INVESTIGATION OF ACTIVE DETUMBLING SOLUTIONS FOR DEBRIS REMOVAL

DETUMBLING

Clean Space Industry Days
24-10-2017

AGENDA

- Project Overview
- Survey of Detumbling Strategies & Mission baseline
- GNC design – Guidance
- GNC design – Control synthesis & Analysis
- Validation campaign – results
- Conclusions

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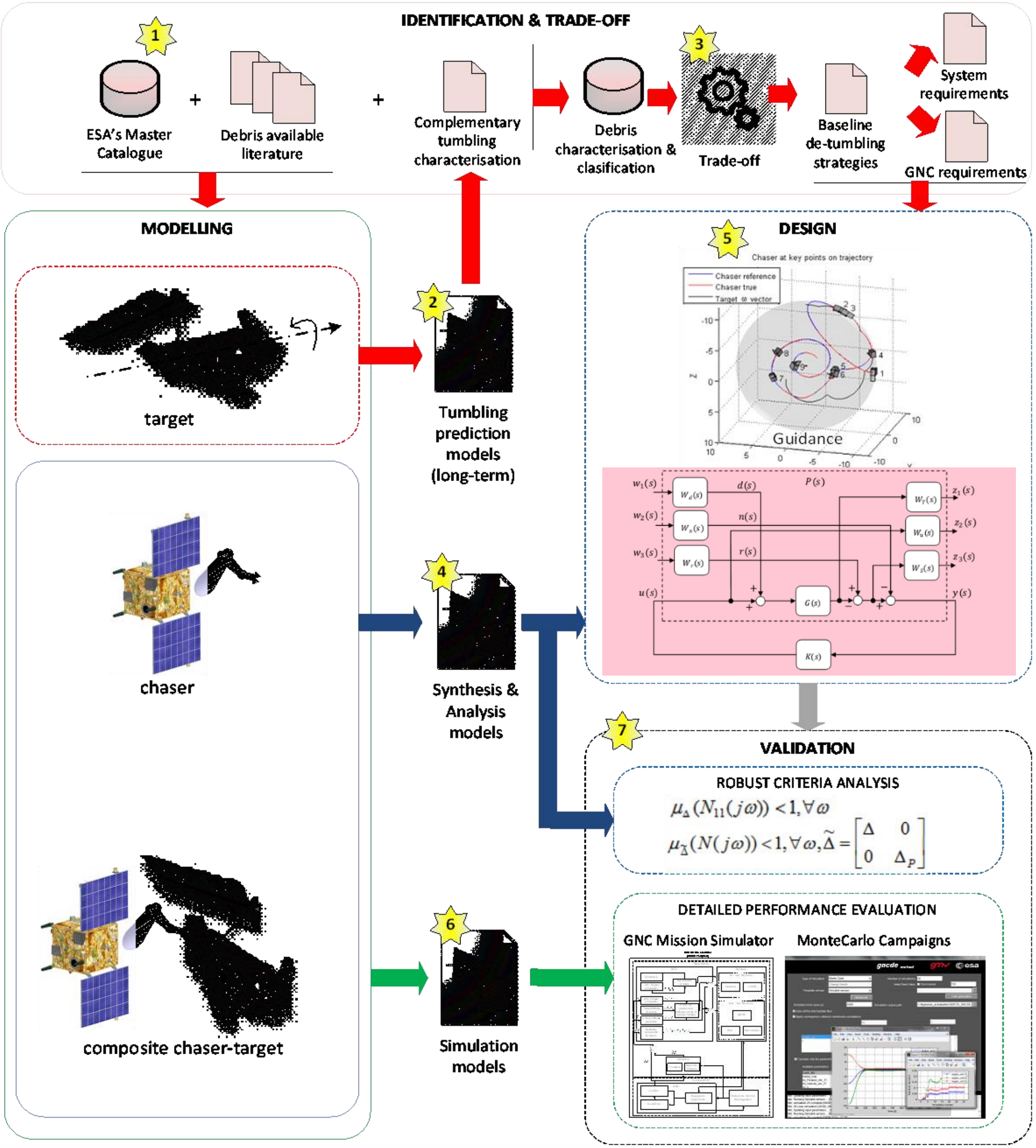
Project Overview

PROJECT OBJECTIVES

- Identification and characterisation of existing **classes of tumbling** objects
- Survey, trade-off and selection of **de-tumbling concepts** and strategies
- Development of mathematical **models** for tumbling debris
  - Prediction models for long term tumbling debris attitude prediction
  - Synthesis models for control design
  - Non-linear models for performance evaluation (both tumbling target and composite multi-body models)
- Baseline of a candidate concept and development of the GNC by means of ROBUST MIMO synthesis and analysis techniques
- Analysis of the applicability/scalability to a wider range of debris classes and contribution to technology Roadmaps

STUDY LOGIC

- Main processes and resources of the activity
  - Identification of candidate concepts
  - LTP modelling
  - Trade-off
  - Synthesis/Analysis models development
  - GNC design
  - Non-linear models development
  - GNC validation (linear + non-linear)



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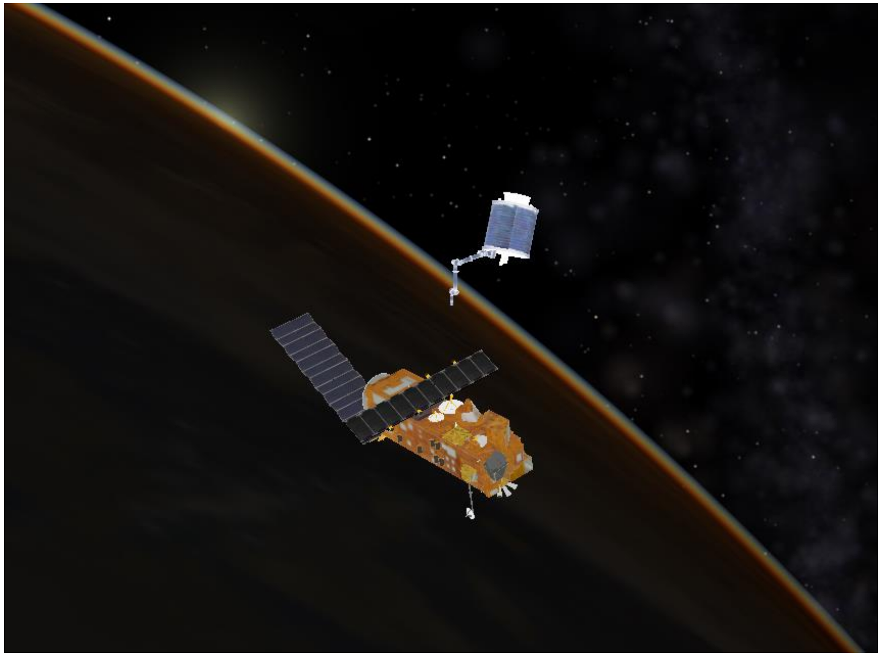
Survey of detumbling strategies & Mission baseline

CONCEPTS TRADE-OFF

- Detumbling concepts trade-off
  - Analytical hierarchy process (*Thomas Saaty, 1970s*) was used for the trade-off:
    - Breakdown of the problem into smaller sub-problems that are arranged in a **hierarchy**, and **pair-wise comparison** of elements
  - **Robotic arm capture** is selected as baseline for TASK 3 (GNC development)
    - <u>Performs well across all three criteria</u> (risk, technical, reliability)
    - High TRL (highest TRL of all capture and de-tumbling techniques)
    - Can partially be tested
    - Least amount of development would be required
  - It is observed that **contactless** methods tend to perform well on risk criterion because
    - No physical contact and no attitude synchronization
    - Plume impingement de-tumbling and electrostatic tractor also perform well on technical criteria
    - Contactless methods tend to *score lower in reliability criterion*

MISSION BASELINE

- **Envisat**
  - De-tumbling mission
    - Arm deployment
    - Close in & Synchronisation up to capture (contact dynamics out of the scope of the activity)
    - Detumbling manoeuvre
  - Purpose of the study is to assess <u>feasibility of MIMO robust control</u> for all phases and point key problems/needs (not to design the GNC for an already defined system)
  - Some eDeorbit facts taken as reference but alternative assumptions/solutions when considered interesting for the study:



- Higher target rotational rates considered here (3º/s – 5º/s)
- No clamping devices for the braking manoeuvre

