Space target capture with optical navigation and chaser-robotic arm combined control

2022 Clean Space Industry Days

October 13th, 2022

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Outline

- The project
- Scenarios description
- Relative navigation
- Combined control
- Functional Engineering Simulator
- Numerical test results
- Roadmap

Objective

The objective of the project was the development of enabling GNC technologies for space target capture.

The goal of the activities was dual:

1.

Development of **algorithms for (A) relative navigation and pose estimation** during close-proximity operations, and for **(B) combined robust control** of the dynamic system composed by the chaser, the robotic arm and, after capture, the target.

2.

Development of **a relevant simulation environment** suitable for the validation of GNC technologies and capable of supporting design and analysis of GNC systems for close-proximity operations.

Team

Centre of Studies and Activities for Space «G. Colombo »
Università degli Studi di Padova

Dept. of Aerospace Science and Technology
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Dept. of Industrial Engineering
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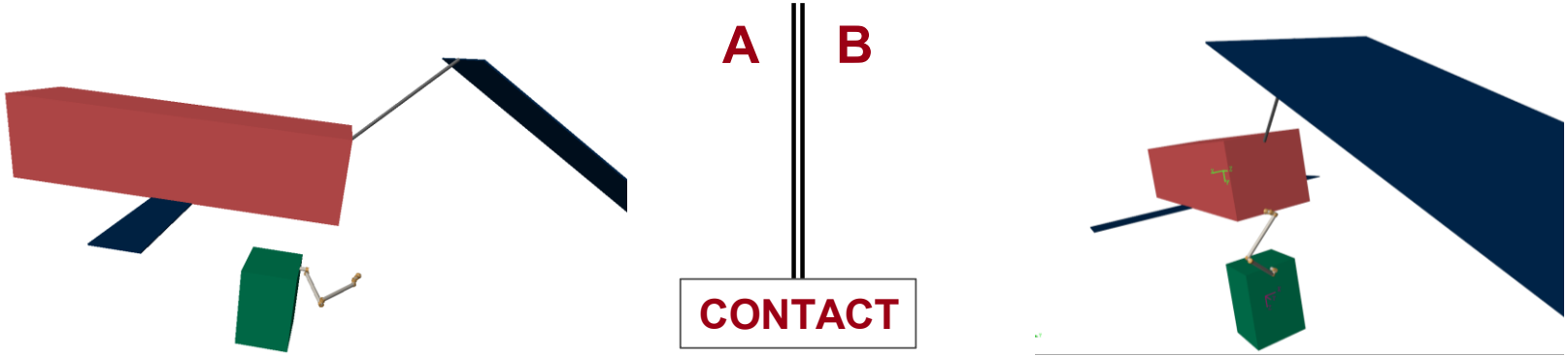
Mission architecture

Development (to TRL 4) of GNC software technologies to support Close Proximity Operations (CPOs) performed by a servicer vehicle (chaser) on a generic orbital object (target) in three scenarios. CPOs refer to the operations after rendezvous and are further divided in two phases:

A. Phase A: Reach and Capture (from a few metres up to contact)

B. Phase B: Post-capture (arm Rigidization + stack Stabilization)



SC1: OOS in GEO

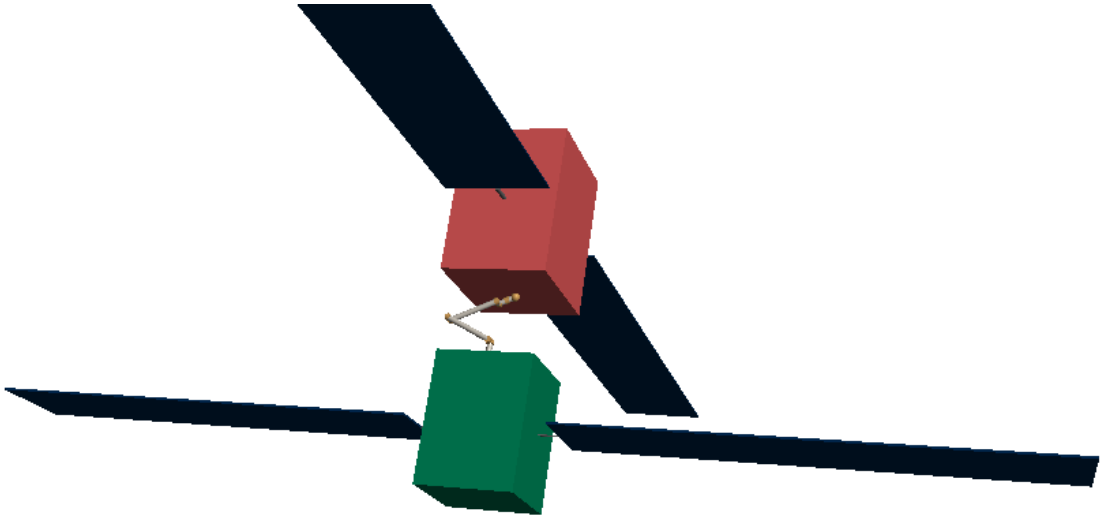
Target:

