GNC design and validation for rendezvous, detumbling, and de-orbiting of ENVISAT using a clamping mechanism (CLGADR study)

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Clean Space Industrial Days
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Contents

1. **Scope and Objectives of the Study**
2. Mission definition and GNC requirements
3. Models for GNC design and simulation
4. Principal GNC outcomes of the study
5. Conclusions

Main Objective of the Study

To evaluate an autonomous **GNC** system, for the **ADR** scenario of rendezvous, capture, detumbling and de-orbiting of an **uncooperative target** using a **clamp** mechanism, to derive requirements for future missions within the **Clean Space** initiative.

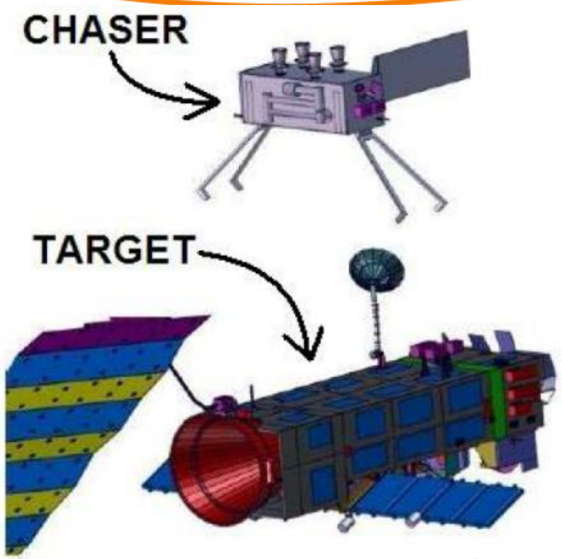

Image source: ESA/ESTEC

Key Objectives

- Develop **a GNC concept and algorithm** that is able to deal with the **multi-body dynamics** of the composite chaser-clamp-target system during capture, stabilization, detumbling and De-orbiting phases;
- Theoretically **analyze the robustness and performance** of the GNC algorithm for the chaser (pre-capture phase) and the coupled chaser-clamp-target stack (post-capture);

Key Objectives (cont)

- Develop a **MIL simulation** framework for **performance assessment** of the GNC concept, supporting GNC and mission trade-offs.
- **Assess the GNC concept performance**, especially with what relates to G&C, sensor characteristics and the clamping mechanism.

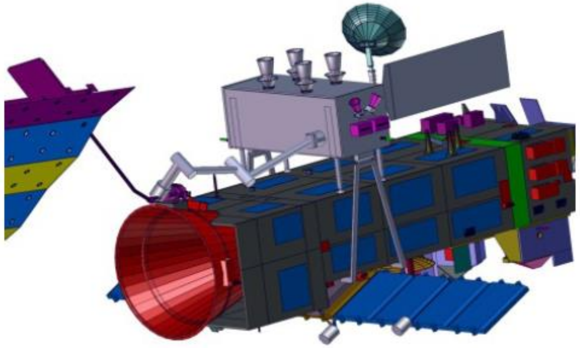

Image source: ESA/ESTEC

- Provide **lessons learnt** on the suitability of the clamp ADR approach and suitable technical GNC solutions.
- Derive **a set of requirements** for future ADR GNC solutions using the Clamp.

Contents

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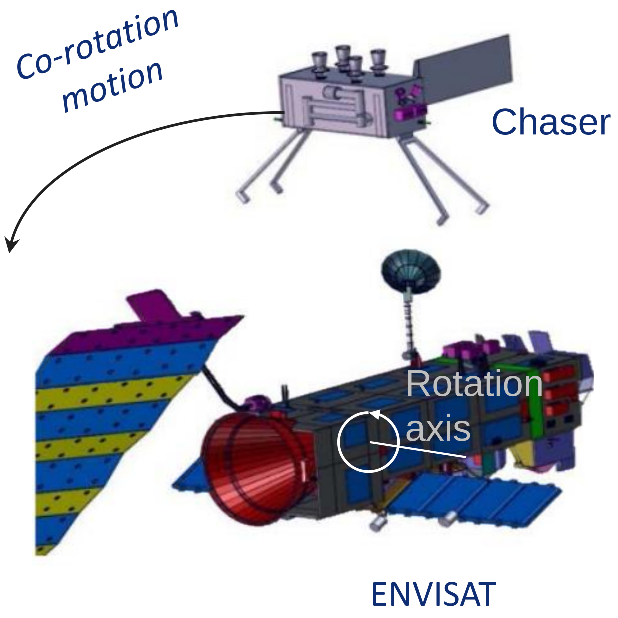
Pre-Capture Phase

Perform a final rendezvous to acquire capture configuration:

- phase starts at station keeping (SK);
- chaser acquires null relative velocity (co-rotation motion);
- finalized by a forced approach to reach capture distance wrt target body;

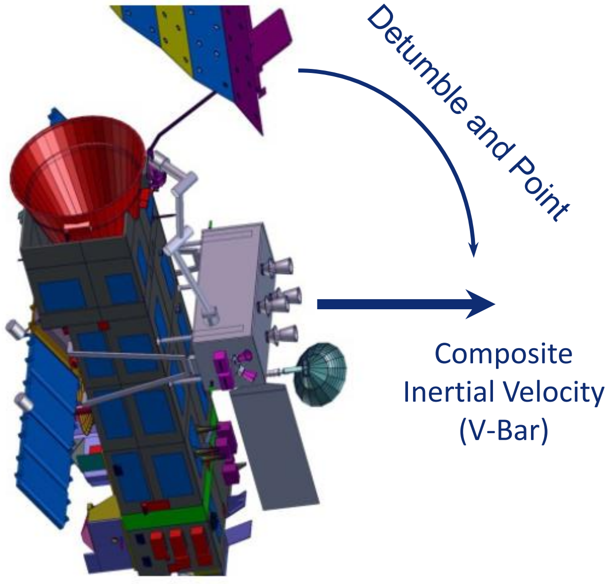


Target Stabilization Phase

Immediately after the clamp deployment, the chaser is clamped to the target and applies torque commands to:

- detumble the target, nullifying its angular velocity;
- point the composite to the attitude required for de-orbiting;

