JOURNÉES DE PRINTEMPS DE LA SAGIP 2022

MODELING, ROBUST CONTROL SYNTHESIS AND WORST-CASE ANALYSIS FOR AN ON-ORBIT SERVICING MISSION WITH LARGE FLEXIBLE SPACECRAFT

PRESENTER: RICARDO RODRIGUES
TUTORS: DANIEL ALAZARD, FRANCESCO SANFEDINO

TUESDAY 24 MAY 2022

SECTION 1

CONTEXT AND MOTIVATION

CONTEXT

- On-orbit servicing is expected to bring a significant transformation to a wide range of space activities. Topic in active research throughout the world with several demonstrator missions planned for the near future.
- From an AOCS/GNC point of view, this type of complex missions is particularly challenging due to the time-varying & coupled flexible dynamics.
- Important to develop a solid framework in which to perform model-based design and worst-case analysis.

OBJECTIVES

Build up expertise on the topic of AOCS/GNC design for on-orbit servicing using modern model-based design methods.

MEV-1 (Credits : Northrop Grumman)

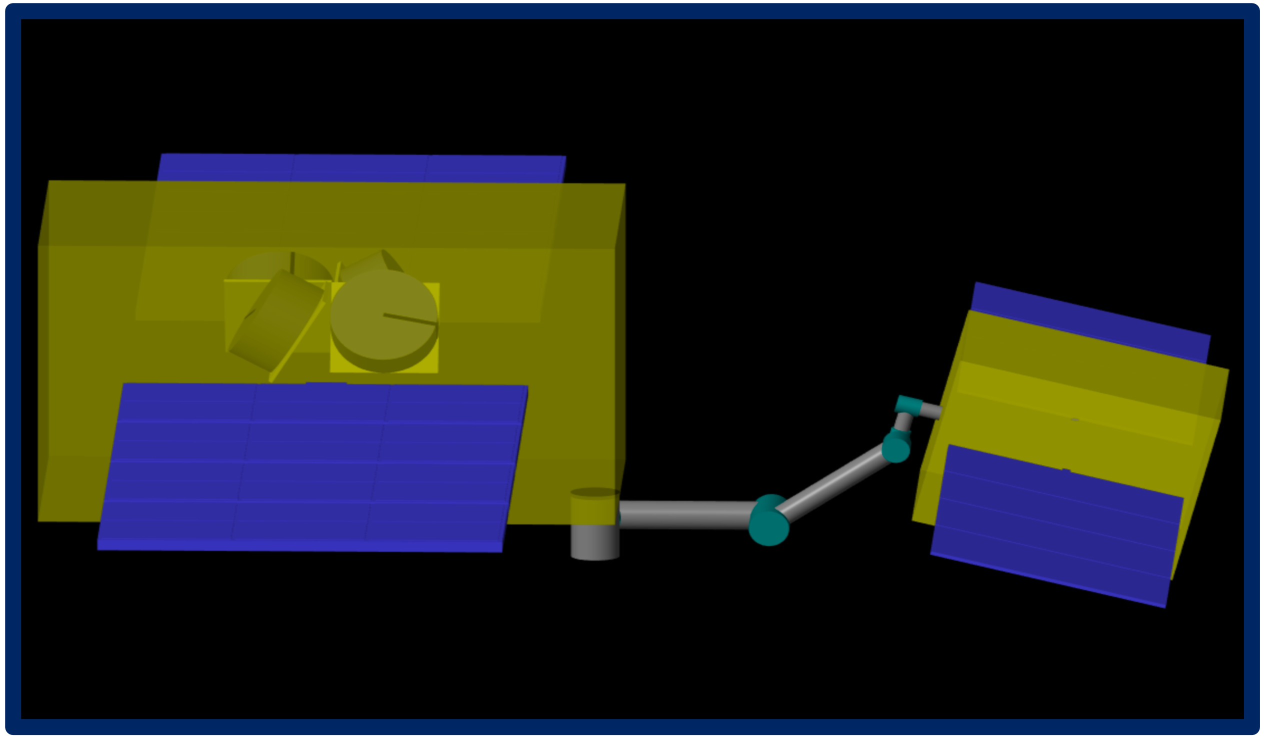
EROSS servicer (Credits : Thales)

MISSION SCENARIO

→ On-orbit servicing of a target satellite.

→ Chaser equipped with one robotic arm for docking to the target spacecraft and service it.

→ Both the chaser and target are equipped with flexible and rotating solar arrays.



CHALLENGES

- Control structure interactions between flexible appendages and AOCS.
- Time-varying inertial properties & flexible dynamics.
- Many system uncertainties and dynamic couplings.

SECTION 2

PROPOSED SOLUTION

STEP 1: BUILD A NONLINEAR SIMULATION

→ Currently built on top of Simscape physics engine.

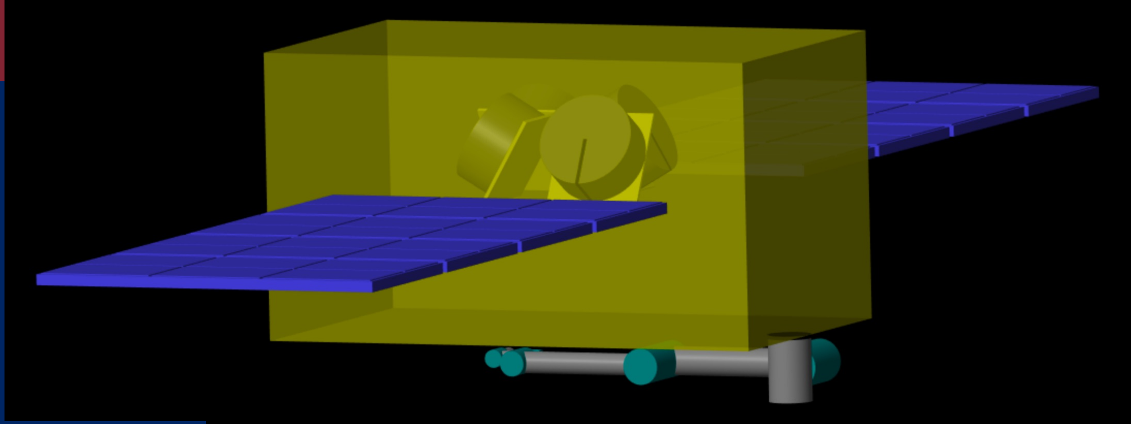
→ Full mode sequence implemeted: approach, docking, servicing.

→ Contact and flexible dynamics.