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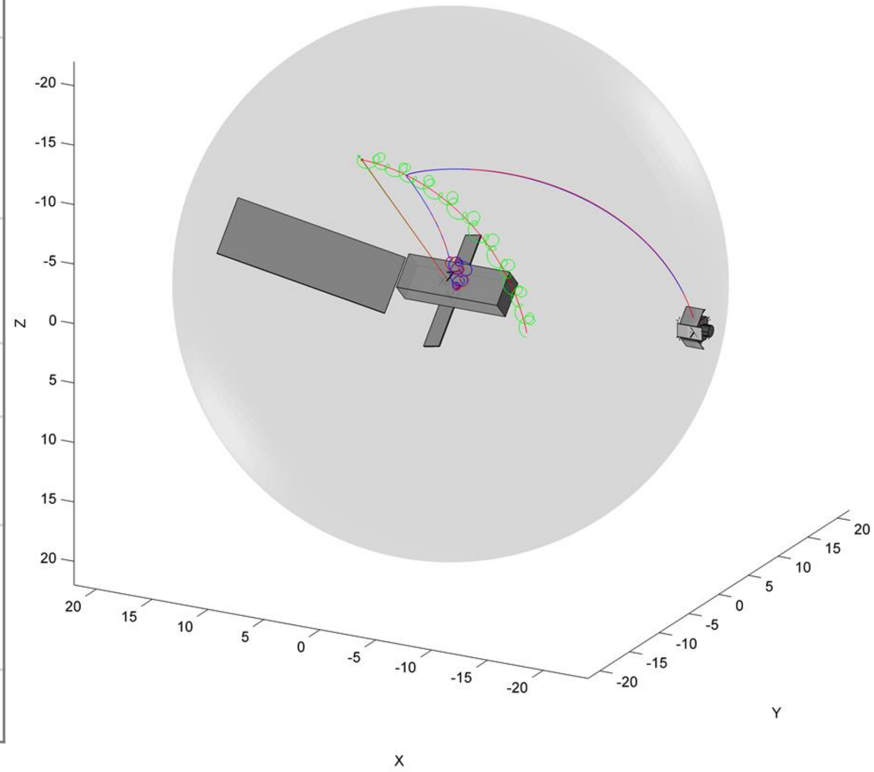
GNC design - Guidance

SYNCHRONISATION GUIDANCE

Manoeuvre	Final conditions	Duration
Station keeping at Parking Hold Point	100 m on Vbar	
Move closer to target	30 m on Vbar	3 min
Transition to a position on the angular momentum axis of the target & synchronize rotation	30 m from the target on angular momentum axis	5 min
Forced approach in straight line over the angular momentum axis	7 m from the target on angular momentum axis	3 min
Transfer to target body frame		
Fly-around in target body frame	7 m from the target in last approach axis (target body frame)	3 min
Forced approach in straight-line to Mating Point	Mating Point (TBC m) from the target in last approach axis (target body frame)	3 min
Station keeping at Mating Point	Mating Point	TBC



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GNC Design - Control synthesis & analysis

GMV INNOVATING SOLUTIONS

GNC IMPLEMENTATION GUIDELINES. CONTROL

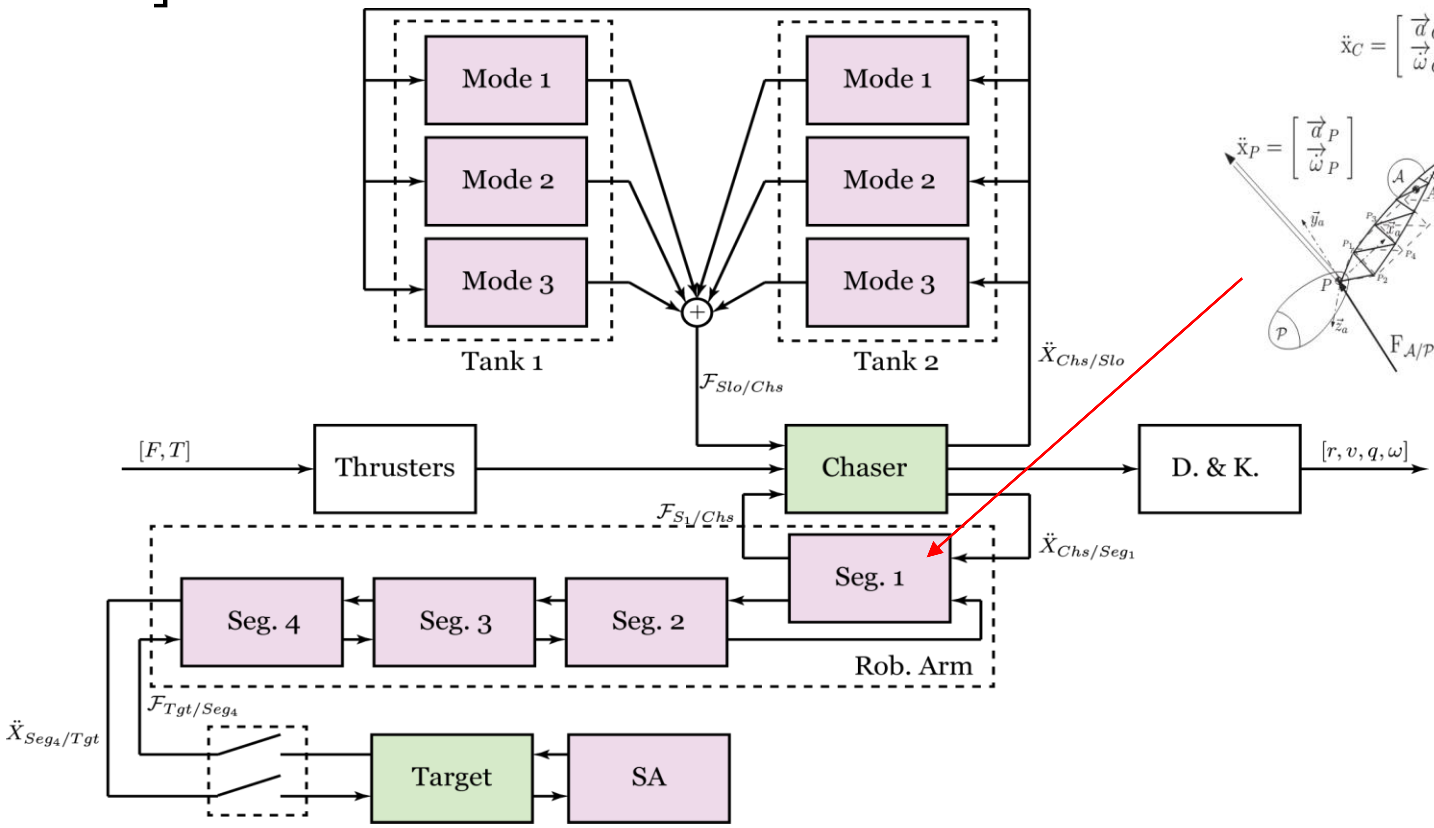
- GNC Design guidelines:
  - **MIMO** controllers (6DOF and 10DOF (6+4))
  - Synthesised/analysed by means of modern robust control techniques
  - Linear plant models with uncertainty representation by means of **LFTs** for synthesis and robustness analyses.
  - Different control modes to be designed according to each S/C configuration and control requirements for each phase (e.g. FMC for synchronisation phase v.s. FMCC for detumbling in composite configuration).
  - Main focus of the activity is put into:
    - the control function and in the evaluation of feasibility of the capture and detumbling operation.
    - performances evaluation and derivation of recommendations for later on-board implementation, system design and consolidation.

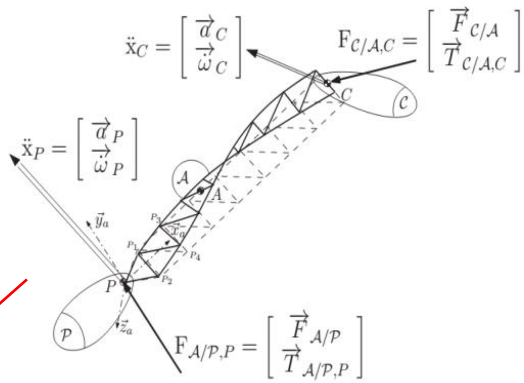
CONTROL SYNTHESIS & ANALYSIS METHODOLOGY - H∞

- **H∞ Design** (synthesis method)
  - Disturbance and noise rejection formulated in the frequency domain.
  - Steady state error requirement and transient response relates with the control bandwidth
  - The requirements specification information included within weighting functions used to augment the plant model entering the synthesis process.
- **μ-Analysis** (analysis method)
  - Robust stability – ensure that, with a given controller, the closed-loop system remains stable for all plants in the defined uncertainty set.
  - Robust performance – determine the amplification from the exogenous inputs to the performance outputs for all plants in the uncertainty set.