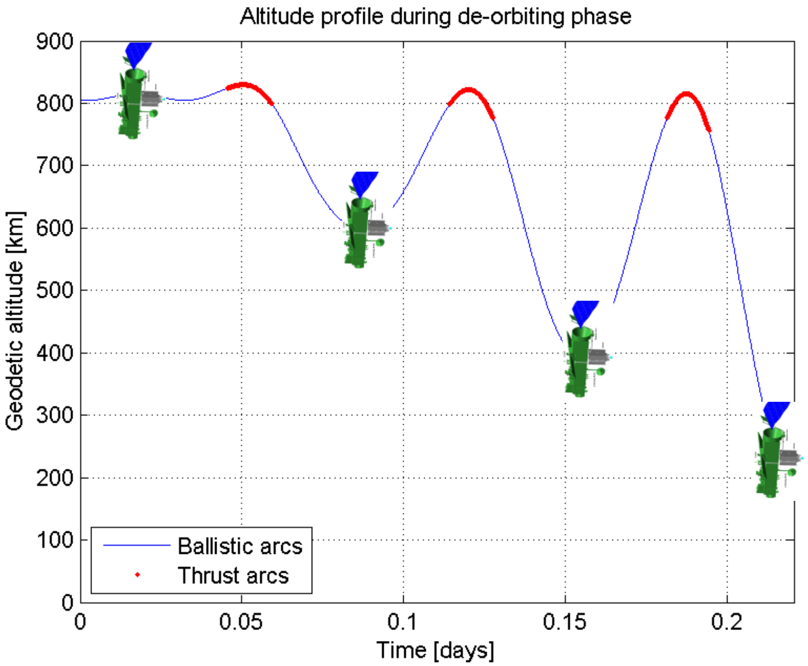
Detumbling and Pointing



Stack Orbit Transfer and Disposal Phase.

The objective is the de-orbiting and disposal of the composite.

A gradual perigee lowering strategy is adopted, with de-orbit boosts at apogee.



GNC Requirements

Design requirements define design specifications of the GNC, such as design method and parameters, and are thus verified by review of design.

These requirements state that the GNC must:

- Use modern **MIMO robust techniques** that:
  - provide **analytical stability** characterization;
  - by design, can cope with **uncertainties** in the model;
- Be **autonomous** (using ground only for high-level decisions) and **generic** (with respect to orbit radius);
- **Attain and perform co-rotation**, with a final relative distance between 2m and 3m point-to-point;
- Perform **6-DoF control of pre-capture** translational and rotational states of chaser relative to the target;
- Perform **3-DoF control of post-capture** rotational state of the composite.

Robustness requirements define what are the effects to which the GNC must be robust.

These requirements state that the GNC must:

- Be robust to:
  - **Sensor and actuator** errors considered in the model;
  - **Sloshing and flexible modes** of both S/C (chaser and target);
  - **Air-drag**, that is significant at lower altitudes of de-orbiting;
  - **De-orbiting boosts**, namely in the on/off commutation;
- Satisfy modern control stability criteria: $\mu<1$, modulus margin >-6dB.
- Be robust to the MCI uncertainties (3-σ)

Chaser	Target
Mass: 5%	**Mass**: 0.2%
Inertia: $\pm\begin{bmatrix}10.0\% & 20.0\% & 20.0\% \\ 20.0\% & 10.0\% & 20.0\% \\ 20.0\% & 20.0\% & 10.0\%\end{bmatrix}$	**Inertia**: $\pm\begin{bmatrix}2.0\% & 25\% & 11.5\% \\ 25\% & 2.4\% & 43.4\% \\ 11.5\% & 43.4\% & 2.3\%\end{bmatrix}$
CoM: 0.10m per axis	**CoM:** 0.01m per axis **CoM slippage**: up to 0.10m wrt chaser during de-orbit.

Performance requirements define quantitatively the desired performance of the GNC.

- The performance requirements establish the accuracy of:
  - Positioning and pointing at pre-capture;
  - Pointing at post-capture;

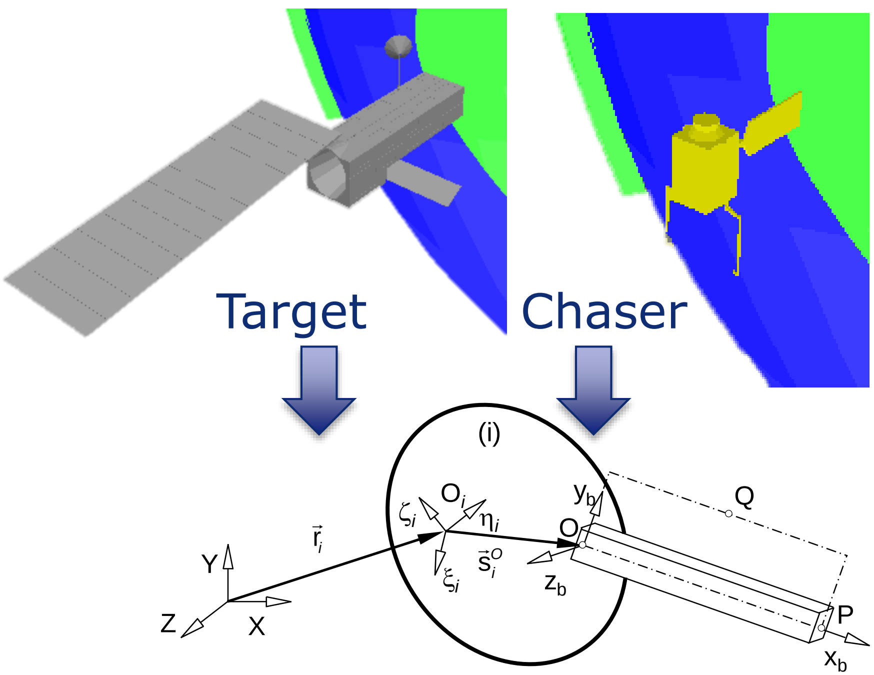
Robustness and performance requirements are the focus of the CLGADR study.

- **By design,** the GNC was made compliant with the requirements.
- The requirements were validated using:
  - **robust control analysis tools**, obtaining analytical guarantees of the desired properties;
  - **extensive Monte Carlo campaign** (designed to obtain 99% confidence levels), complementing/confirming the analytical results.