- 2000 kg
- Body: 2.5 x 2.8 x 3.5 m
- Panels (tip-to-tip): 31 m
- Semi-collaborative
- Semi-cooperative
- Controlled attitude

Chaser:

- 1900 kg
- Body: 2.1 x 2.3 x 3.1 m
- Robotic arm: 3 m

Scenario 1 (SC1): On-Orbit Servicing (OOS) of GEO operational satellite for life extension.



SC2: OOS/ADR in LEO

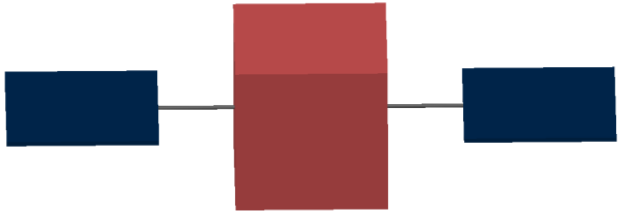
Target:

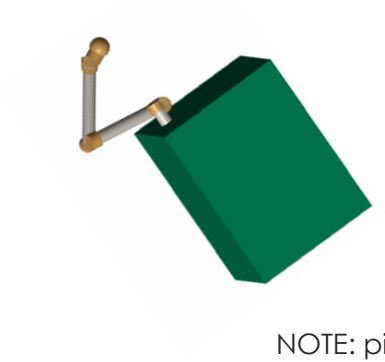
- 150 kg
- Body: 1 x 1 x 1 m
- Panels (tip-to-tip): 4 m
- Non-collaborative
- Semi-cooperative
- Rotating at 2.5 deg/s

Chaser:

- 372 kg
- Body: 1.3 x 1.3 x 1.75 m
- Robotic arm: 2 m

Scenario 2 (SC2): Capture of a large-constellation platform in LEO for servicing and/or removal.





NOTE: pictures not in scale

SC3: ADR in LEO

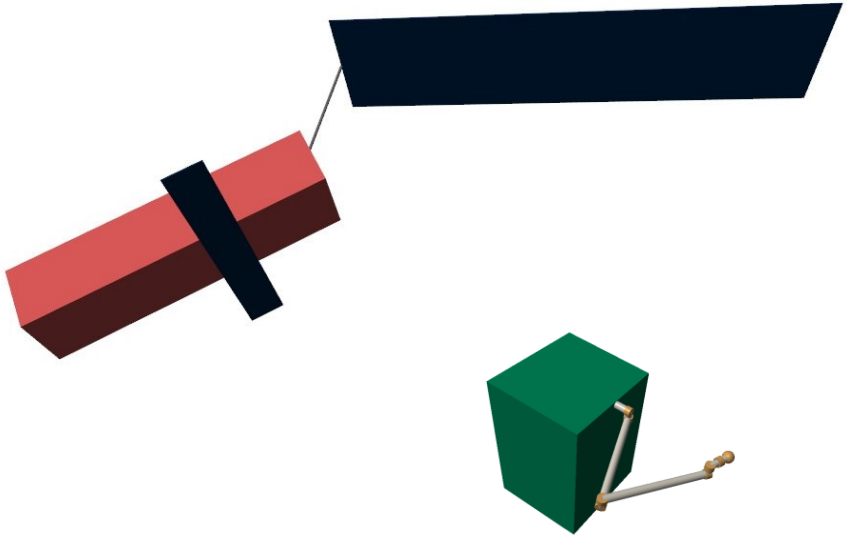
Target:

- 8110 kg
- ENVISAT
- Non-collaborative
- Non-cooperative
- Rotating at 5 deg/s

Chaser:

- 1200 kg
- Body: 2.0 x 1.8 x 2.75 mm
- Robotic arm: 4 m

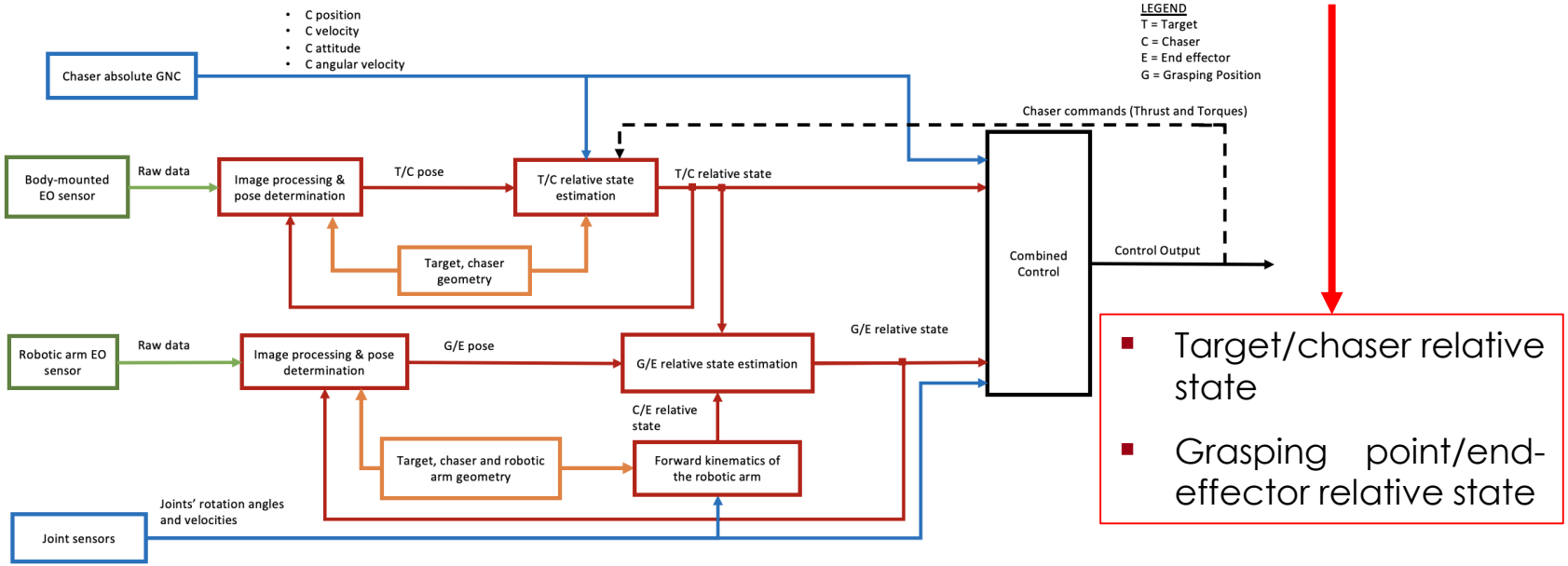
Scenario 3 (SC3): Active Debris Removal (ADR) of a large debris object in LEO.



NOTE: pictures not in scale

Architectural solution

The relative navigation task is entrusted to **electro-optical sensors** whose measurements are integrated within a **loosely coupled architecture** to estimate



- Target/chaser relative state
- Grasping point/end-effector relative state

Sensors' selection

Trade-off analysis carried out considering **system budgets** (SWaP constraints), **system complexity**, **cost**, **angular resolution** and **accuracy**, **direct distance measurements capability**, **illumination robustness**, and **algorithmic complexity**

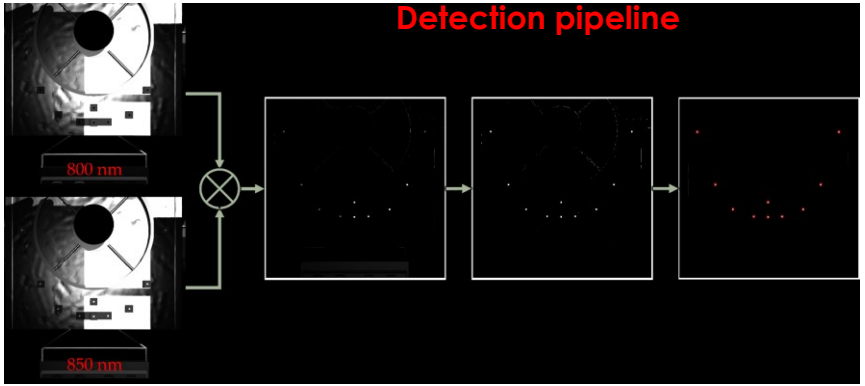
Scenario	Body-fixed EO sensor	End-effector EO sensor
SC1	Monocular camera	Monocular camera
SC2	Monocular camera	Monocular camera
SC3	Flash LIDAR	TOF camera