MODELLING – SYNTHESIS/ANALYSIS PLANTS

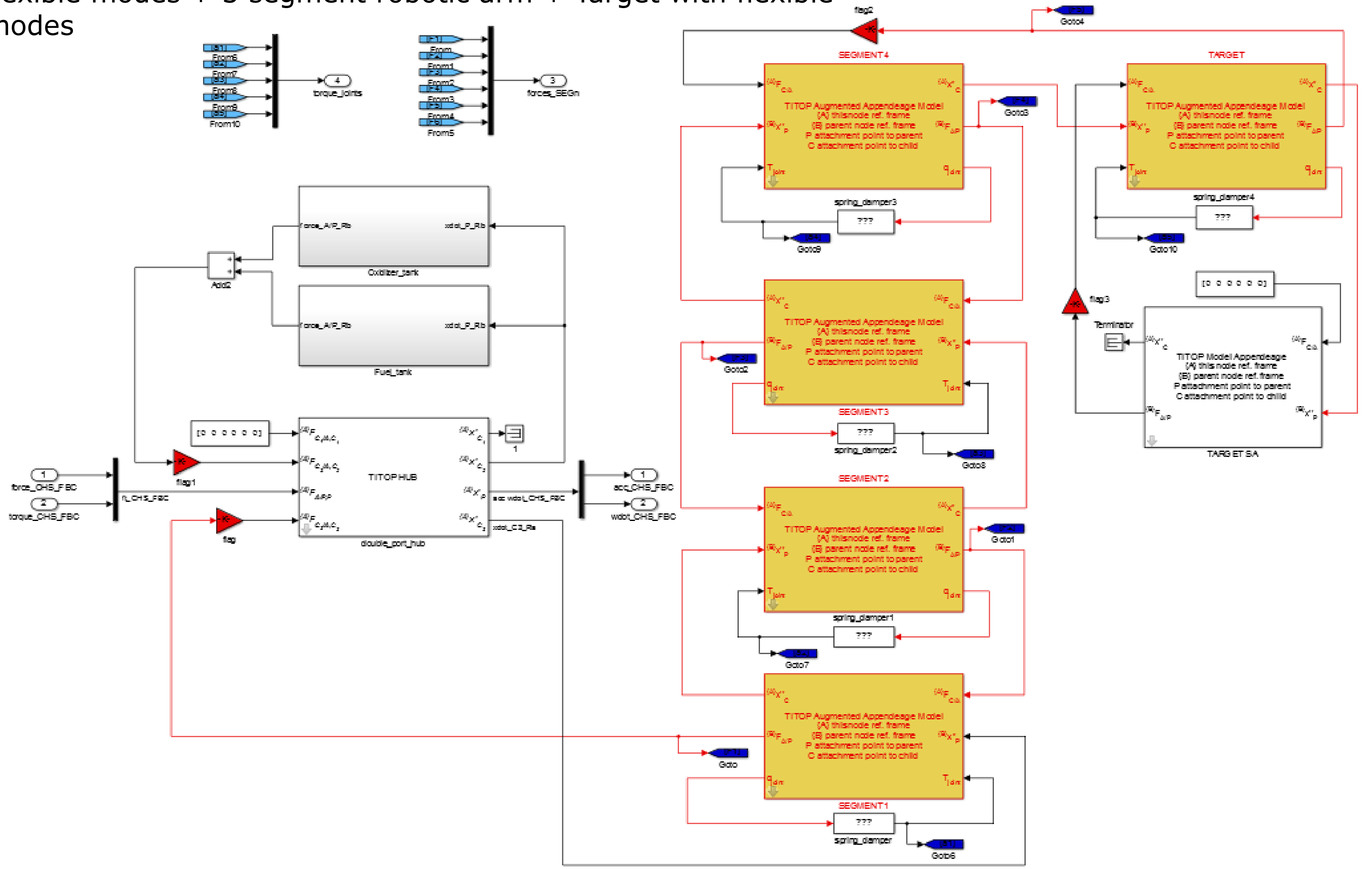
- Multibody model based on [2-port model Alzard, et all “Two-input two-output port model for mechanical systems”, AIAA 2015]





MODELLING – SYNTHESIS/ANALYSIS PLANTS

Interconnection using the TITOP models: Chaser with slosh and flexible modes + 3 segment robotic arm + Target with flexible modes