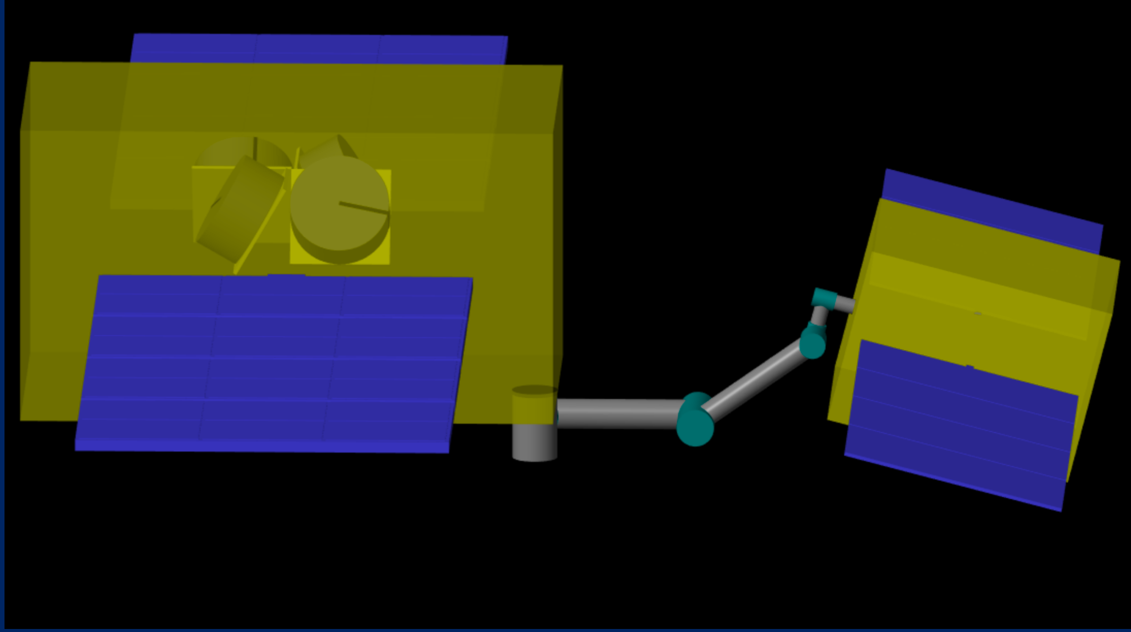
→ 6 degrees of freedom robotic arm based on Universal Robots' UR5 but any serial robot can be incorporated.

→ The robotic arm is responsible for docking to the target. A fifth-order trajectory is generated such that there is no collision between the arm and the target.

Chaser



Coupled System

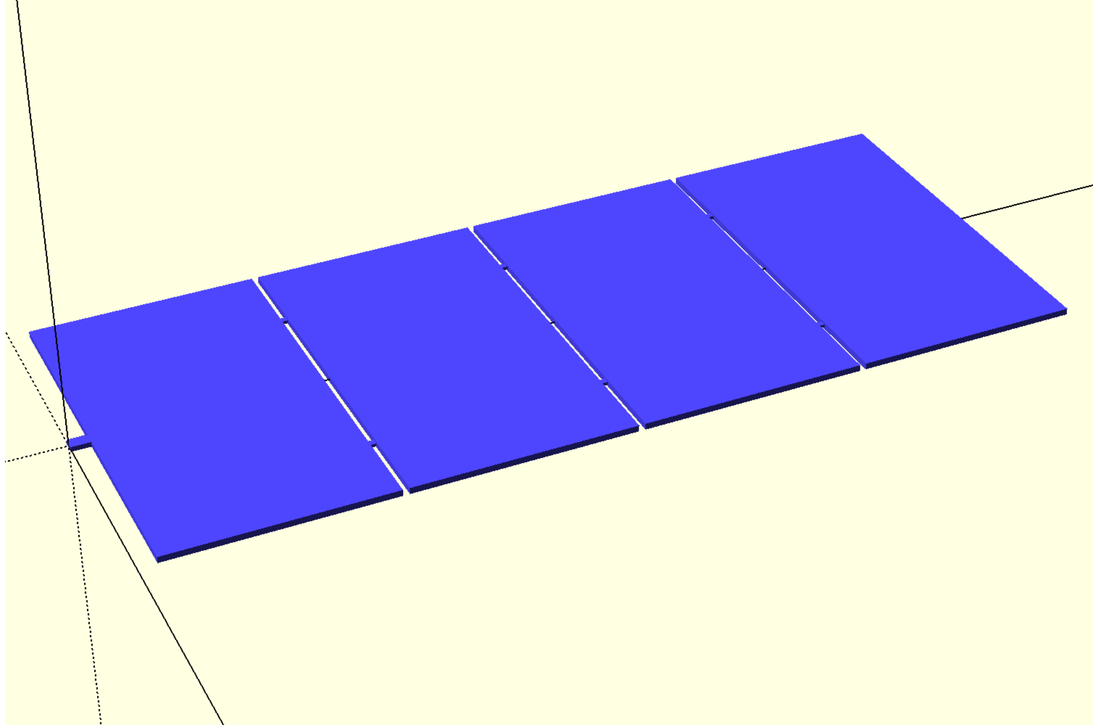


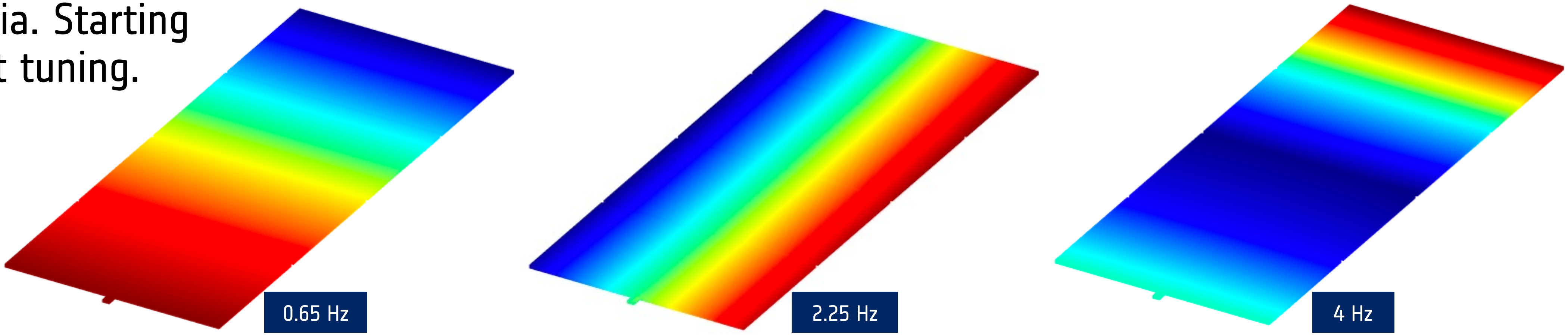
FLEXIBILITY AND BASELINE CONTROLLER

→ Six flexible modes are considered for each spacecraft solar array.

→ Designed AOCS has a natural frequency of 0.1 rad/s.