- Highly accurate Line of Sight (LOS) measurements from monocular sensors can lead to highly accurate relative state estimates in the case of semi-cooperative targets
- Active sensors producing direct distance estimates are required to deal with non-cooperative targets

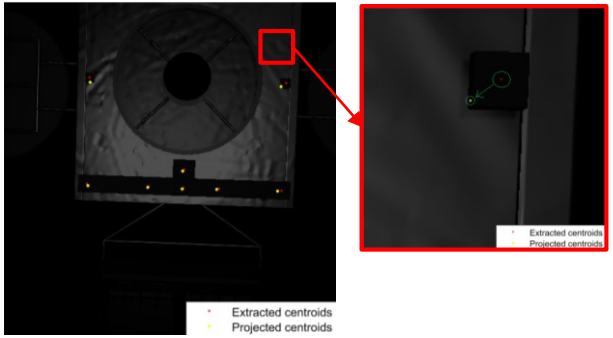
IP and pose determination – Algorithms' selection SC1

Body-mounted camera --- retroreflectors

Detection	Identification	PnP solution
Main steps - Image subtraction - Binarization (global thresholding) - Outlier rejection - Centroiding	Main steps - Markers reprojection - Nearest Neighbour (NN) matching	Levenberg-Marquardt (LM)-based least squares minimization of reprojection error



NN-based identification



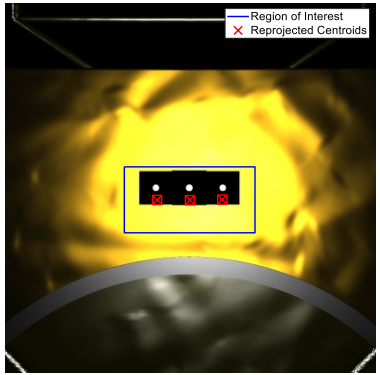
Opromolla, R., Vela, C., Nocerino, A., & Lombardi, C. (2022). Monocular-Based Pose Estimation Based on Fiducial Markers for Space Robotic Capture Operations in GEO. *Remote Sensing*, *14*(18), 4483.

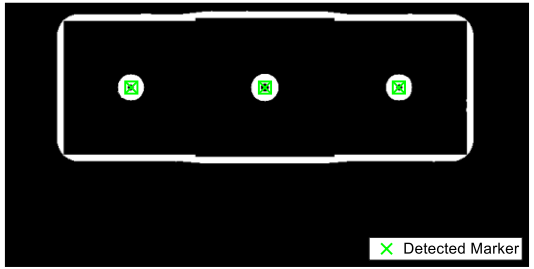
IP and pose determination – Algorithms' selection SC1

Robotic arm camera IP --- visible high-contrast markers

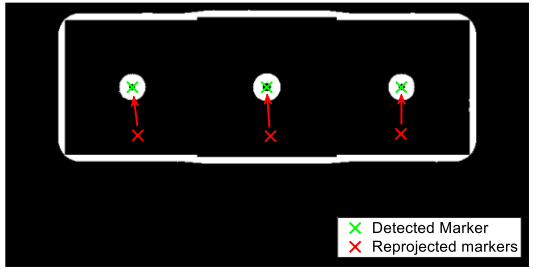
Detection	Identification	PnP solution
Main steps - Search area definition - Binarization (adaptive thresholding) - Centroiding	Main steps - Markers reprojection - NN-based matching	Levenberg-Marquardt (LM)-based least squares minimization of reprojection error

Detection pipeline





NN-based identification



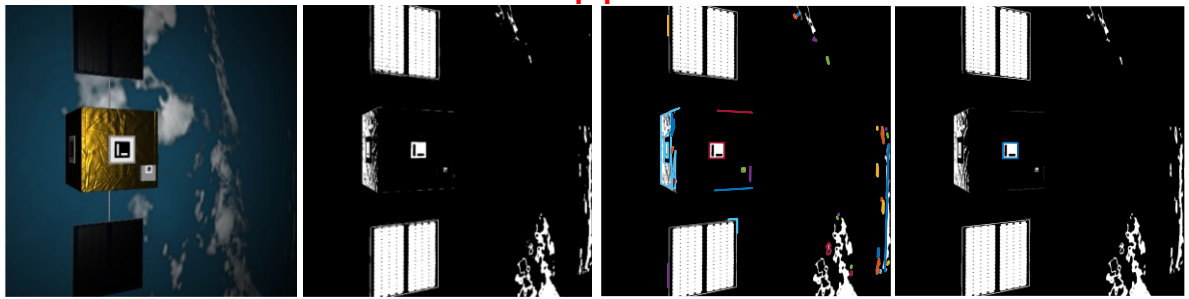
Opromolla, R., Vela, C., Nocerino, A., & Lombardi, C. (2022). Monocular-Based Pose Estimation Based on Fiducial Markers for Space Robotic Capture Operations in GEO. *Remote Sensing*, *14*(18), 4483.

