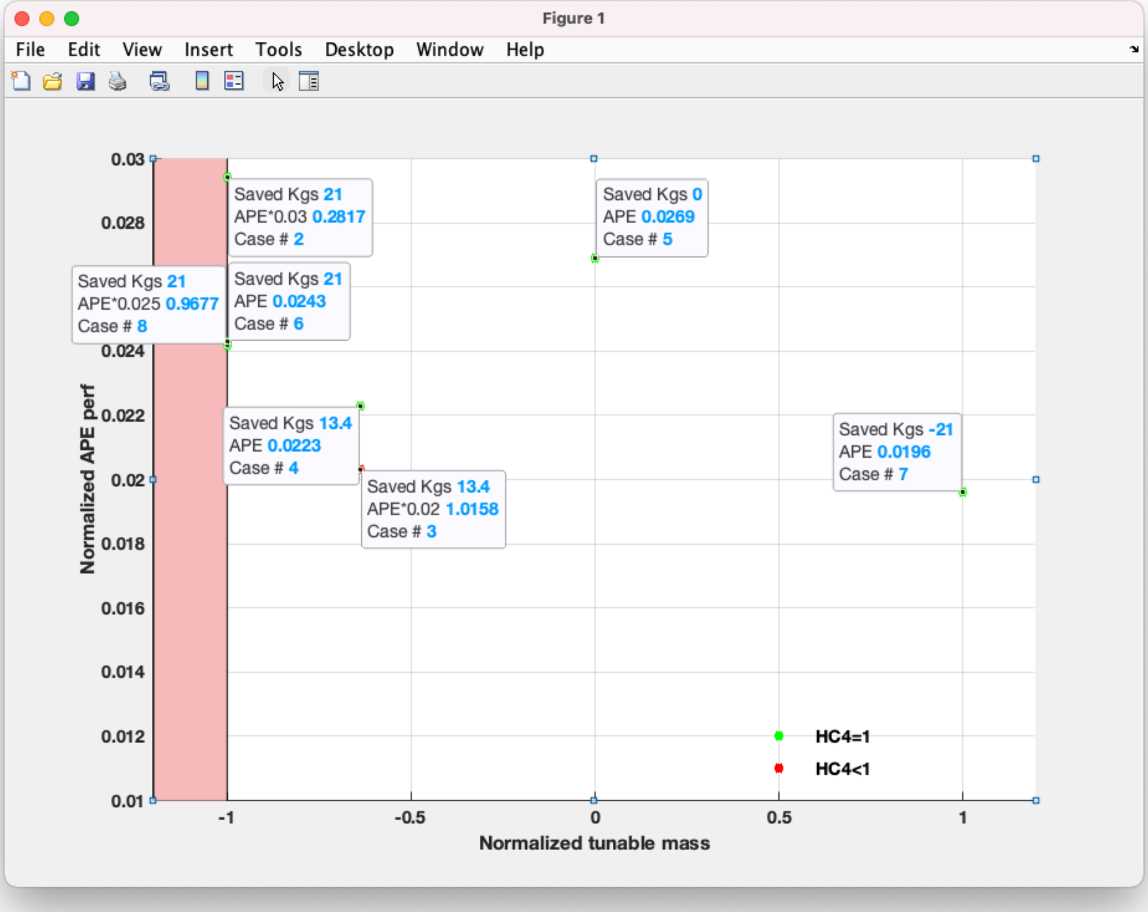


Figure 5-2: “Pareto” front.

6 ITERATIVE CO-DESIGN

In this section we present how to deal with the same optimization problem proposed in the previous chapter by using the iterative approach outlined in [RD-05].

12 mechanical design parameters are taken into account:

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

6.1 Definition of optimization cost function

At each particle swarm iteration of the Particle Swarm optimization (see [RD-05]) the following cost function will be evaluated:

$$\begin{cases} fBest = \dfrac{m - m_{cb}}{m_{max} - m_{cb}} + J_c & if\ f^{launch} > f^{launch}_{min} \\ fBest = 10 & otherwise \end{cases}$$

Where m is the total mass of the spacecraft at the current swarm iteration, m_{cb} is the nominal mass of the central rigid body, m_{max} is the maximum expected mass whose value is imposed by the range of the admissible mechanical design parameters and $J_c = \max_i \gamma_{c_i}$ is the maximum among the 5 control requirements γ_{c_i}.