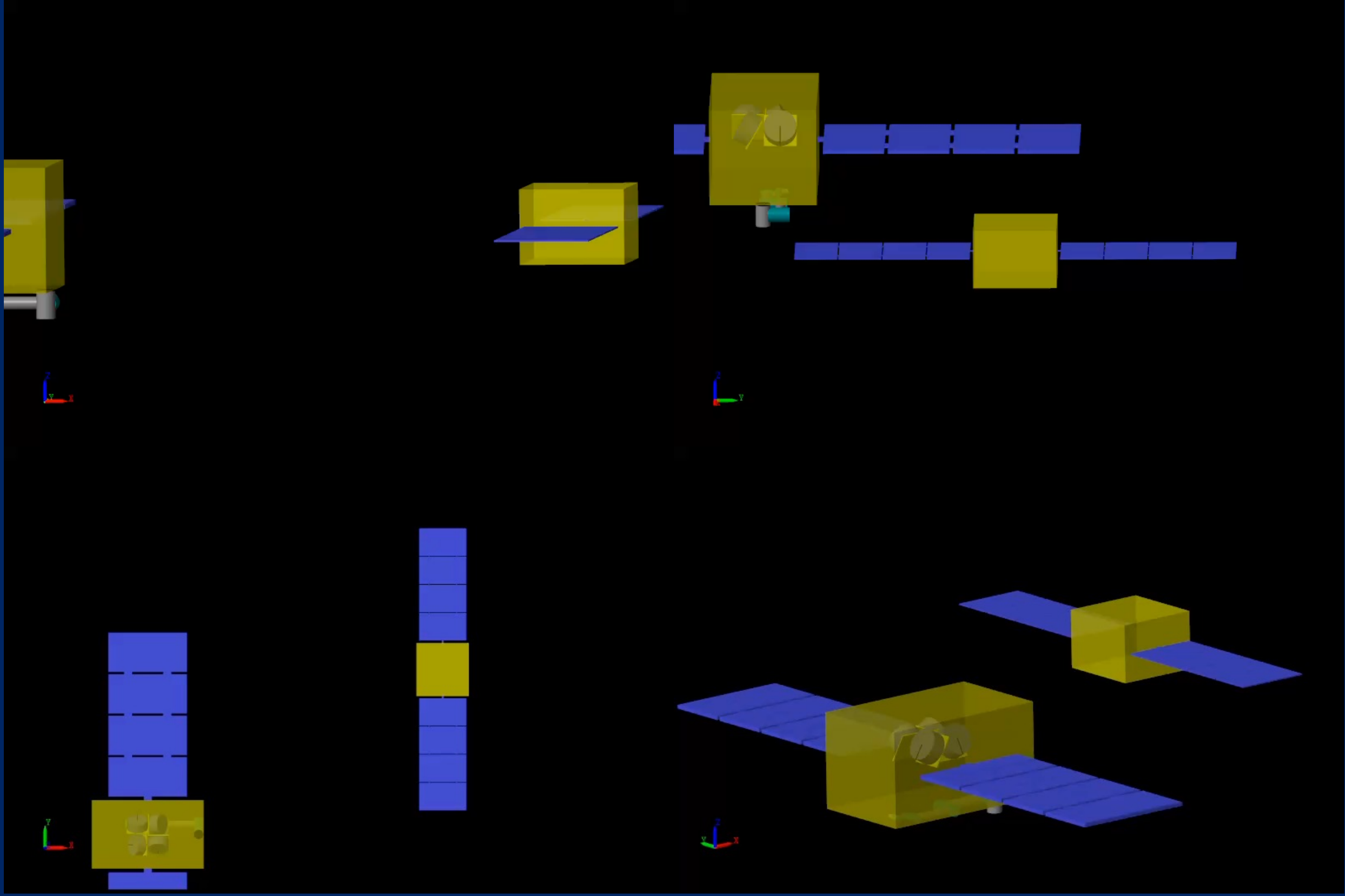
→ Baseline AOCS tuning based on static combined mass and inertia. Starting point for robust tuning.





SIMSCAPE SIMULATION OF THE SCENARIO

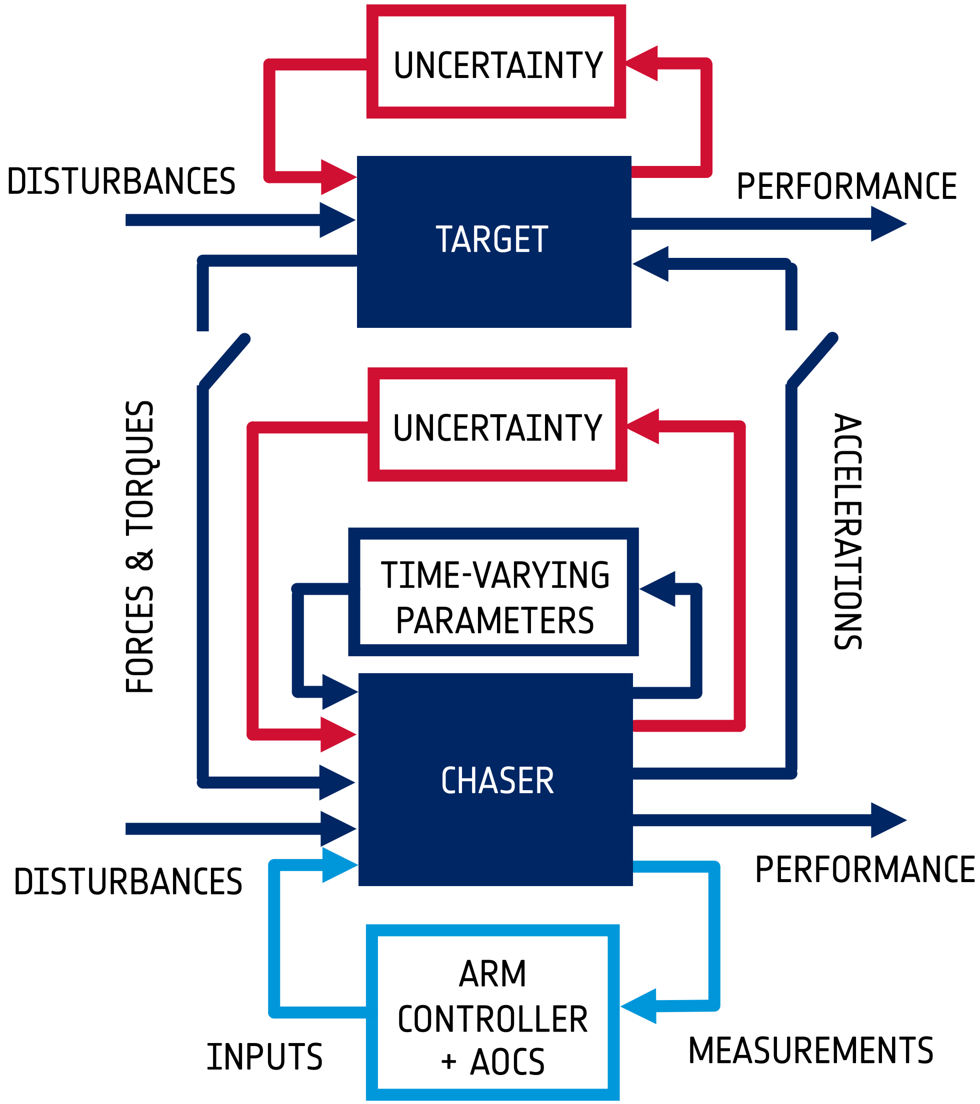
(PLAYBACK X64)



NEXT STEP: EXTRACTING A SYMBOLIC LINEAR MODEL

- To do a model-based AOCS/GNC design, a linear model of the decoupled/coupled system was developed in parallel to the nonlinear simulator.
- Such a model is needed to fully capture all the subtle interactions and uncertainty effects in a compact representation.
- The Linear Fractional Representation (LFR) is a well known & excellent way to capture the effects of uncertainty or parameter changes in the dynamics.
- Once such a model is obtained, modern methods can be deployed to perform intelligent AOCS/GNC tuning and worst-case analysis without relying on Monte-Carlo simulations or manual tuning.

LINEARIZED UNCERTAIN DYNAMICAL MODEL



- Extract a complete uncertain model of the chaser/target system prior and after capture (switched system).
- Robotic joints and solar array angles parameterize the dynamics.
- Use knowledge for adaptable AOCS and worst-case analysis.
- Model is built using the LFR formalism, ready to be used with robust control techniques.