Contents

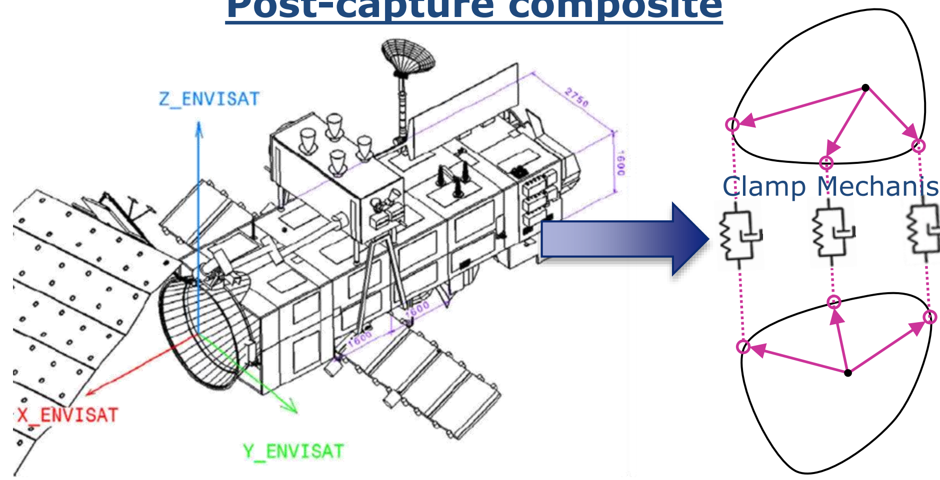
1. Scope and Objectives of the Study
2. Mission definition and GNC requirements
3. **Models for GNC design and simulation**
4. Principal GNC outcomes of the study
5. Conclusions

Pre-capture S/C modeling



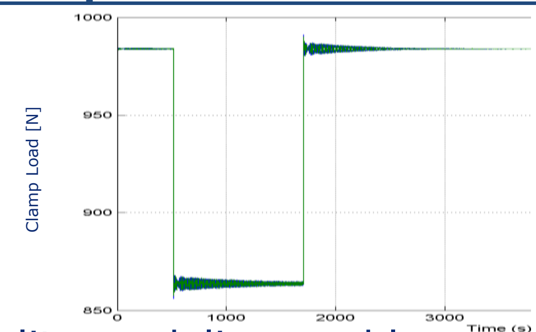
Each S/C is modeled as a rigid body with a flexible appendage and sloshing effects.

Post-capture composite



The post-capture model considers both S/C attached by a clamping mechanism.

Clamp Mechanism Monitoring



High-fidelity modeling enables monitoring of clamp load and time-domain response.

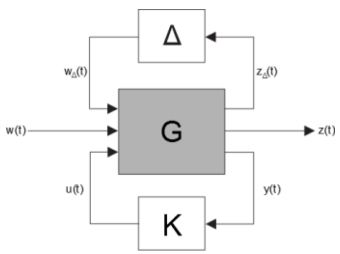
Model-in-the-Loop (MIL) Simulator

A Model-in-the-loop (MIL) simulator was developed for time-domain validation of the GNC, being characterized by:

- **High-fidelity simulation of many configurations** considered in the study:
  - single and multi-body S/C dynamics;
  - clamping mechanism;
  - three ENVISAT rotational scenarios;
  - three relative sensor performances (LIDAR, VISCAM, IRCAM);
  - the dynamics of the S/C appendages (flexible modes, sloshing);
  - the validation type (single-shot vs MC campaign).
- **High-fidelity simulation of environmental effects** such as third body, drag, solar radiation pressure and gravity harmonics;
- **Representative simulation of sensors and actuators models**, and associated non-idealities.

LFT Modeling approach

For each phase (pre-/post-capture), three models are synthesized:



Nonlinear MBD model
- Highly nonlinear
- High fidelity
- Appropriate for simulation purposes

LFT models:

Model for closed-loop analysis
- Large number of uncertain parameters
- Intermediate complexity and conservatism

Model for controller synthesis
- Adopts a subset of the parameters and simplified models if necessary
- Model mismatch due to simplification is approximated by exogenous disturbances

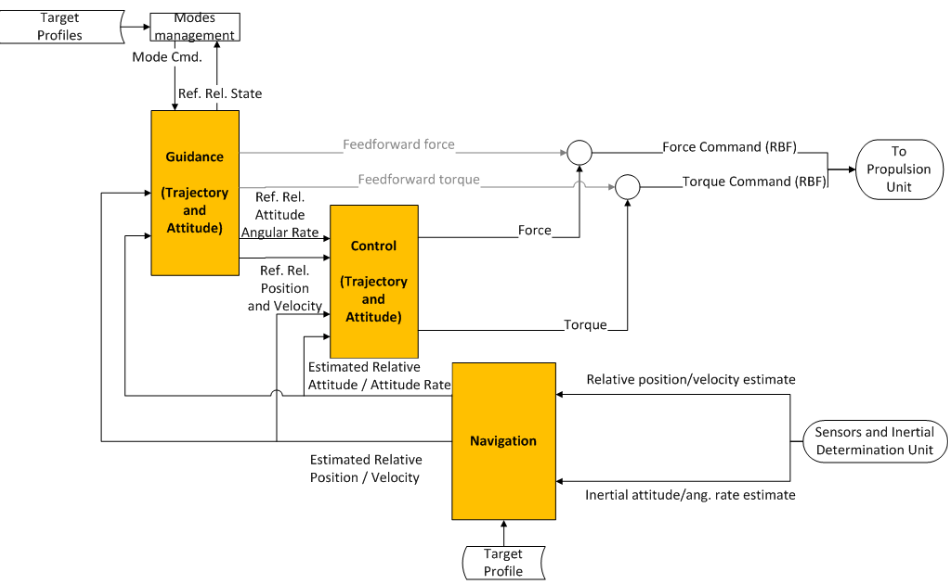
↑ Model Complexity

Contents

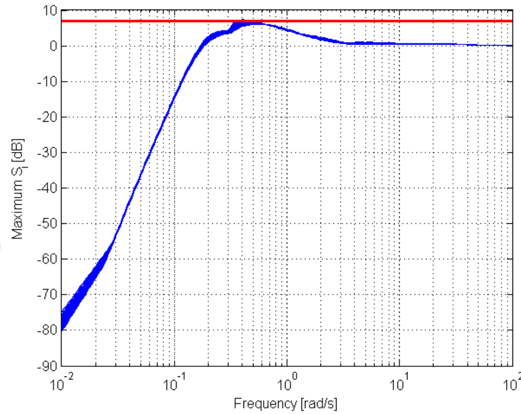
1. Scope and Objectives of the Study
2. Mission definition and GNC requirements
3. Models for GNC design and simulation
4. **Principal GNC outcomes of the study**
    1. **Pre-capture phase**
    2. **Post-capture phase**
5. Conclusions