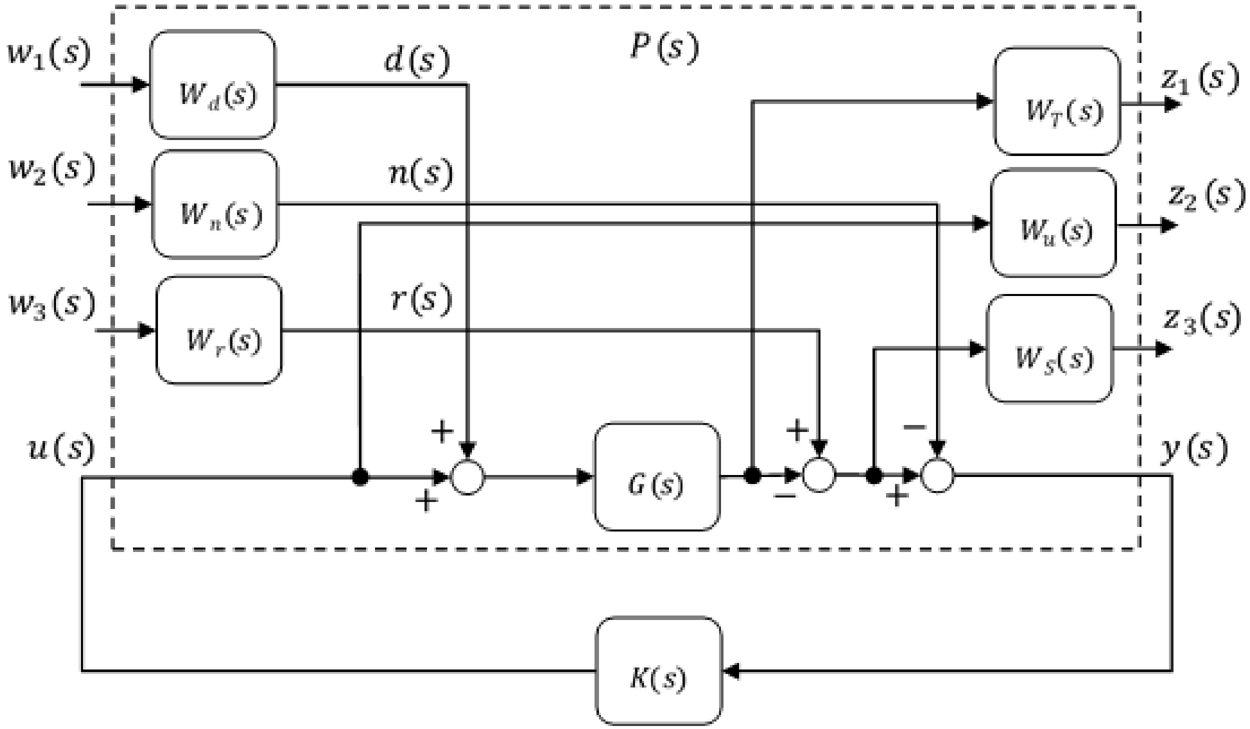


CONTROL MODES CHARACTERISATION

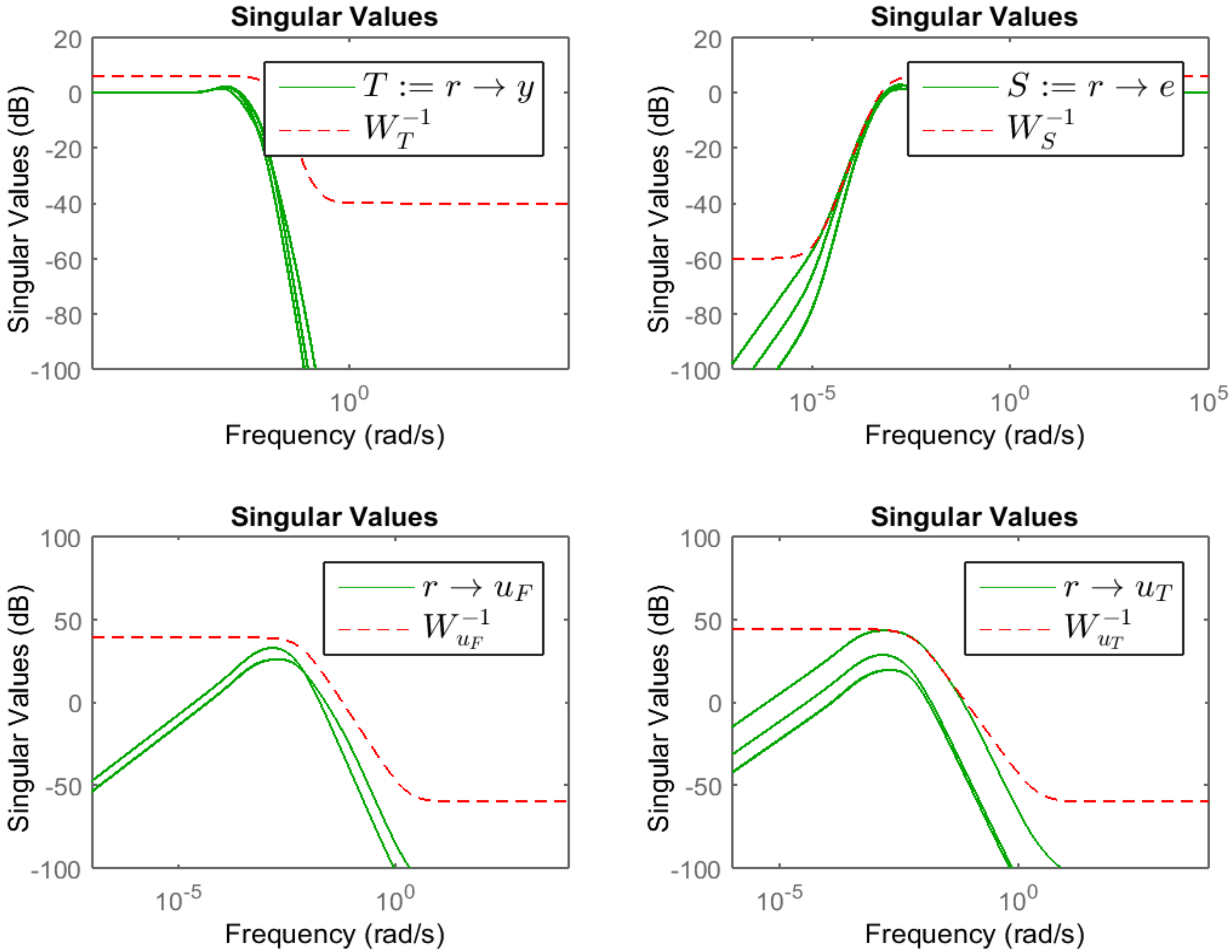
- **Forced motion control mode (FMC):** 6DOF control mode for forced motion (*Station keeping, Forced motion in LVLH, Forced motion in target body frame)*
- **Forced motion control mode 2 (FMC2):** 10DOF control mode for forced motion (combined control of the chaser COM, attitude and the state of the end-effector of the robotic arm using simultaneously the thrusters and the arm joints).
- **Forced Motion Control of Composite (FMCC):** Forced motion during de-tumbling (composite braking manoeuvre).
- **Forced Motion Control of Composite with simultaneous Chaser relocation (FMCC2):** The Chaser is simultaneously relocated by arm movement while

CONTROL SYNTHESIS/ANALYSIS - WEIGHTS

- The dynamic model is extended with frequency weights for Hinf design allowing for the characterization of noise, reference, disturbances, tracking error, actuation spectrum and input-output behaviour

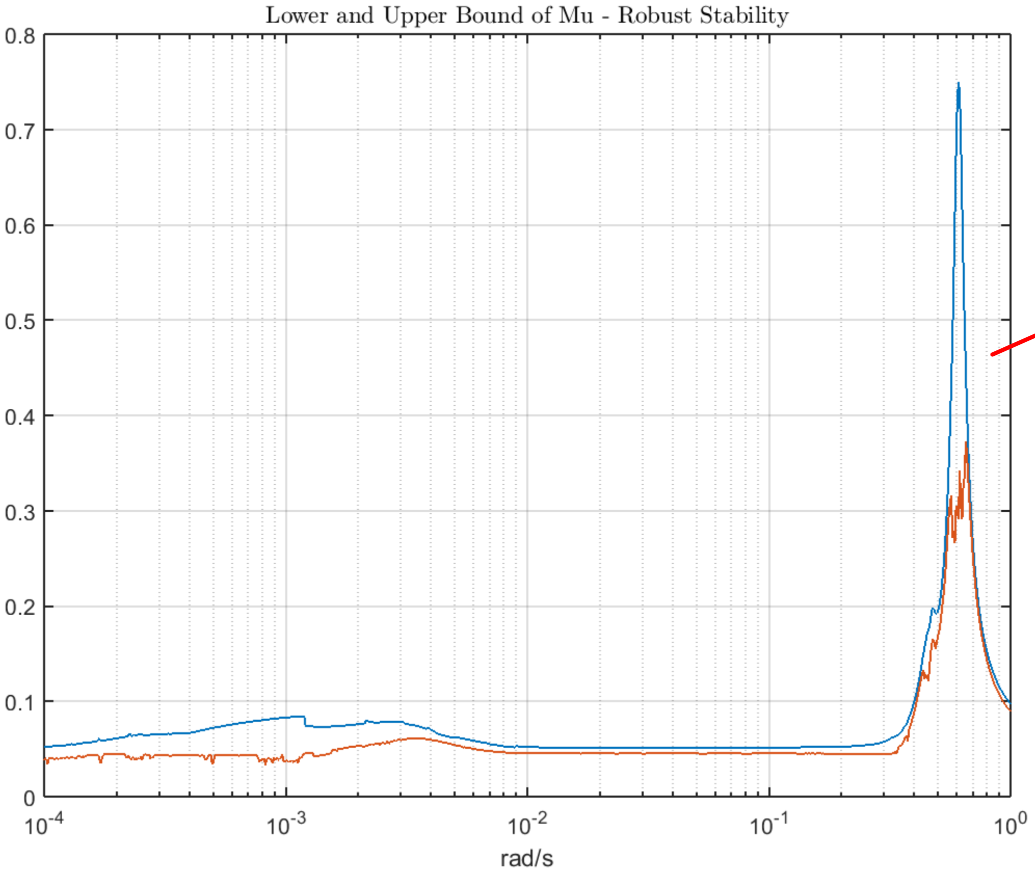


CONTROL SYNTHESIS: FMCC– SIGMA PLOTS

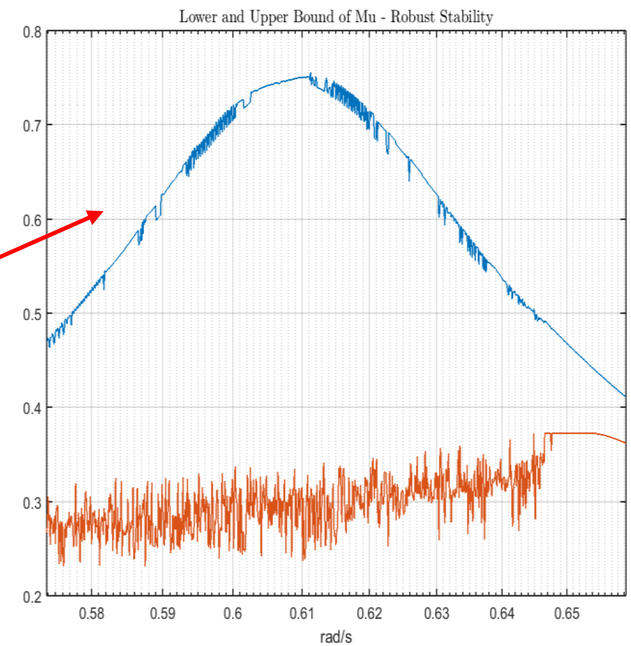


FMCC–ANALYSIS

Robust stability

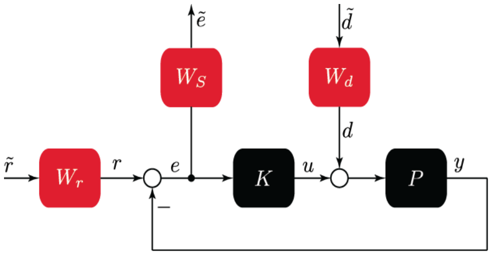


Wide frequency region (1000 points)