IP and pose determination – Algorithms' selection SC2

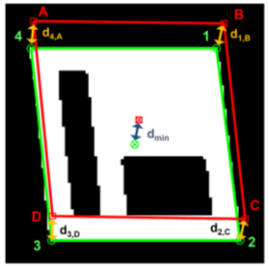
Body-mounted & robotic arm camera --- code based markers (AruCo)

Detection	Identification	PnP solution
Main steps - HSV-based segmentation - Polygons detection - Quadrilateral detection - Outlier rejections - Corner refinement	Main steps - Markers reprojection - 2-stage Nearest Neighbour matching	Levenberg-Marquardt (LM)-based least squares minimization of reprojection error

Detection pipeline



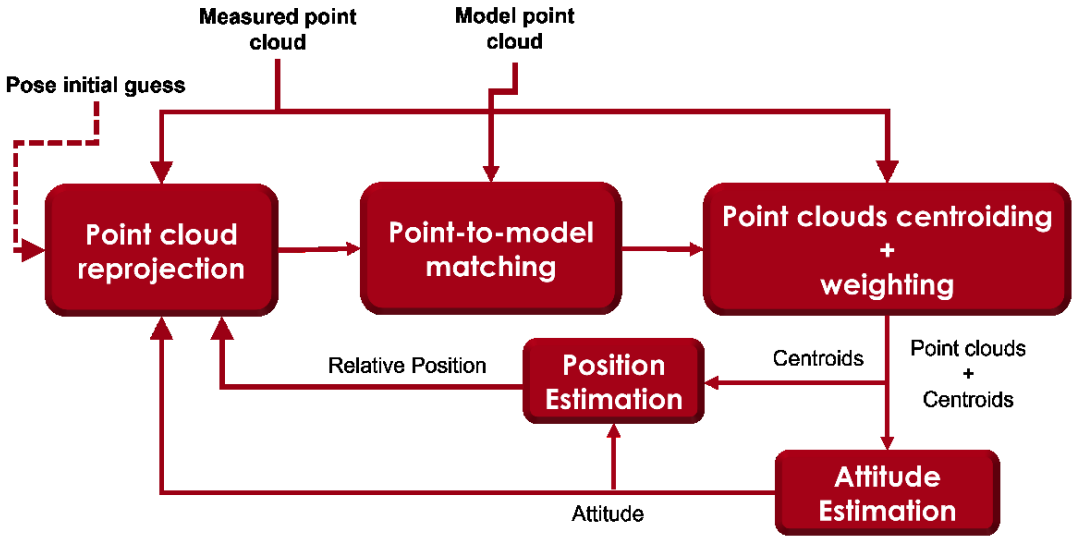
2-stage NN-based matching

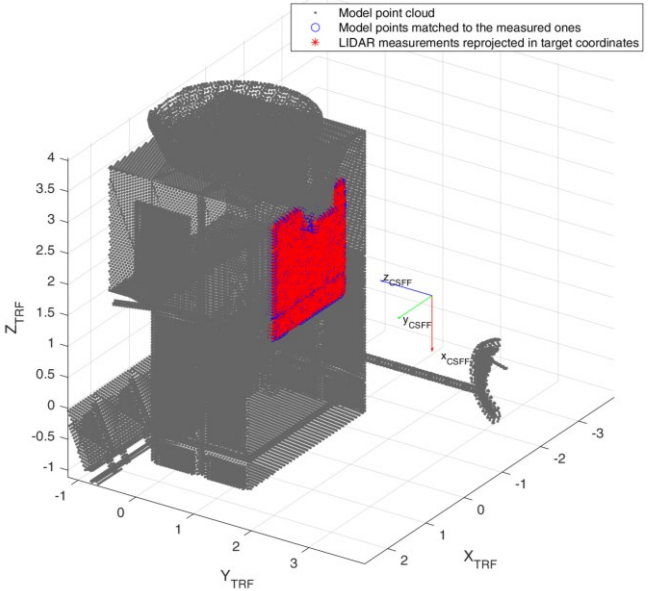


Vela, C., Fasano, G., & Opromolla, R. (2022). Pose determination of passively cooperative spacecraft in close proximity using a monocular camera and AruCo markers. *Acta Astronautica*, *201*, 22-38.