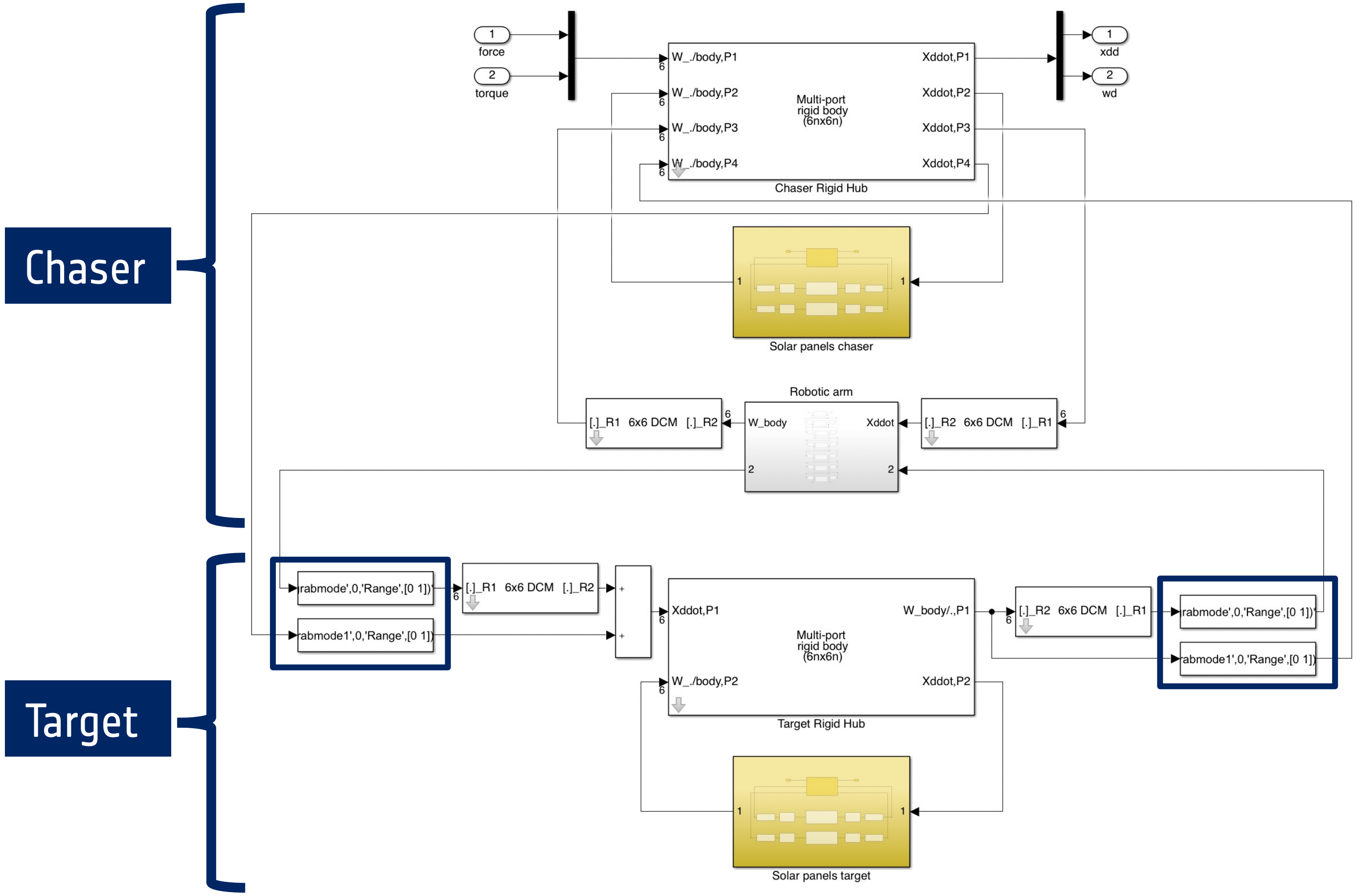
Satellite Dynamics Toolbox (SDT) User's Guide at: https://personnel.isae-supaero.fr/daniel-alazard/matlab-packages/satellite-dynamics-toolbox.html SDT toolbox was improved within ESA contracts.

LINEARIZED UNCERTAIN DYNAMICAL MODEL

→ Built using SDT from interconnected basic components.

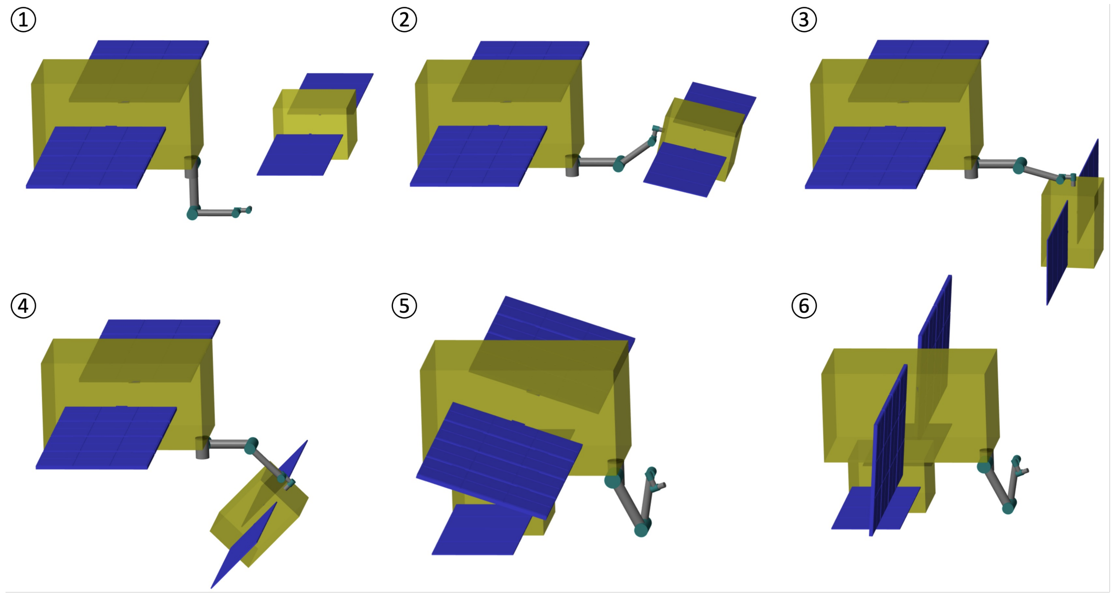
→ Fully captures the dynamics & interactions between all subsystems: robotic arm, flexible appendages, coupled / free configurations in a single LFR.

→ Uncertainty can be included in any system parameter. For this study: inertial and mass properties of the target, natural frequencies of some flexible modes.