PRINCIPAL GNC OUTCOMES OF THE STUDY
Pre-capture phase

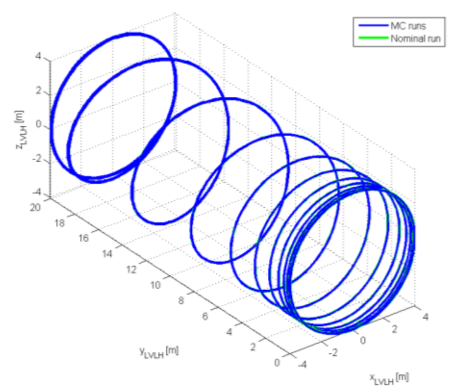
❑ Robust GNC for Final Rendezvous



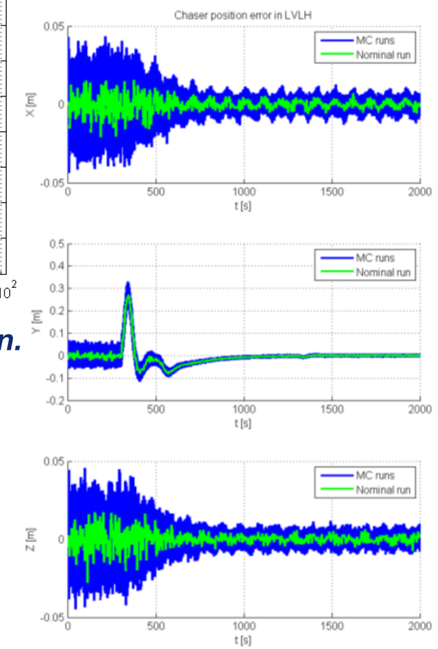
Pre-capture GNC architecture.



Robust analysis of modulus margin.



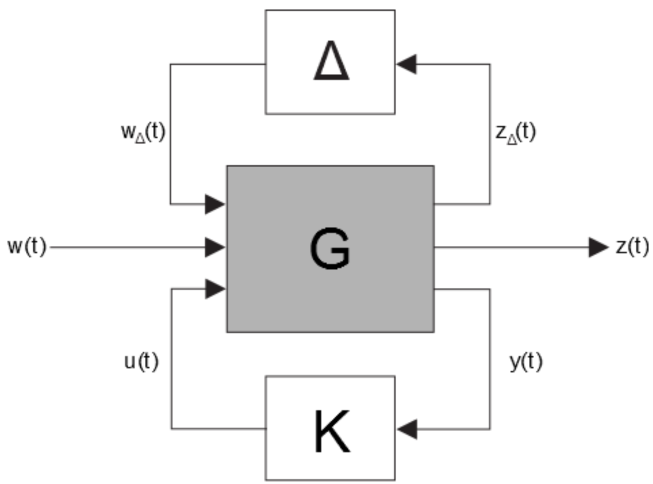
Design and validation of rendezvous co-rotation profile.

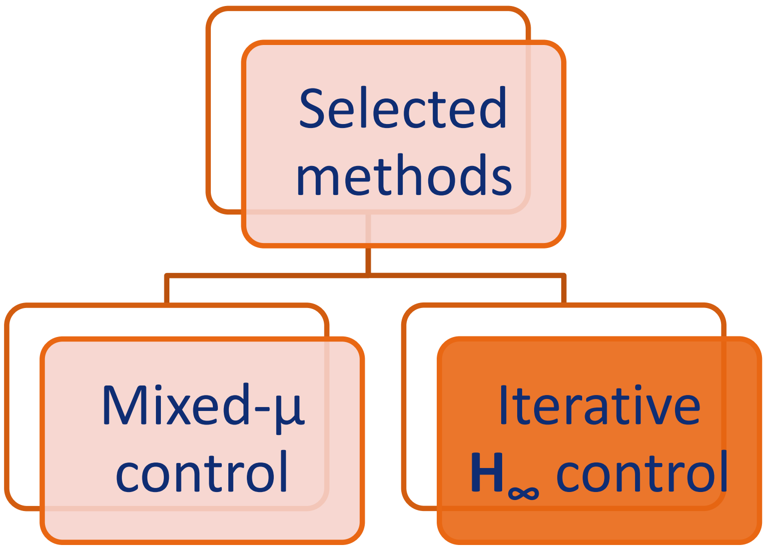


Results of Monte-Carlo GNC position performance.

Controller Design/Synthesis

General Setup





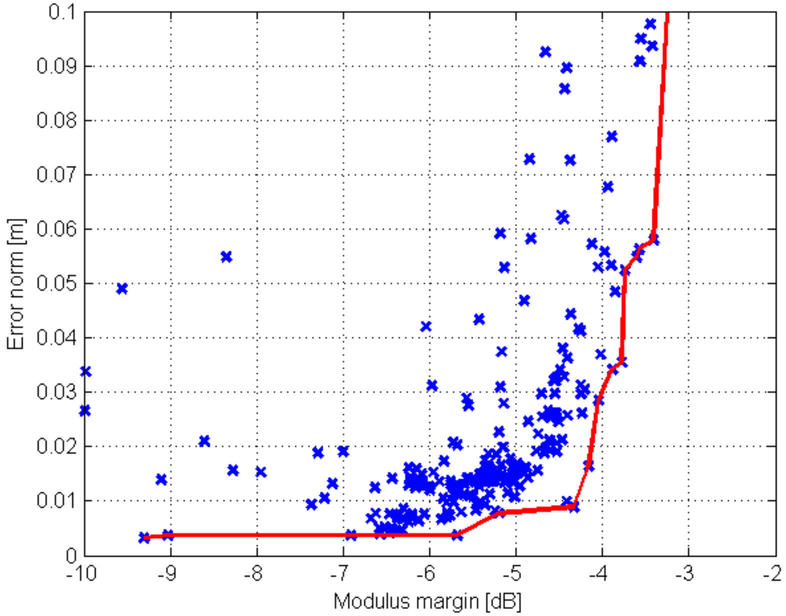
For pre-capture, the following robust control synthesis tools were adopted:

- Design method is an **iterative unstructured H_∞ control**, using Hybrid Differential Evolution (HDE) to tune the dynamic weights;
- Control framework provides for a **robust feed-forward term** (in addition to feedback term). This command improves the tracking performance (similar to Guidance classical feed-forward), but explicitly takes into account model uncertainty.