In the case that the empirical frequency of the first stowed solar panel computed with Eq. (1) is less than $f^{launch}_{min} = 38\ Hz$, then the cost function is penalized as $fBest = 10$.

6.2 Results of the iterative co-design

The total time to perform 20 iterations (10 swarm particles/iteration) of Particle Swarm is approximatively 10 hours.

The results of the optimization of the mass are summarized in Table 6-1. The saved mass w.r.t. the max expected nominal satellite mass is approximatively 60 kg, which represents 43% of the total mass of the 5 flexible structures to be optimized.

The maximum control index corresponding to the optimal solution is 0.924266.

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**

Table 6-1: Iterative co-design.

A details of the mass saved for each flexible appendage is outlined in Table 6-2.

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 %**

Table 6-2: Iterative co-design results – Flexible Appendage optimization.

The evolution of the cost function evaluation along the Particle Swarm iterations is shown in Figure 6-1. In particular, in this figure, all solutions not satisfying the launch constraints are removed from the quantile plot for clarity.

The pareto front of mass and control indexes is shown in Figure 6-2. It is clear that for the beginning of the optimization, the particles migrate towards the global optimum which is a compromise of low mass and high control performance.

Note that better mass performance could be reached by leaving the control performance index to reach unity. In this case, a different formulation of the cost function should be used. The reason why the control index is simply minimized is that some margin w.r.t. unity can help at the V&V stage, where a bigger set of uncertainties can be considered w.r.t. to those used for controller synthesis.

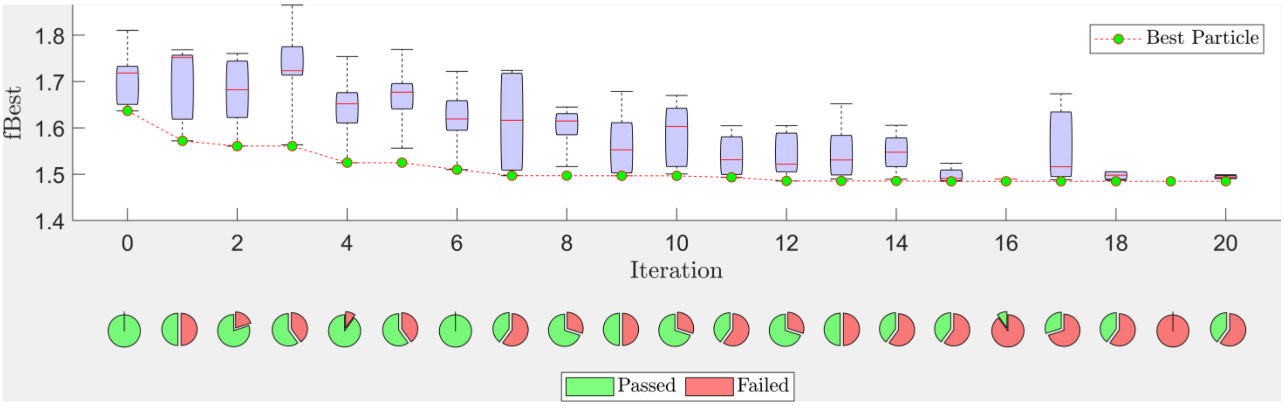


Figure 6-1: Evolution of the cost function during Particle Swarm iterations. The pie-plots show the percentage of solutions passing the launch constraint test.