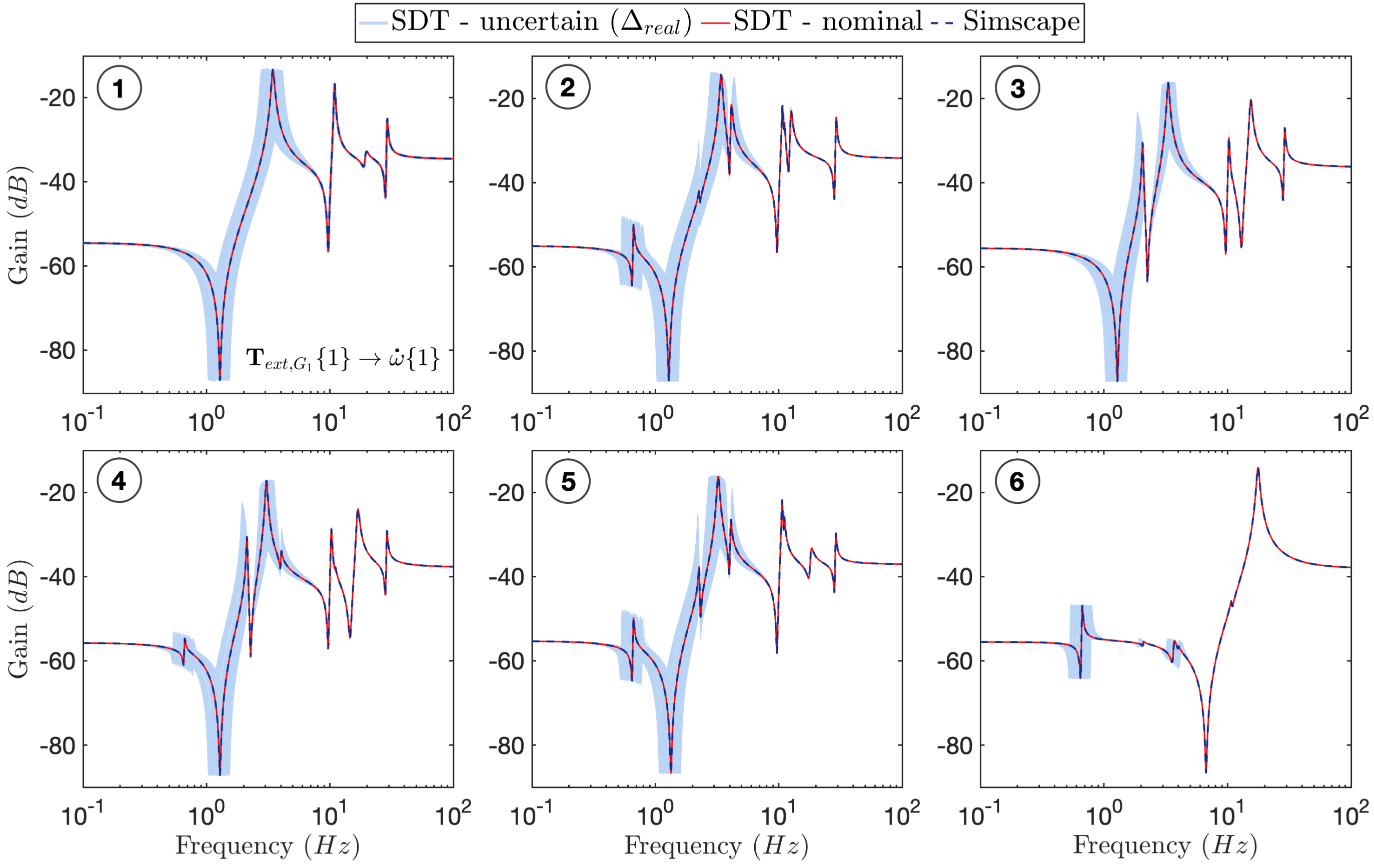


LINEARIZED UNCERTAIN DYNAMICAL MODEL

Six different illustrations of the decoupled and coupled systems regarding the OOS mission scenario being studied.

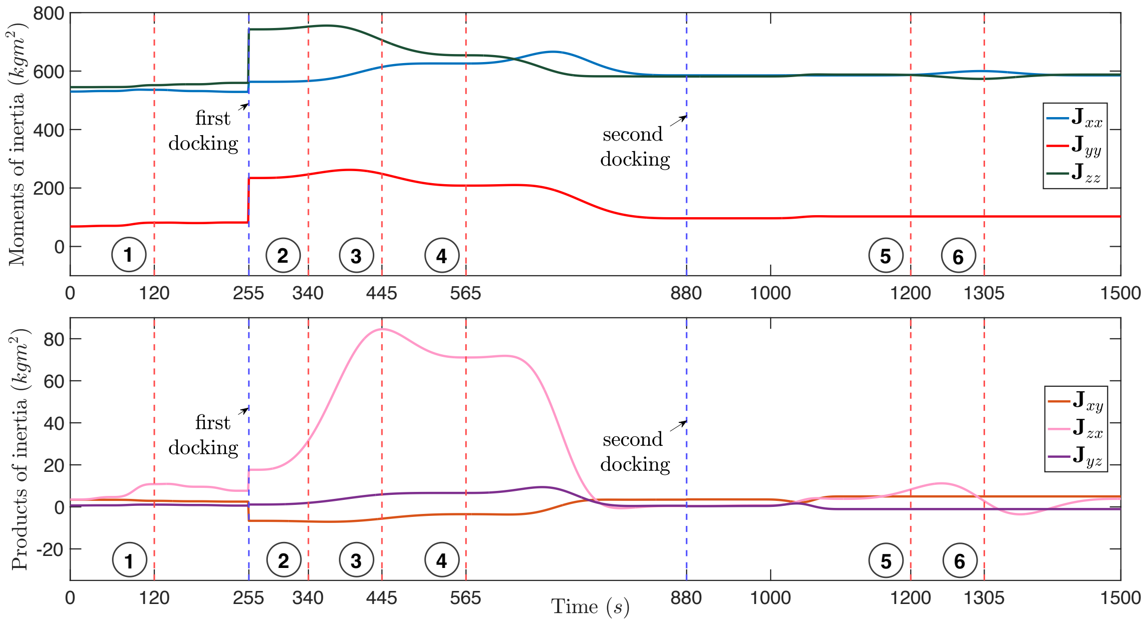


Comparison between the gains of the SDT - uncertain, SDT - nominal and Simscape systems for the six different moments; transfer between the first components of the external torque and angular acceleration.

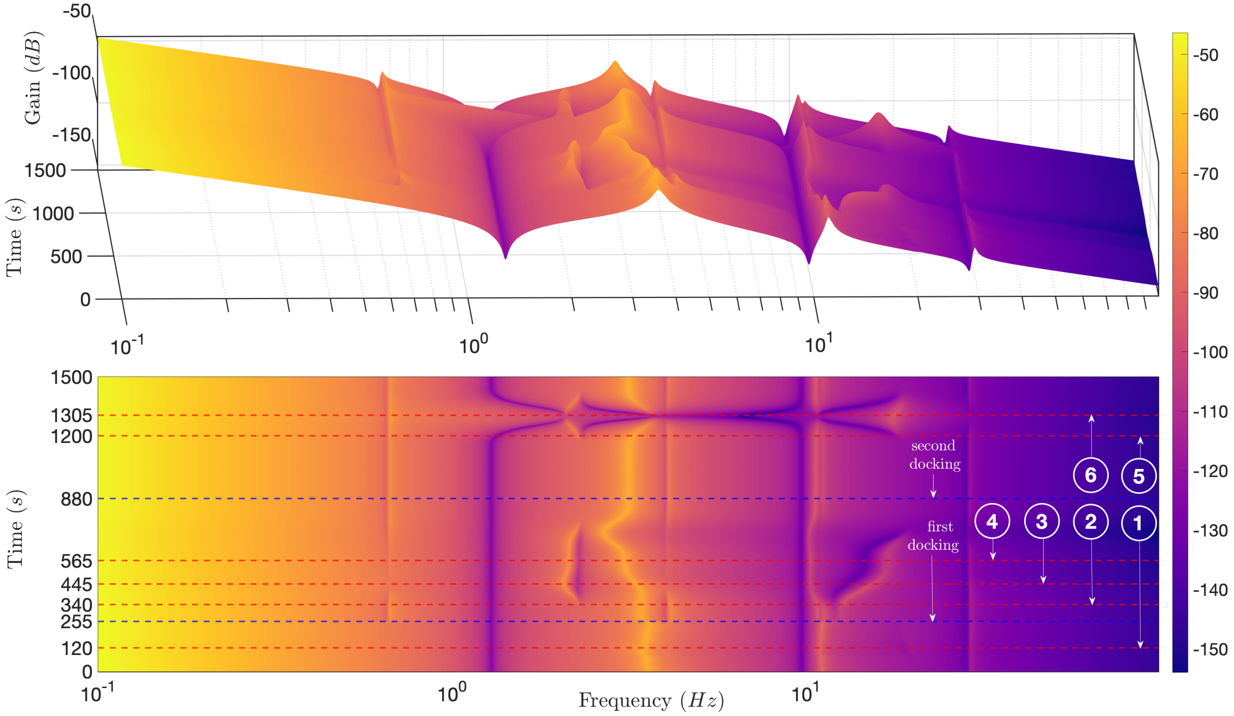


LINEARIZED UNCERTAIN DYNAMICAL MODEL

Evolution of the nominal open loop system's inertia tensor entries with respect to time.