IP and pose determination – Algorithms' selection SC3

The **Iterative Closest Point algorithm** is used to provide pose measurements for both the body-mounted and robotic arm sensor by registering the measured point cloud with a model point cloud obtained from the target CAD model

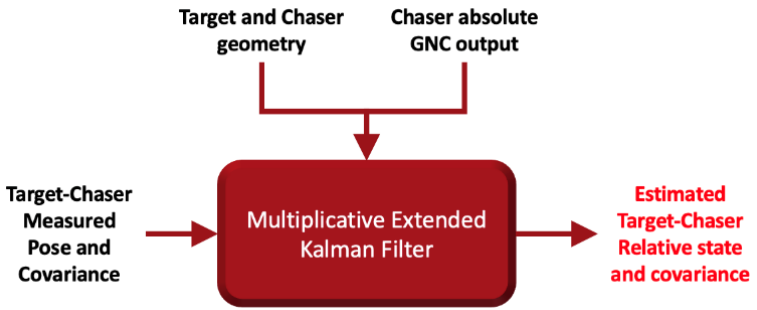




Filtering schemes

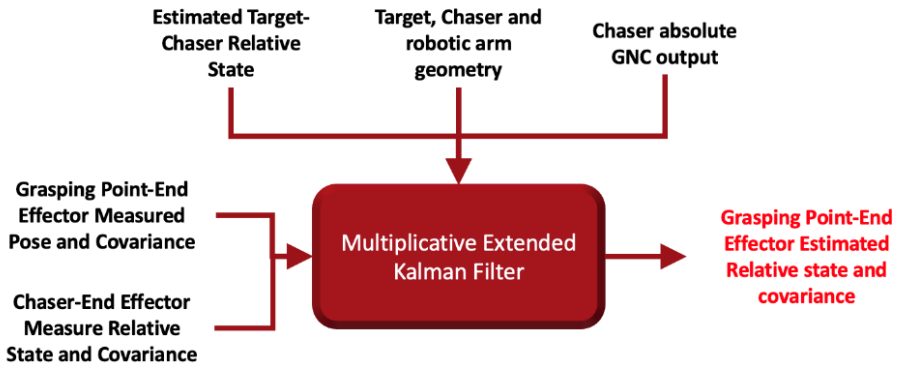
Target/Chaser (T/C)

The state vector includes T/C relative position, attitude and velocity, and the target angular velocity



Grasping point/end-effector (G/E)

The state vector includes G/E relative position, attitude, velocity, angular velocity.



Control-oriented model using recursive Formulation

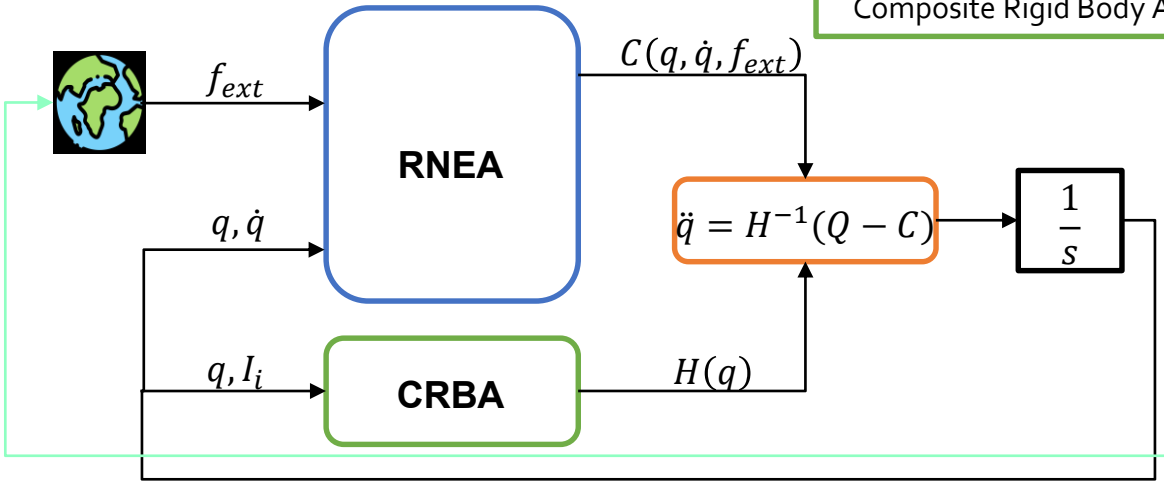
- Obtain $H(q), C(q, \dot{q}, f_{ext}), Q$ by recursively applying dynamic balances at each body.