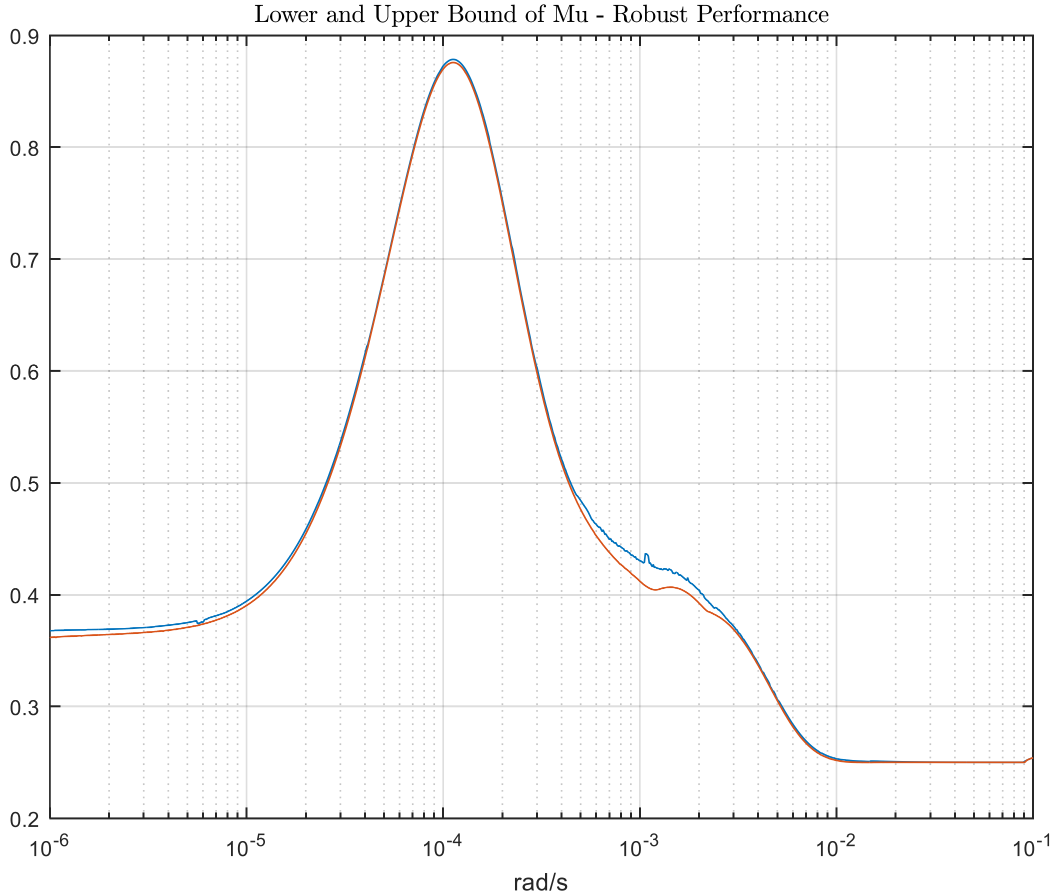


Small region (800 points)

FMCC–ANALYSIS



Robust performance



Wide frequency region (1000 points)

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Validation campaign

FUNCTIONAL ENGINEERING SIMULATOR AND VALIDATION CAMPAIGN

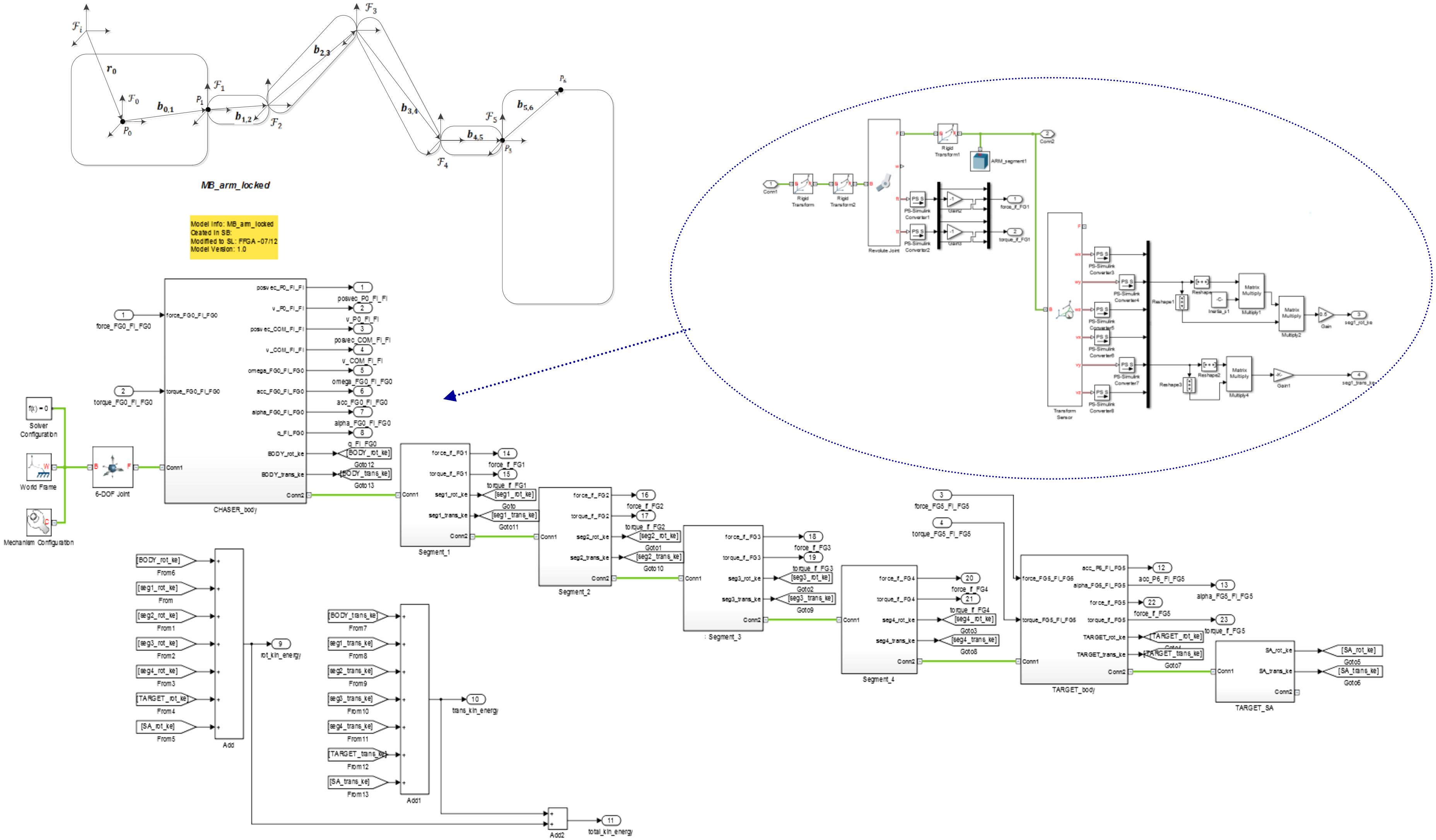
- FES accounts for **effects that could not be captured in the linear** analyses:
  - **M.B. dynamics/kinematics** non-linear effects (e.g. second order terms in accelerations, full attitude kinematics…)
  - **Measurements** non-linearities (rate limits, discretization, Sun blinding etc …) and more complex error models (e.g. Gauss-Markov processes for representing time evolution of the bias terms).
  - **Actuation** system non-linearities:
    - Thrusters Management Function (simplex optimisation of the thruster firings)
    - Thrusters MIB, saturation and other effects in their error modelling
    - Much more approximate evaluation of the propellant consumption (by accounting for real geometry and thrust limitations of the different thrusters sets).
- Implementation:
  - As **GNCDE Templates**: GNCDE v3.8.1 (Running on Matlab R2015a 64 bits)
  - Independent implementation for several phases was considered cleaner and more efficient

MULTI-BODY DYNAMICS

- **M.B. dynamics/kinematics models**:
  - multi-body attitude and position dynamics and kinematics of a chain composed of several elements**: base + arm segments + target + SA** connected by means of **revolute joints.**
  - several versions of the model implemented:
    - **MB_arm_locked**
    - **MB_arm_free**
    - **MB_arm_free_target**
  - Simscape multibody implementation validated against the formulation proposed in *Queen S. (NASA Goddard) "Momentum-Based Dynamics for Spacecraft with Chained Revolute Appendages"*

MULTI-BODY DYNAMICS

- **M.B. dynamics/kinematics**



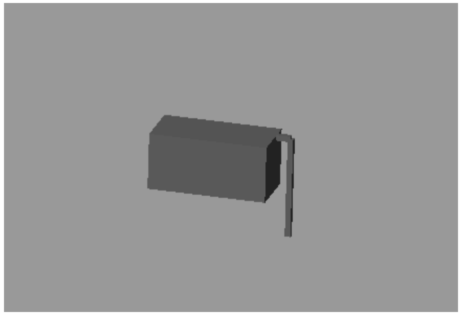
NON-LINEAR VALIDATION (MC CAMPAIGN)