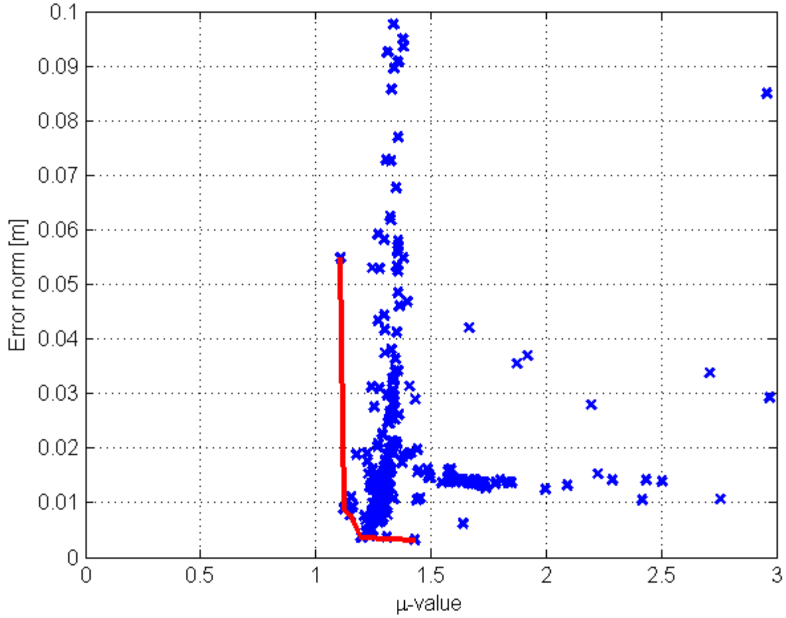
PRINCIPAL GNC OUTCOMES OF THE STUDY
Design of the pre-capture control subsystem

Controller Synthesis (Hybrid Differential Evolution)

Performance vs modulus margin



Performance vs μ-value UB



- ❑ The controller synthesis applies a global optimization algorithm to search for the dynamic weights that best comply with the requirements;
- ❑ The figures show the optimization results, depicting performance of the GNC at capture vs modulus margin (left) and vs μ-value (right).
- ❑ The selected controller ensures the required modulus margin and μ.

PRINCIPAL GNC OUTCOMES OF THE STUDY
V&V framework applied to pre-capture GNC

Advanced Verification and Validation

- Advanced V&V provides analytical results of interest for GNC validation, namely
  - **robustness criteria** (μ, modulus margin);
  - **worst-case conditions** for stability and performance.

- Furthermore, the worst-case analysis provides **insight on the physics of the problem.** Worst-case parameter characterization can be obtained as shown below.

Uncertain parameter description	Parameter	WC value
Chaser inertia uncertainty (diagonal elements)	I_{xx}	**Maximum**
	I_{yy}	*Minimum*
	I_{zz}	*Minimum*
Chaser flexible modes (gap between 1st and 2nd modes)	Frequency gap	*Minimum*
	Damping gap	*Minimum*
Chaser center-of-mass	Displacement in x_{RSF}	**Maximum**
	Displacement in y_{RSF}	*Minimum*
	Displacement in z_{RSF}	**Maximum**
Chaser mass	m_c	**Maximum**

- In the case of pre-capture, **worst-case conditions** correspond to highest chase mass and smallest gap between the frequencies of chaser’s flexible modes.

PRINCIPAL GNC OUTCOMES OF THE STUDY
Time-domain validation of pre-capture GNC

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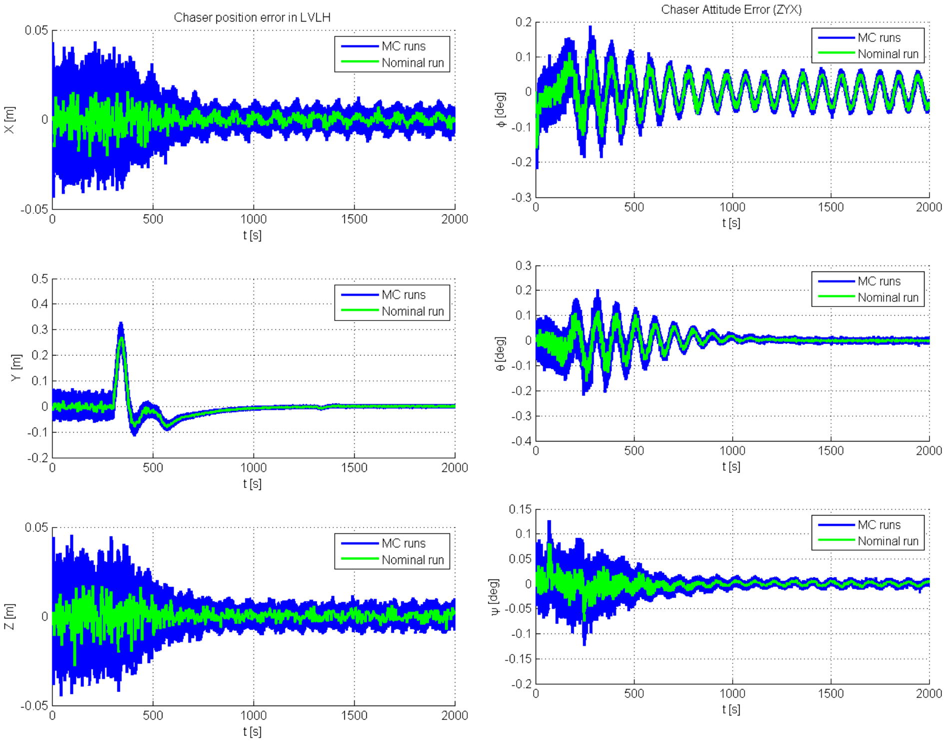
GNC time-domain validation