$$H(q)\ddot{q} + C(q, \dot{q}, f_{ext}) = Q$$

$H(q)$ is obtained with the Composite Rigid Body Algorithm

Q is computed by the controller

$C(q, \dot{q}, f_{ext})$ is obtained with the Recursive Newton-Euler Algorithm



Proximity Dynamics:
A disturbance force is applied to each body, hence resulting in coupled effects at the system's level

Control algorithm
Guidance Strategy

Strategy SC1 & SC2: Chaser keep a fixed relative position and attitude wrt LVLH
Strategy SC3: Chaser synchronized to keep a fixed relative position and attitude wrt TGFF

+

t_{start}: manipulator starts maneuver

t_{point}: end-effector camera directed towards grasping point

t_{grasp}: end-effector brought onto grasping point

t_{end}: end of maneuver

Task Space

Target motion propagation

Propagate target speed and attitude up to 'pointing' and 'grasping' times, t_{point} and t_{grasp}

Compute coefficients of the 5th order polynomial trajectory knowing current configuration, 'pointing' and 'capture' conditions

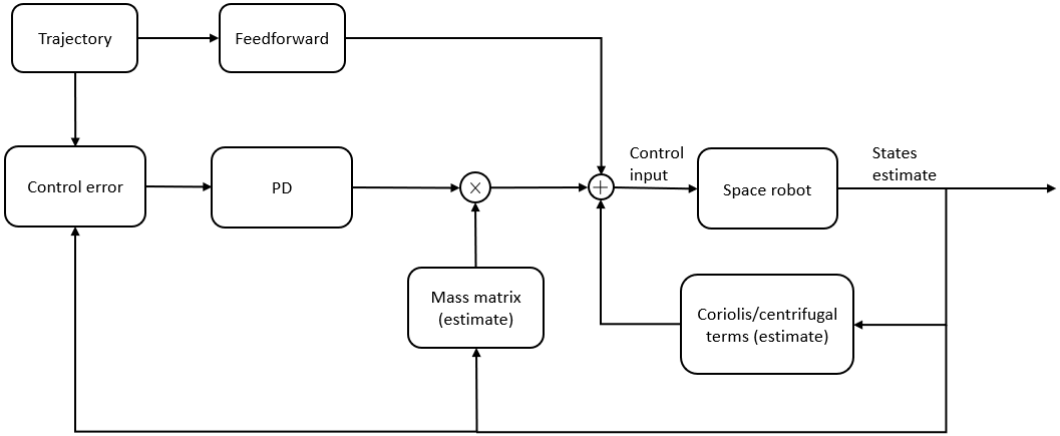
Joint Space

Track base and end-effector attitude / position setpoints

Guidance in Task Space + Control in Joint Space = need of Inverse kinematics

Computed torque control

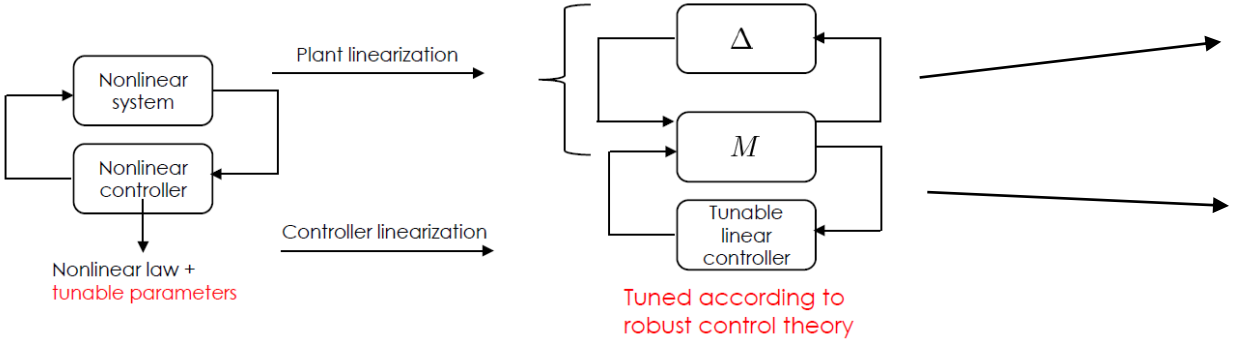
- Well-known control paradigm in ground robotics
- Theory extended for **combined control** of space robots



Robustification of nonlinear control laws

- Pro/Cons of computed torque control
  - Accounts for large motion nonlinearities
  - Asymptotic tracking in ideal conditions
  - Limited robustness guarantees (developed using rigid body models and feedback linearization)
  - Difficult tuning

- Use of **robust control synthesis methods** allows systematic and optimal tuning