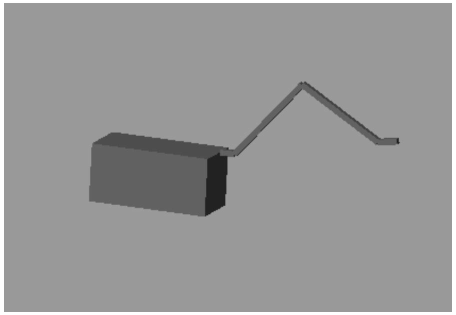
- Monte Carlo campaign in Fast Accelerator mode.
  - Target rotation: 3º/s to 5º/s
  - Propulsion system baseline: 6x4 22N thrusters (Isp = 290s). Simplex thrust optimisation method.
  - Multi-body dynamics for sub-phases: Arm-deployment, Capture, Detumbling and Detumbling with simultaneous Chaser relocation.
  - Arm not sensored (only joint encoders)
  - Absolute attitude/attitude rate sensors simulated + relative navigation behavioural models
- Parameters variation according to defined boundaries (same as LFTs **> 60 parameters** varied in FMCC mode) + noise model seeds and others
  - High sensitivity to chaser physical properties (mass,inertia, COM position) and sloshing parameters (freq. and damping)

NON-LINEAR VALIDATION (MC CAMPAIGN)

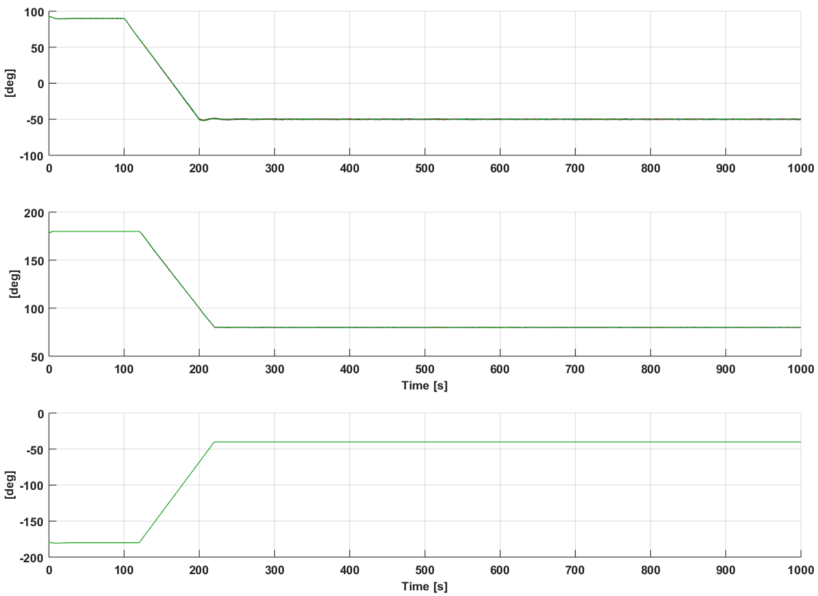
- **Arm unfolding**

Joint	Start time [s]	Start angle [deg]	End time [s]	End angle [deg]
1	0	0	0	0
2	100	90	200	-50
3	120	180	220	80
4	120	-180	220	-40

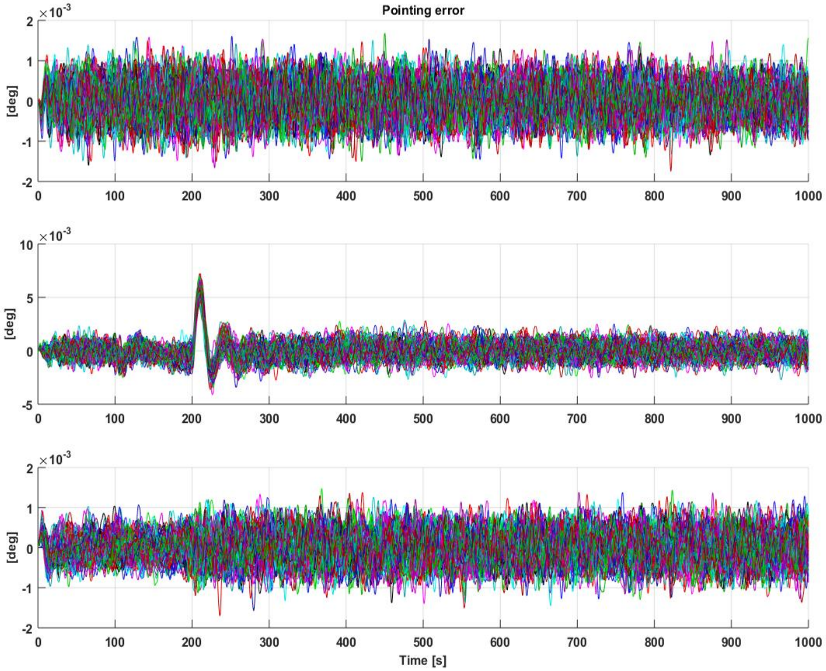




Joints 2,3 and 4 angles profile



Pointing error (321Euler angles [deg]) – 100 cases

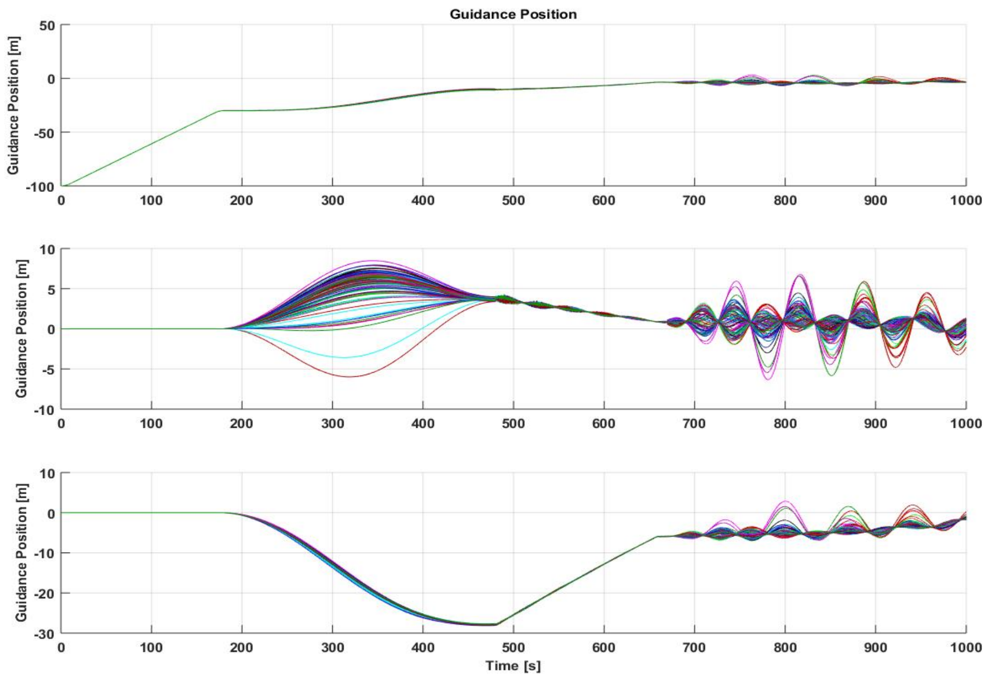


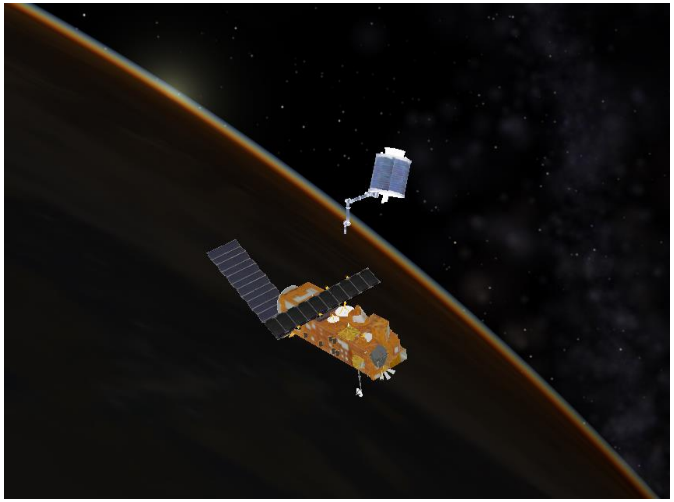
NON-LINEAR VALIDATION (MC CAMPAIGN)

- **Chaser close-in and synchronization with target (FMC)**

Sub-phase id.	Description	Duration [s]	Start distance	End distance
1	V-bar forced approach	180	100	30
2	Fly around to H (angular momentum) vector	300	30	30
3	Chaser closing along H vector direction	180	30	7
4	Chaser transfer to target frame	10	7	7
5	Fly-around the target	180	7	7
6	Chaser close in target frame	180	7	0