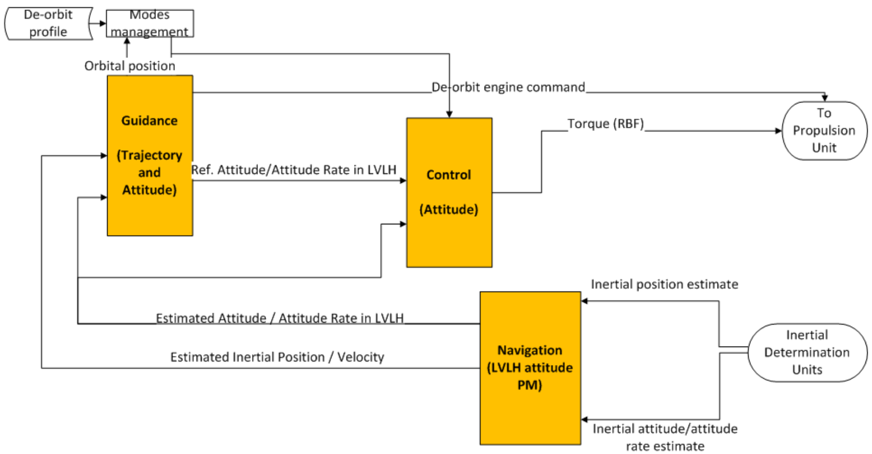
- The results are obtained for:
  - 300 MC shots with GNC in the loop;
  - nominal rotation scenario;
  - dispersion in all the parameters.
- The results show that:
  - co-rotation and target-pointing profiles are tracked by GNC;
  - actuation is commanded within actuator limits;
  - stability is verified for all dispersions;
  - GNC accuracy is within performance requirements of the mission.



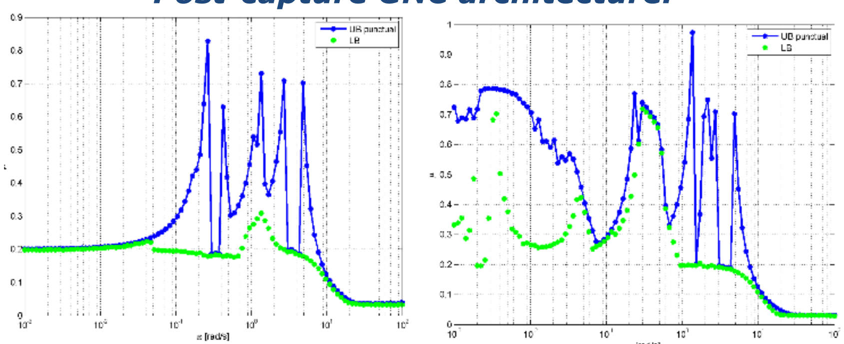
	Required/Allowed GNC Accuracy			
	Position	Velocity	Attitude	Angular rate
Station keeping (20m)	20.0 cm	2.0 cm/s	-	-
Capture position (4m)	1.2 cm	0.5 cm/s	1 deg	0.1 deg/s

PRINCIPAL GNC OUTCOMES OF THE STUDY
Post-capture phase

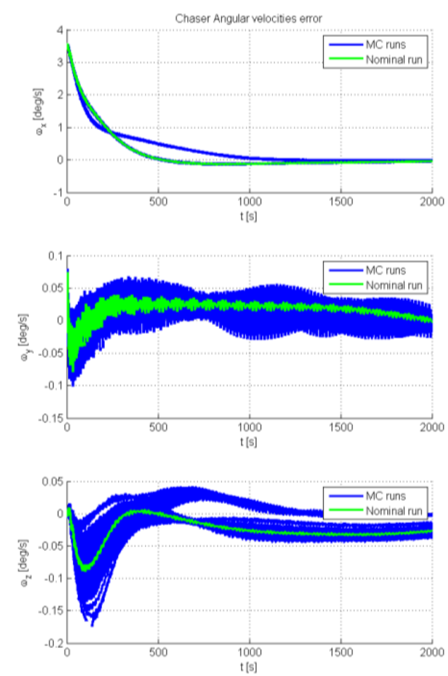
- ❑ Robust GNC for multi-body systems, such as the post-capture composite;
- ❑ GNC is designed for operations such as detumbling, pointing and de-orbiting.



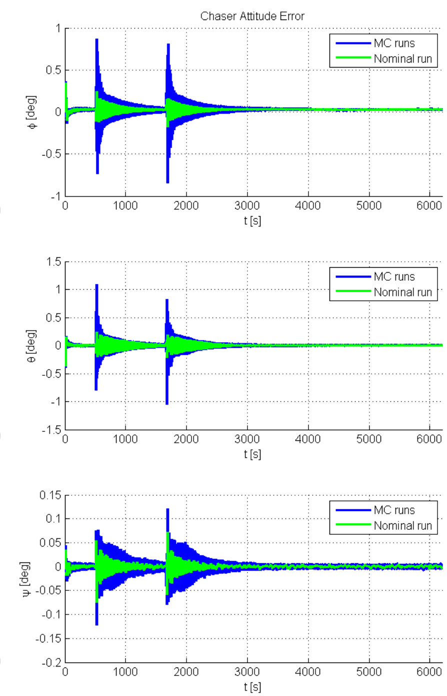
Post-capture GNC architecture.



Robust analysis of structured singular value for detumbling (top) and pointing (bottom).



Results of Monte-Carlo stabilization of composite angular velocity (detumbling).



Results of Monte-Carlo stabilization of composite attitude (de-orbiting).

PRINCIPAL GNC OUTCOMES OF THE STUDY
Analytical validation of post-capture GNC

Robust analysis results

- Resulting GNC attains **stability and performance robustness** (μ-UB<1 for all frequencies).

- **Physical insight** is provided:
  - Highest values of μ-LB are around frequency of flexible modes.
  - Worst-case conditions correspond to lowest damping and lowest frequency of flexible modes.