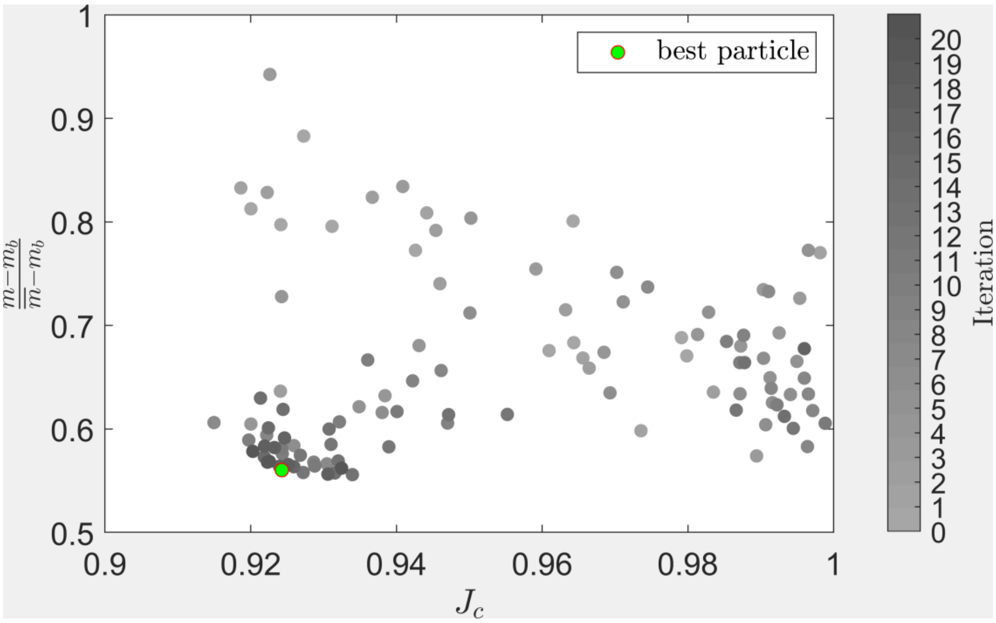


Figure 6-2: Pareto plot.

7 CONCLUSIONS

In this study, a GNC design cycle was performed using an integrated control-structures co-design using the EnVision mission as a 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. In order to achieve this, an integrated modelling, design and verification framework was developed which is generic and can also be applied to other missions. This framework was developed and matured via a number of study cases resulting in the final delivered software. 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.

Two methods of co-design developed in the study are presented: direct co-design and iterative co-design. Both cases show successful optimisation of the spacecraft total mass whilst satisfying the performance requirements assumed.

The direct co-design involves optimising the controller gains and structural design parameters simultaneously via the MATLAB tool systune. An LFT is used by systune that contains the optimisable parameters of the controller gains and the structural parameters as well as the system uncertainties. The APRICOT tool is used in the generation of this LFT which creates a polynomial fit from a number of FEM which is then assembled into the full spacecraft LFT via the SDT tool.

The iterative co-design uses an outer global optimisation loop (e.g. particle swarm) to optimise the structural parameters and an inner systune optimisation for the robust controller synthesis. Rather than using the polynomial fitted LFT from APRICOT, the iterative co-design runs NASTRAN at each iteration of the outer global optimisation loop to provide the inputs required for SDT to assemble the full spacecraft.

Notable gaps and limitations identified during the co-design are as follows:

- Adoption of a more challenging scenario to better explore the pareto front of the optimisation, in particular using larger range limits for the optimised structural design parameters such that the optimal structural parameters would not lie on the limits
- The use of analytical models of thin plates, thereby removing the need to use NASTRAN for structures such as the SAR and solar arrays
- Incorporation of launch constraints test in the direct co-design in order to have a fair comparison between direct and iterative co-design
- Use of multicore to reduce synthesis runtime
- Modelling of appendage deflection in the co-design synthesis and analysis, thereby ensuring that boresight accuracy requirements are met

Notable gaps and limitations identified during the V&V are as follows:

- Sufficient margins should be taken on assumptions at the synthesis stage to mitigate against unforeseen degradations to performance, thereby ensuring that the verification against requirements is successful at the V&V stage
- The planning should be revised in future studies such that an additional co-design re-synthesis can be performed following the V&V in order to correct for any issues discovered at the V&V stage, thereby avoiding potential non-compliance of requirements in the final outcome of the study

DOCUMENT CHANGE DETAILS

ISSUE	CHANGE AUTHORITY	CLASS	RELEVANT INFORMATION/INSTRUCTIONS
Issue 1.0	-	-	First Issue delivered to ESA for the Final Data Package

DISTRIBUTION LIST

INTERNAL	EXTERNAL
Configuration Management	ESA Configuration Management