Guidance profiles (100 cases)

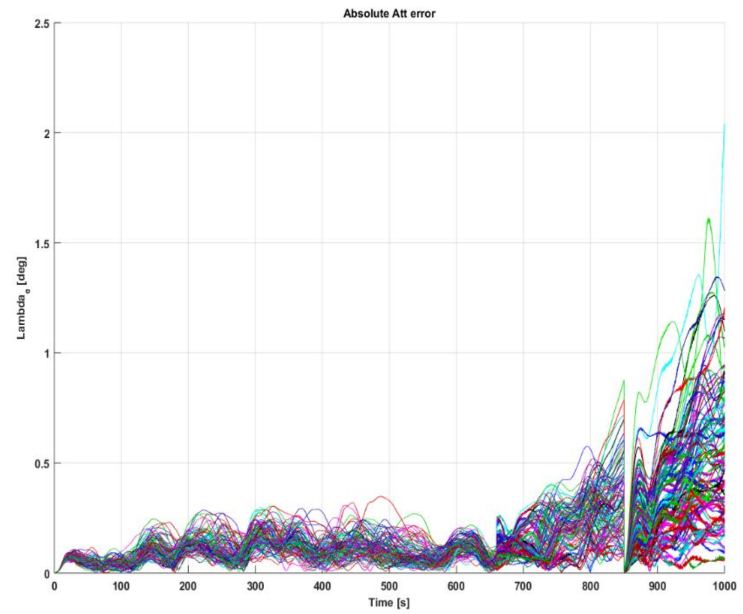




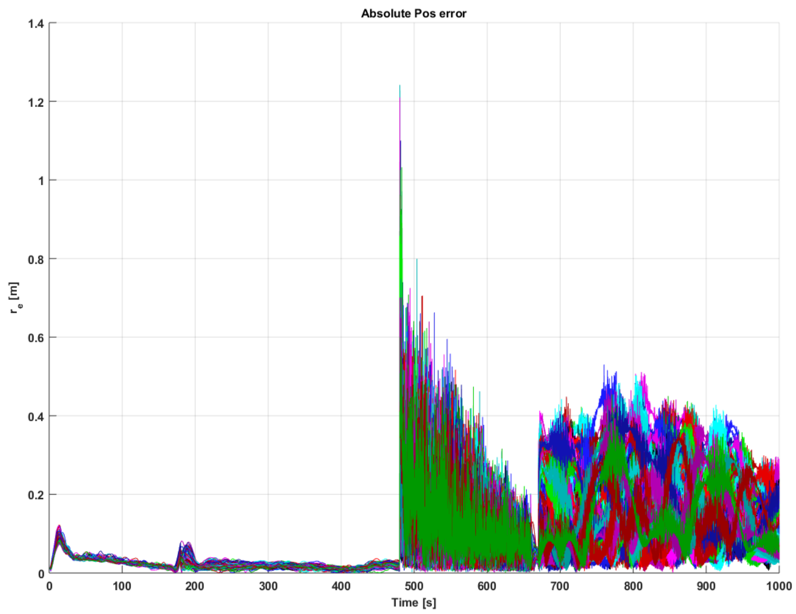
NON-LINEAR VALIDATION (MC CAMPAIGN)

- **Chaser close-in and synchronization with target**

Pointing error (100 cases) along all sub-phases



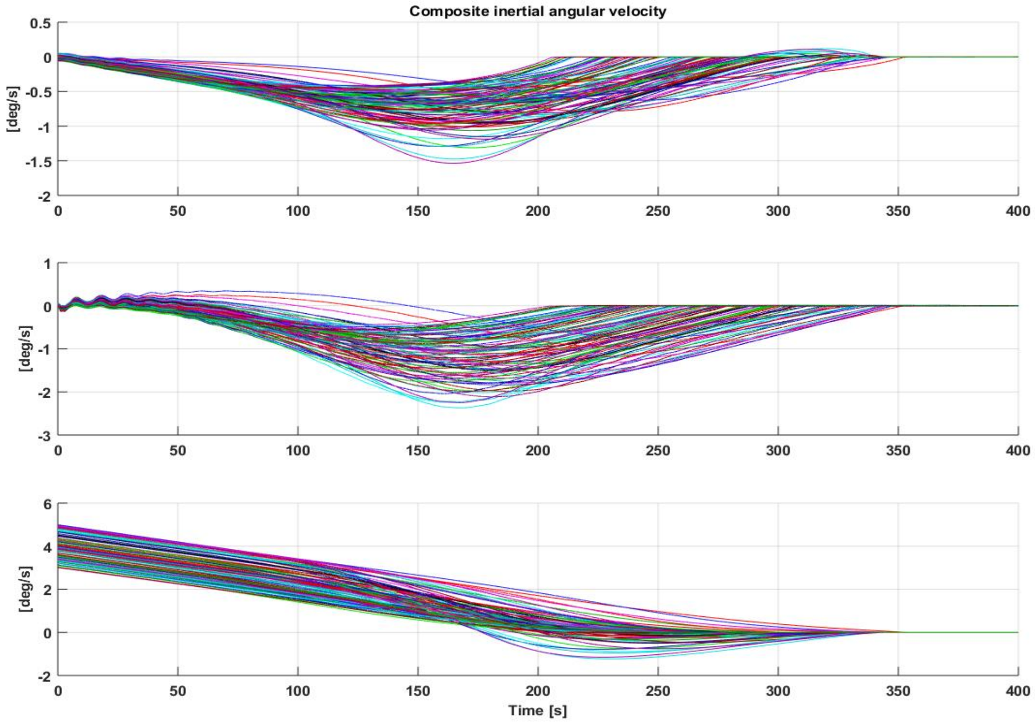
Position error (100 cases) along all sub-phases

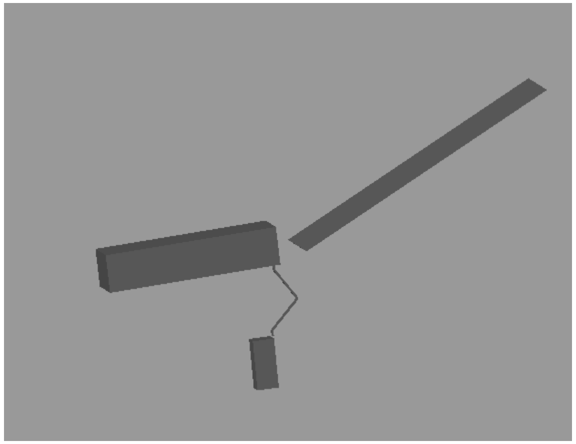


NON-LINEAR VALIDATION (MC CAMPAIGN)

- **Detumbling phase (FMCC)**
  - Chaser initially synchronised to target rotational state
  - Arm joints in locked in fixed configuration (rigidised)

Evolution of COMPOSITE angular velocity (100 cases)