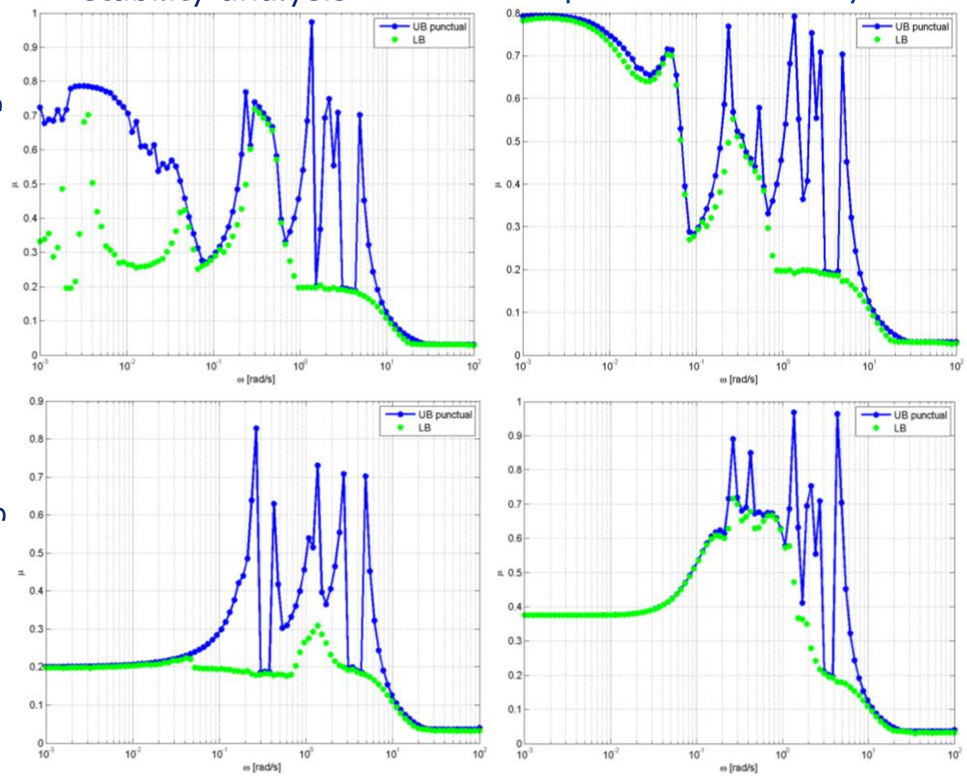
- **Monte-Carlo campaign** is adopted to confirm that robustness is indeed attained. It also resolves limitations and justifies assumptions of analytical validation.