Singular values of the nominal open loop system with respect to time and along a dense grid of frequencies; transfer between the first components of the external torque and attitude of the main body.

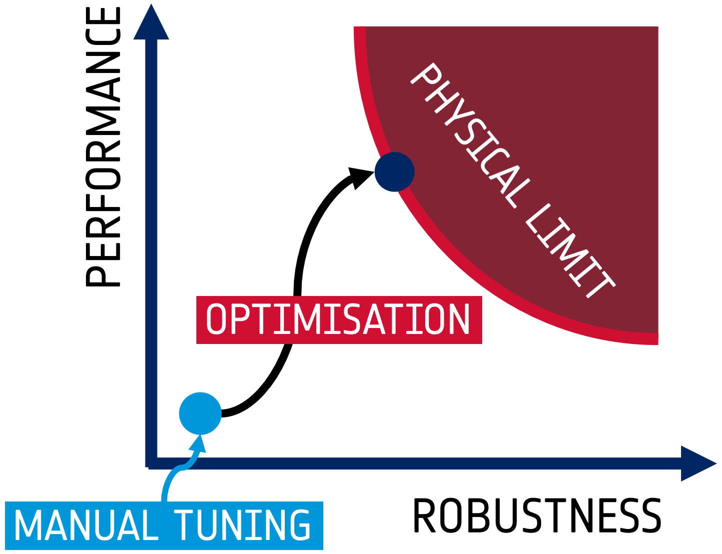


ROBUST CONTROL

→ Limit the influence of disturbances on key performance signals.

→ Trade-off between performance & robustness. Perform tuning in a systematic way using modern optimization methods.

→ Manual tuning & LTI design can lead to poor peformance & robusness.



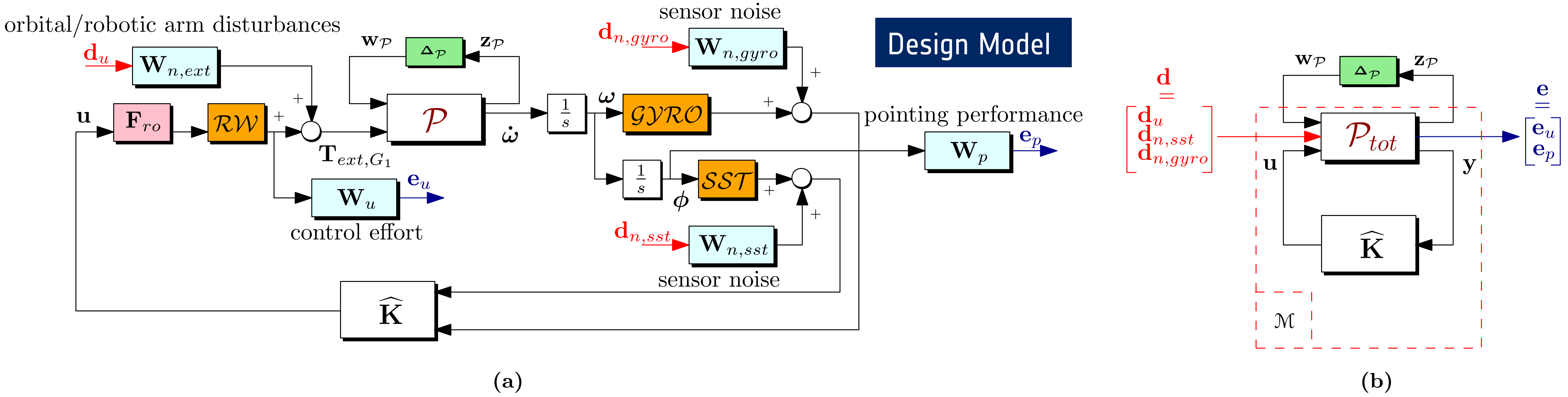
WORST-CASE ANALYSIS

→ Compute robust stability & robust performance margins via structural singular value analysis.

→ Exact problematic worst-cases.

→ Use these results to inform the control & system design process and perform quick iterations.

ROBUST CONTROL

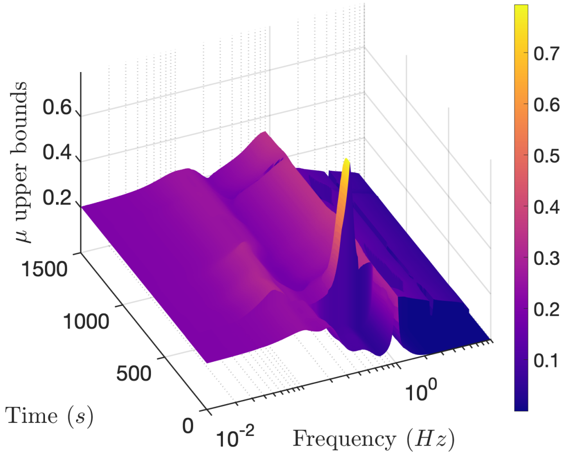


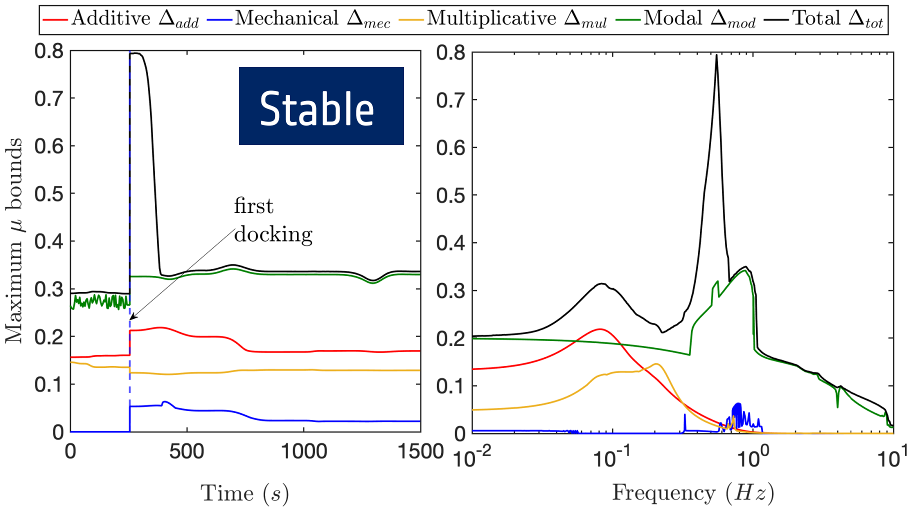
(a) System architecture used for controller synthesis and worst-case analysis. (b) Equivalent standard form of the interconnection.

- → Design model includes actuator and sensor dynamics, as well as a roll-off filter.
- → Disturbance Weights are included to model the upper bound on the expected amplitude of the closed-loop noise measurements and orbital/robotic arm disturbances.
- → Similarly, Performance Weights are considered in order to impose a desired closed-loop upper bound on the worst-case actuator signal and also on the Absolute Pointing Error (APE).