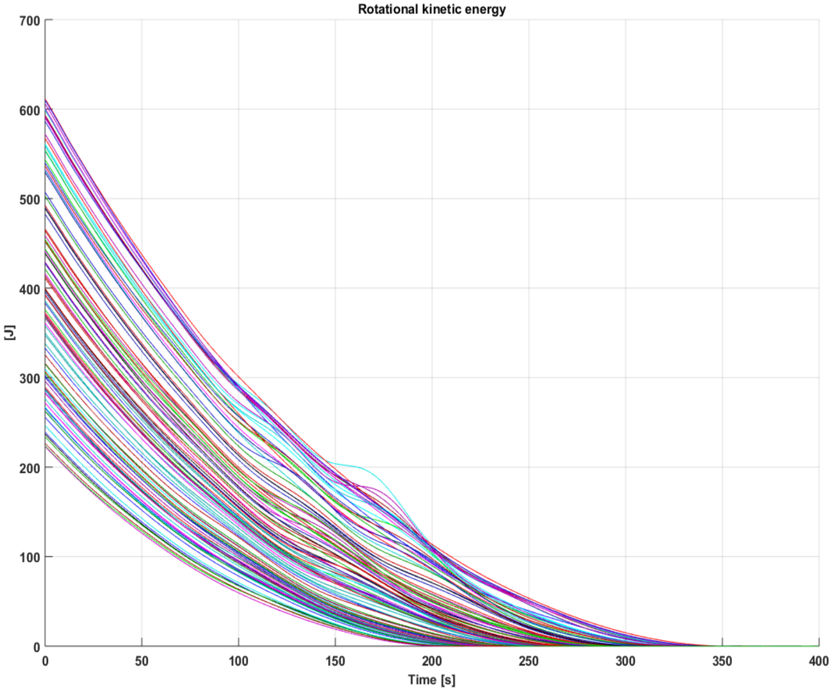




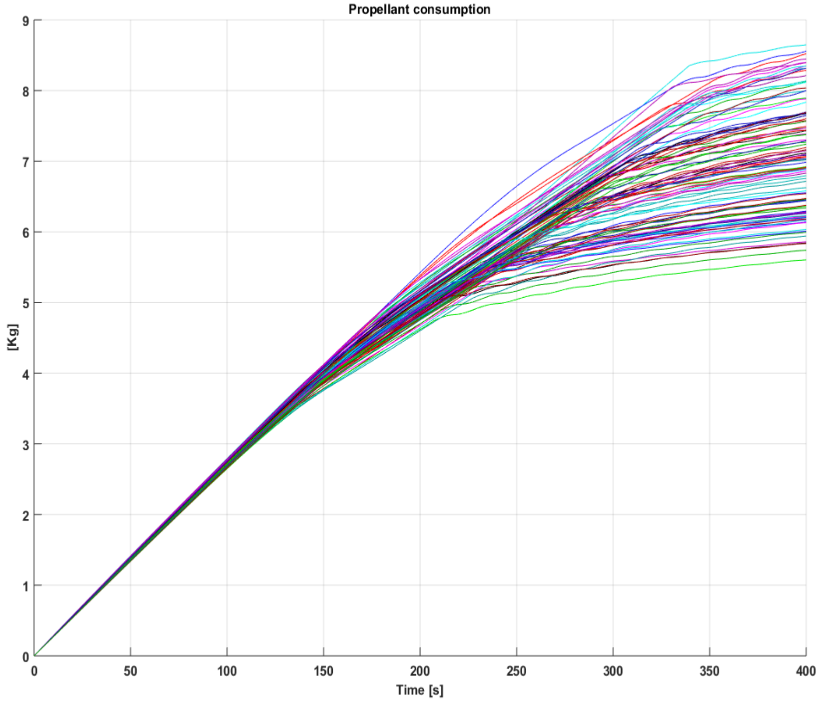
NON-LINEAR VALIDATION (MC CAMPAIGN)

– Control effort (main variation due to initial COMPOSITE rotational kinetic energy)

Evolution of COMPOSITE rotational kinetic energy (100 cases)

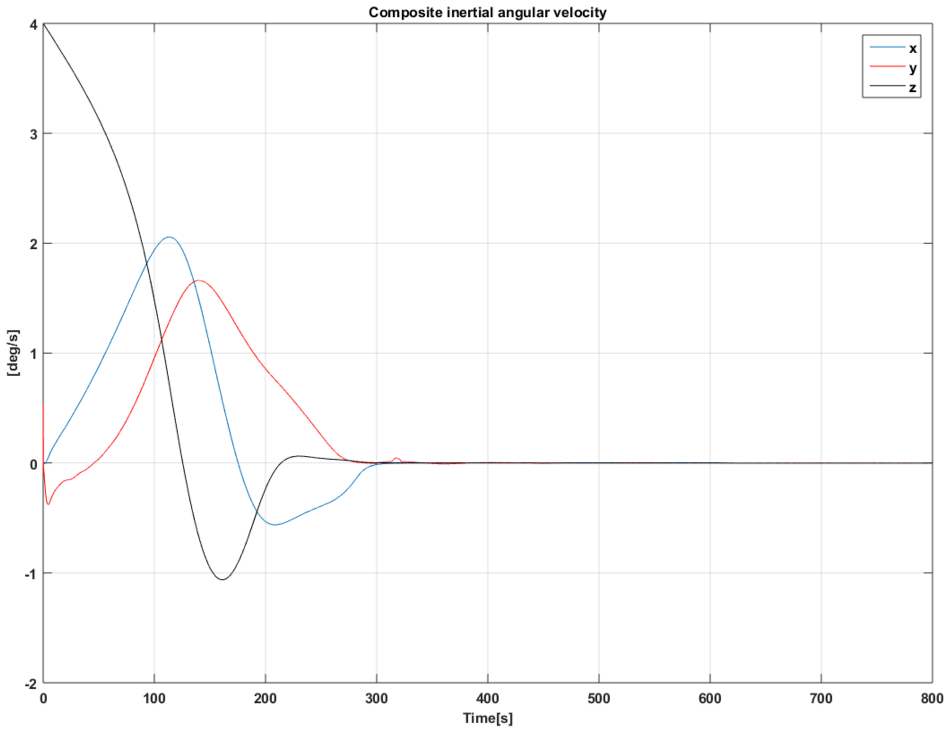


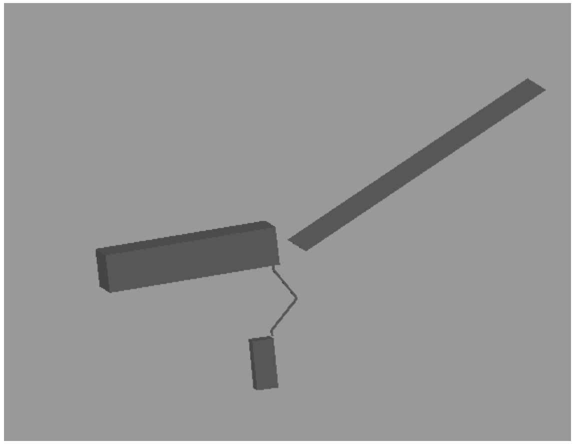
Propellant consumption (100 cases)

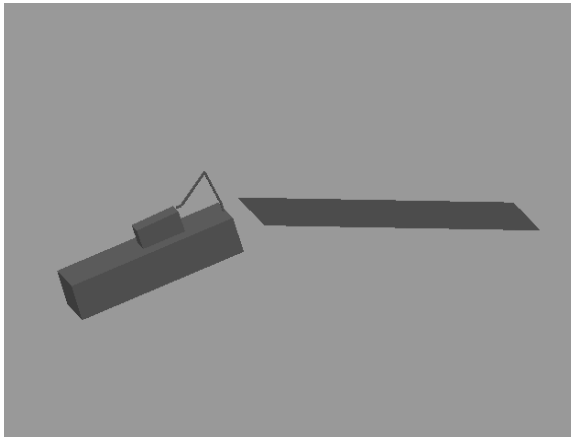


NON-LINEAR VALIDATION

- **Detumbling phase with simultaneous chaser relocation (FMCC2)**
  - Chaser initially synchronised to target rotational state
  - Arm joints controlled to relocate the







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Conclusions

CONCLUSIONS - I

- MIMO **Robust synthesis/analysis** approach demonstrated to be valid for all sub-phases of a robotic arm detumbling mission (contact capture phases out of the scope of the study)
- MonteCarlo campaign **confirmed robust stability/performance** of the designed controllers for all phases.
- **Arm unfolding phase**: no significant impact on the chaser attitude stabilisation while in target pointing (ts < 50s and control actions <1.5Nm for unfolding time = 100s)
- **Synchronisation phase:** very demanding for the GNC (high agility + low actuation and navigation errors) due to **target body rotation rate** (up to 5º/s).
  - FMC1 mean pointing error (<1deg) for the whole synchronisation phase.
  - Relative position errors in the limit of usability → Propulsion system for higher agility and lower noise levels seems required for dealing with targets rotating at such a high rate.

CONCLUSIONS - II

- **Detumbling phase:** impact of large target rotation rate and size of the target. Analyses show:
  - Just **centripetal loads** while in composite configuration could be able to cause mechanical problems. Keeping an almost perfect synchronisation of the chaser to the target tumbling state is required, but it cannot be achieved with current relative navigation technology.
  - **Arm loads measuring** (indirect way of measuring the synchronization) seems highly desirable for this phase.
  - If not relying on sensored joints (as is our study case), careful selection of the nominal **arm geometry** has demonstrated being able to contain the maximum loads on joints. Also efficient **feed-forward** laws that help reducing the composite kinetic energy quicker (before chaser desynchronization is large) have demonstrated to be very useful.
- **Simultaneous Composite braking and chaser relocation:**
  - Demonstrated to be feasible with MIMO robust control.
  - No significant impact on settling time, control effort and joint loads.
  - To properly perform the relocation manoeuvre, torques provided by the joint control inner loops (joint motors) are required to withstand centripetal loads (if no relocation, joint brakes withstand the loads appearing in the joint axes directions).

DETUMBLING

Questions ?

gmv

INNOVATING SOLUTIONS

Thank you

Thomas Vincent Peters (GMV)
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Fernando Gandía(GMV)

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