Mixed-μ robust stability analysis

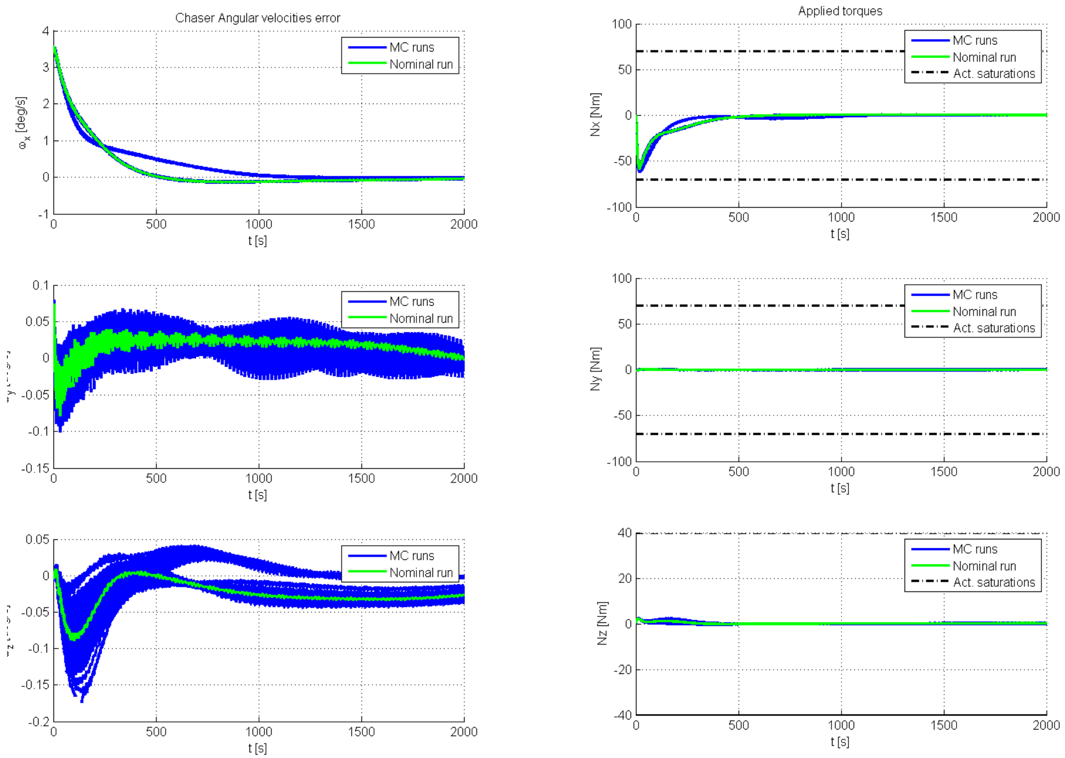
Mixed-μ robust performance analysis

Detumbling

Pointing



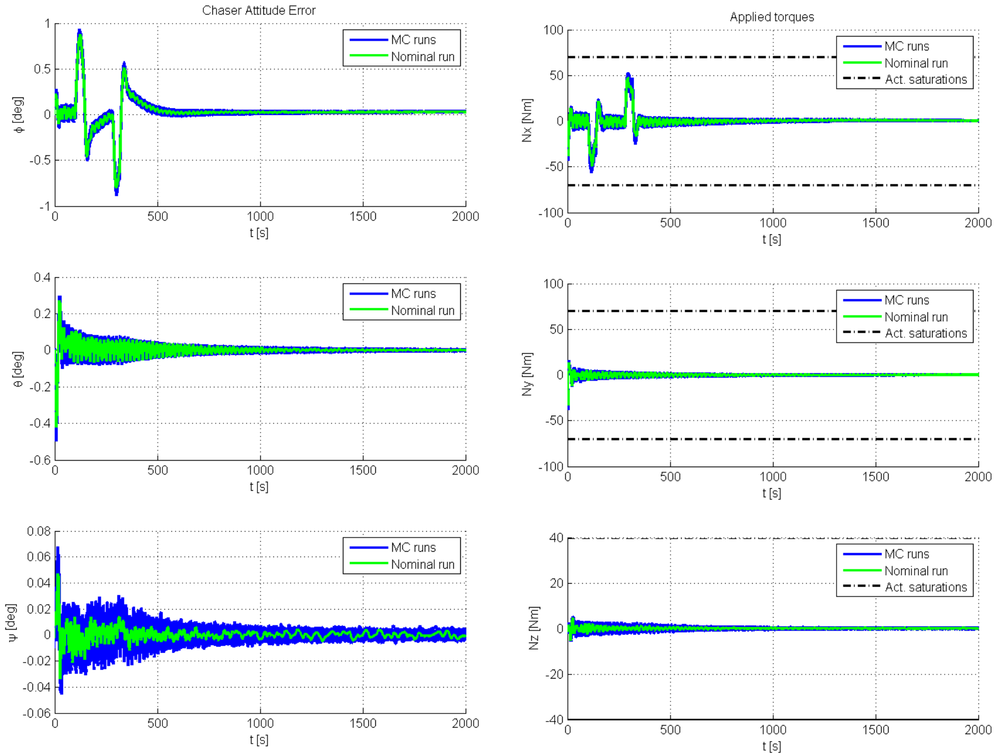
Detumbling time-domain validation



- The results are obtained for 100 MC shots with GNC in the loop, nominal rotation scenario, and dispersion in all the parameters;
- The results show that
  - the composite is effectively detumbled, satisfying the requirements;
  - the applied torque is within saturation bounds.

PRINCIPAL GNC OUTCOMES OF THE STUDY
Time-domain validation of GNC: pointing

Pointing time-domain validation

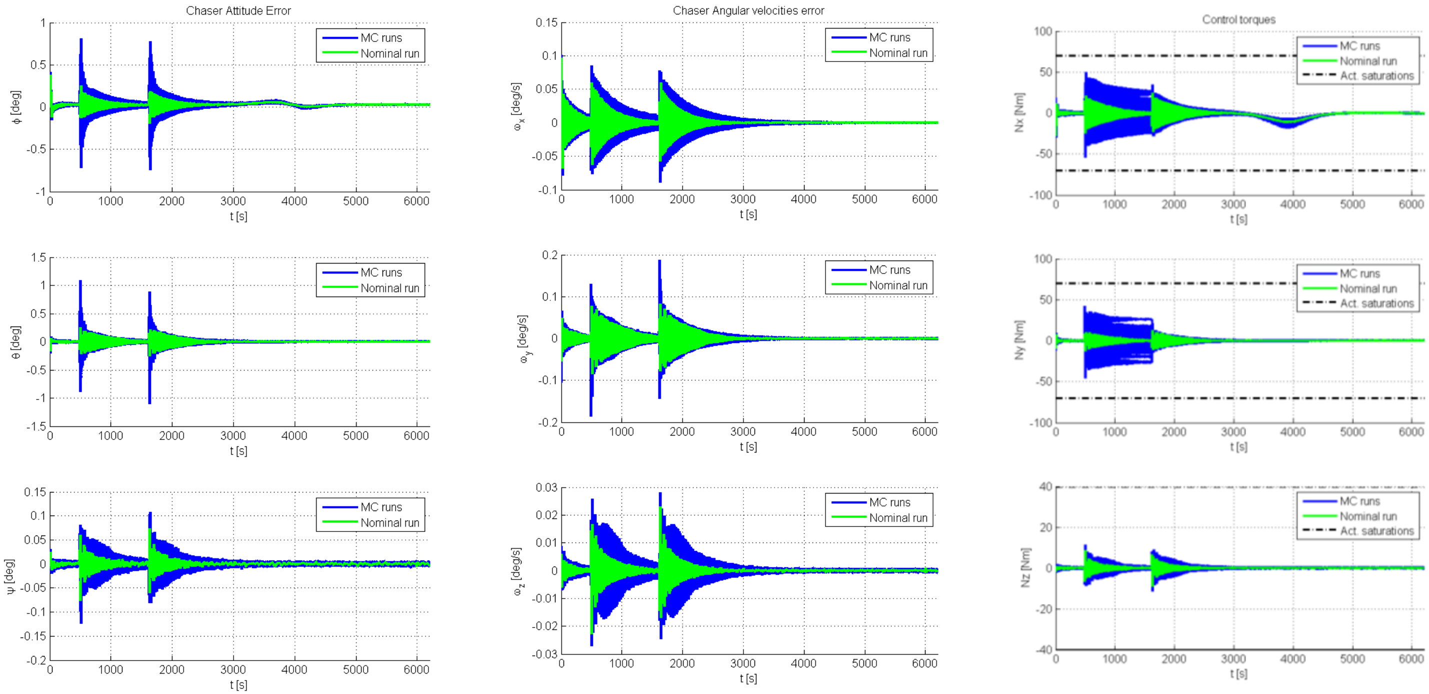


- ❑ The results are obtained for 100 MC shots with GNC in the loop, nominal rotation scenario, and dispersion in all the parameters;

- ❑ The results show that
  - composite pointing is attained within requirements;
  - the applied torque is within saturation bounds.

PRINCIPAL GNC OUTCOMES OF THE STUDY
Time-domain validation of GNC: de-orbiting

De-orbiting time-domain validation



- The de-orbiting phase is simulated for 100 shots with GNC in the loop and dispersion in all the parameters.
- The results, illustrated above for the 3rd burn, are similar for all burns, and show that:
  - Attitude control satisfies performance and stability requirements;
  - Torque actuation is within bounds for all the de-orbit burns;
  - Closed-loop GNC effectively counteracts the effect of 10cm (3σ) slippage of target with respect to chaser.

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CONCLUSIONS

- **ADR GNC architecture and algorithms** were designed for the capture and de-orbiting of ENVISAT using a clamp mechanism.
- The design of the GNC addressed the problems of **stability and performance** robustness, for **multi-body systems**.
- The validation of key requirements was obtained in an **advanced verification and validation framework**, that combined analytical and simulation-based validations.
- **The requirements are satisfied in general.** Some refinements to the requirements were produced.
- The representativeness of the results is supported by the **several scenarios considered**, the **adopted verification and validation framework**, the **high-fidelity simulation framework**.
- These can be considered valuable in **upcoming e.Deorbit phases**, as well as in other Active Debris Removal studies/programs.

Thank you

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