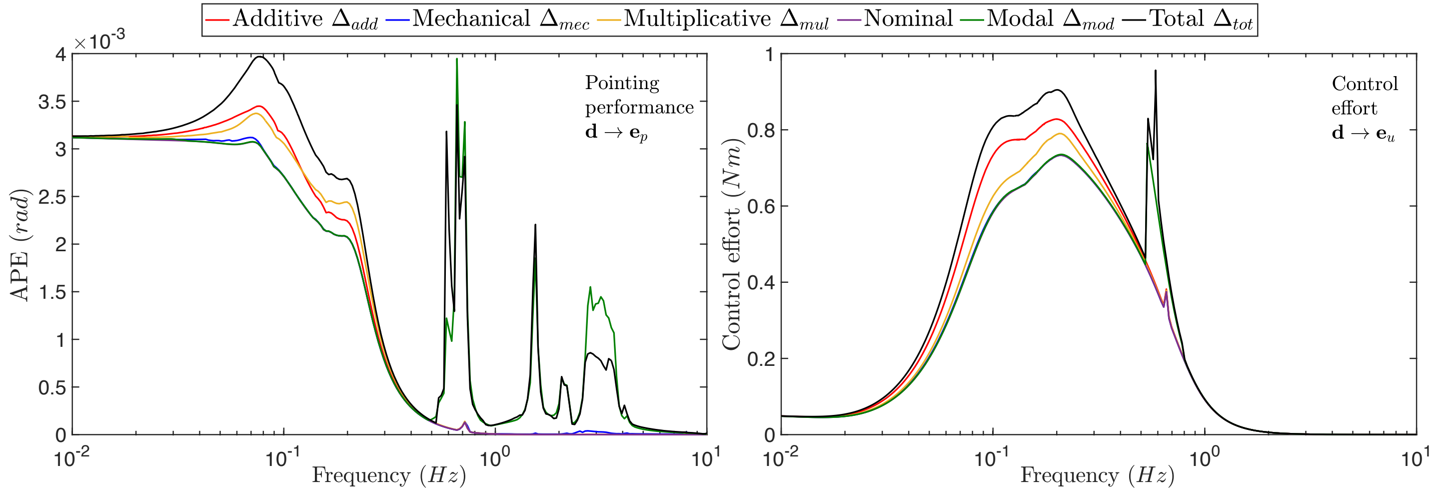
MU-ANALYSIS

→ Study the influence of the effect of different uncertainties on either closed-loop stability or performance.





Robust stability plots; upper bound across a dense grid of frequencies and different geometrical configurations.



Upper bounds on the gains of different performance channels with respect to several uncertainty sets.

DOCKING MECHANISMS

→ In reality, docking mechanisms do not act as simple clamped connections. For that purpose, local spring-dampers are used.

$$\begin{cases} \mathbf{W}_{\mathcal{SM}_\bullet/.,C} = -\left(\mathbf{K}_{Q_\bullet}\delta\mathbf{x}_{Q_\bullet} + \mathbf{D}_{Q_\bullet}\delta\dot{\mathbf{x}}_{Q_\bullet}\right) \\ \mathbf{W}_{\mathcal{SM}_\bullet/.,P} = \mathbf{K}_{Q_\bullet}\delta\mathbf{x}_{Q_\bullet} + \mathbf{D}_{Q_\bullet}\delta\dot{\mathbf{x}}_{Q_\bullet} \end{cases}$$

$$\mathbf{K}_{Q_\bullet} = \begin{bmatrix} \delta_{K_\bullet}^{shear}\mathbf{I}_3 & 0_{3\times3} \\ 0_{3\times3} & \delta_{K_\bullet}^{tors}\mathbf{I}_3 \end{bmatrix}$$

$$\mathbf{D}_{Q_\bullet} = \begin{bmatrix} \delta_{D_\bullet}^{shear}\mathbf{I}_3 & 0_{3\times3} \\ 0_{3\times3} & \delta_{D_\bullet}^{tors}\mathbf{I}_3 \end{bmatrix}$$

Dynamic model of a general spring-damper system.

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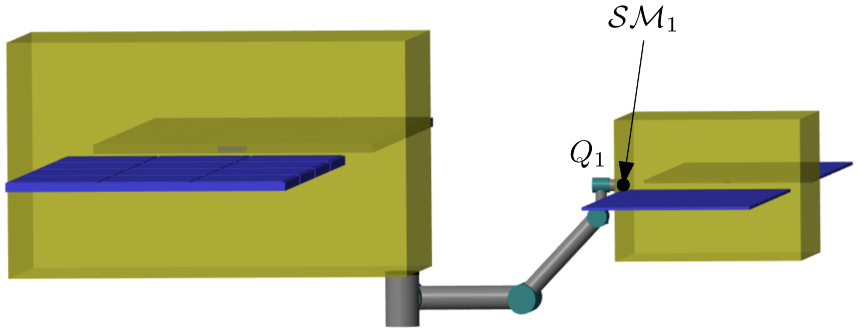

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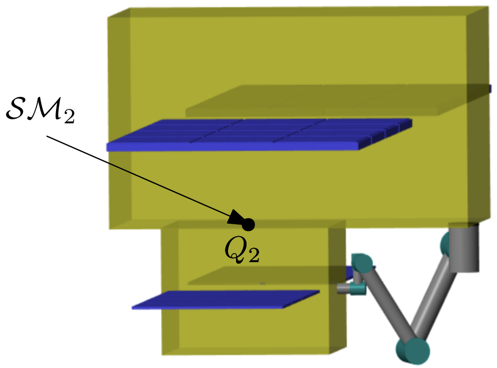
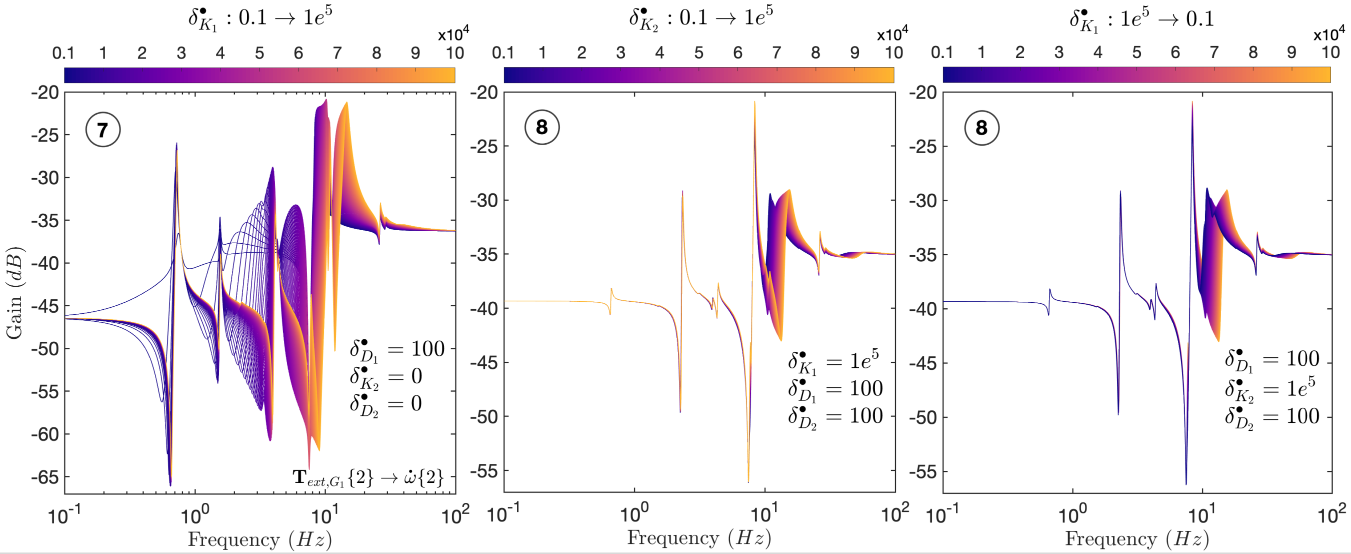


Two different moments where docking takes place.



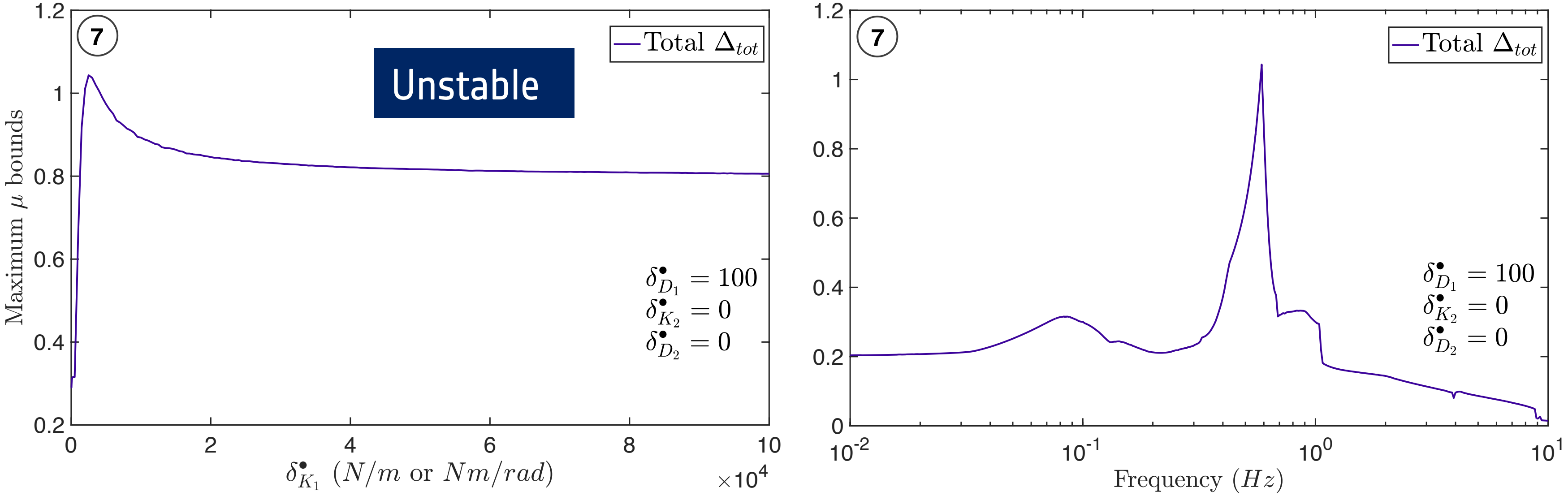
Singular values for the docking moments when considering two spring-damper systems.

MU-ANALYSIS

→ Spring-damper systems parameterized according to their stiffness and damping characteristics.

→ These LFR models can be used when designing a controller, so that the closed-loop system does not go unstable when docking takes place.

→ These models can also be used for worst-case analysis and controller validation.



Robust stability plots: side views of the upper bounds.

$$\boldsymbol{\Delta}_{\mathcal{SM}_\bullet} = \mathrm{diag}\left(\delta^{shear}_{K_\bullet}\mathbf{I}_3, \delta^{tors}_{K_\bullet}\mathbf{I}_3, \delta^{shear}_{D_\bullet}\mathbf{I}_3, \delta^{tors}_{D_\bullet}\mathbf{I}_3\right)$$

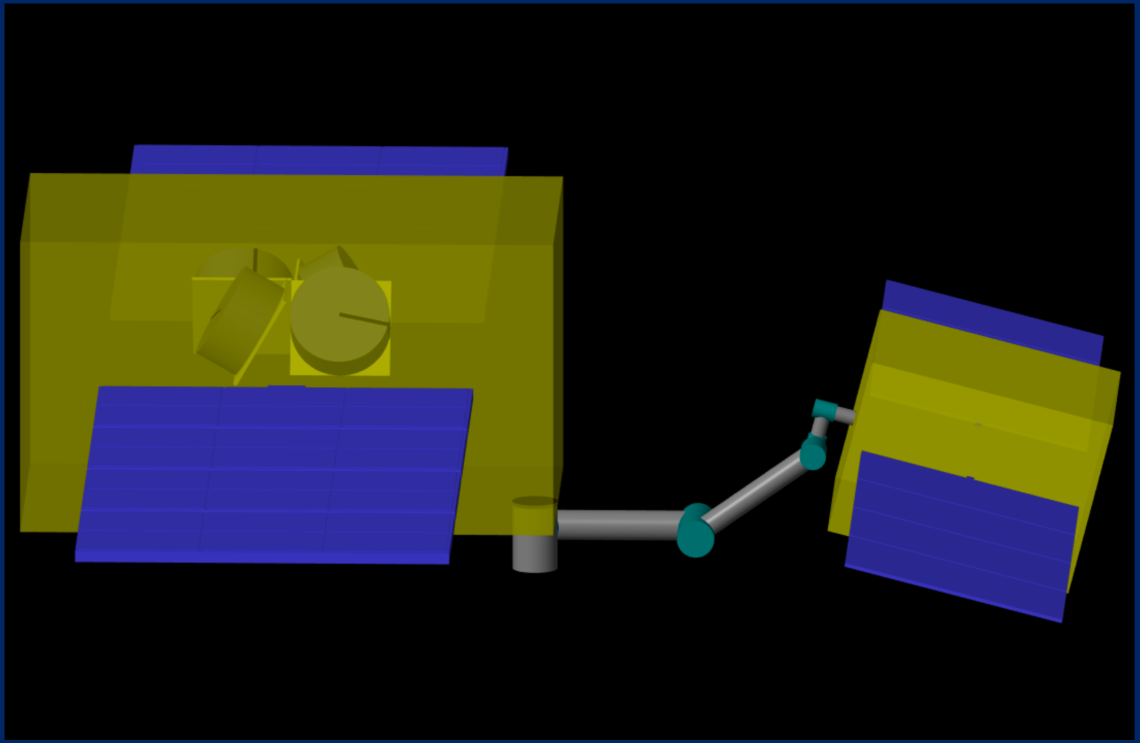
LESSONS LEARNED

- The topic of coupled flexible spacecraft & robotic arm interactions can be **one of the most challenging topics in both theory and practice.**
- SDT is a very powerful tool allowing for the individual modeling of each subsystem and posterior association through rigid or dynamic connections.
- Simscape represents a very good non-linear simulator where one can perform validation of the designed controller.

NEXT STEPS

- Consolidation of the obtained results in the form of a paper.
- Development of the SDT tool (non-linear models, other customized functions, etc...).
- Improve the non-linear Simscape simulator (add a feed-forward term for the robotic arm).

CONCLUSIONS



- → Robust control and mu-analysis provide an excellent framework to meet the needs of future space missions that deal with this type of dynamical systems.
- → This framework is able to capture the effect of uncertainty on the system behaviour very well.
- → Validation & Verification cycles without the need of expensive simulations (Monte-Carlo) in the preliminary phases.

ACKNOWLEDGEMENTS