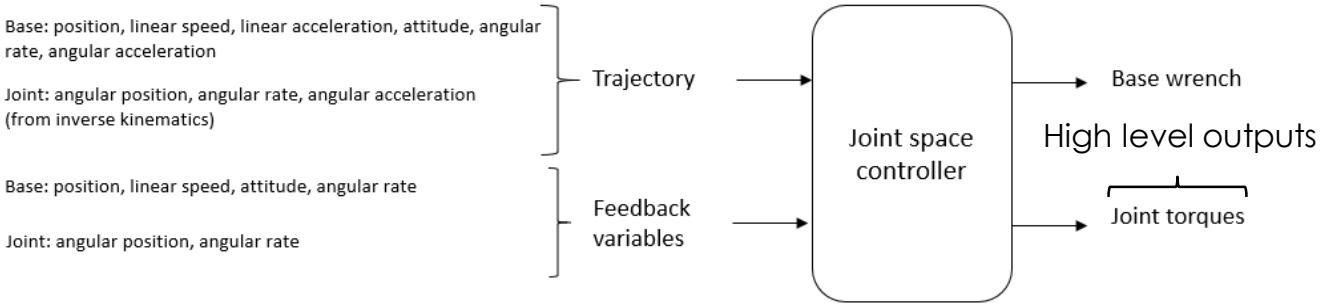
Linearized plant in LFT form (it may contain orbital dynamics)

Linearized control law (nonlinearities varying over trajectory + tunable parameters as *e.g.*, PD gains)

Combined control architectures

A **joint space** control architecture has been selected:

- Base pose (attitude + position)
- Joint angles (obtained using inverse kinematics)



The architecture changes in the **stabilization phase**

- Position and linear velocity of stack not relevant
- Critical part: stopping relative chaser target motion
- Combined control of base attitude and manipulator until manipulator motion stops

Linearized control-oriented models for controller tuning

- Linearization of the dynamics and kinematics about a **reference setpoint** (capture configuration)

$$\dot{x} = \begin{bmatrix} 0 & A_{kin} \\ -H^{-1}C_{/x_{kin}} & -H^{-1}C_{/x_{dyn}} \end{bmatrix} x + \begin{bmatrix} 0 \\ H^{-1} \end{bmatrix} u$$

- Inclusion of **parametric uncertainties** of chaser (mass, moments of inertia, products of inertia, CoM position) using MATLAB robust control toolbox

- Inclusion of **sloshing** as perturbation to the rigid dynamics

- Lumped approach to model **flexibility** of solar panels (SC2).

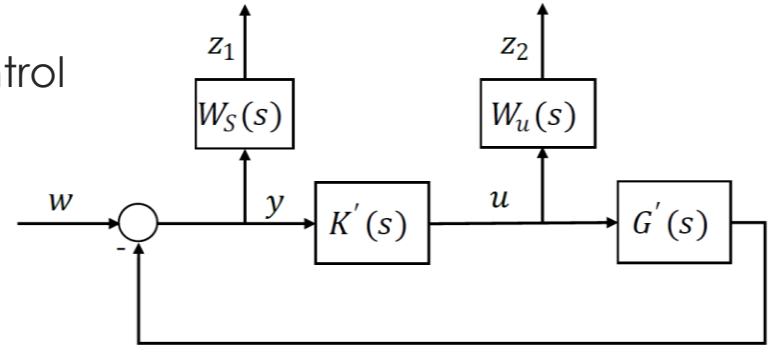
Control synthesis

- Control synthesis formulated as an optimization problem (H_∞ framework)

$$\begin{aligned} &\text{minimize } \gamma \\ &\text{s.t. } \|F_l(P,K)\|_\infty \leq \gamma \end{aligned}$$

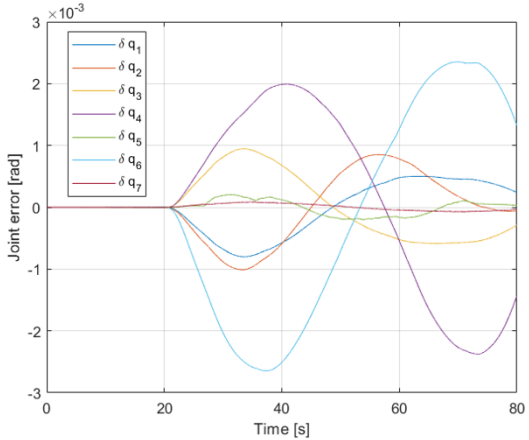
- Reference signal = exogenous input
  Control error + control effort = performance output

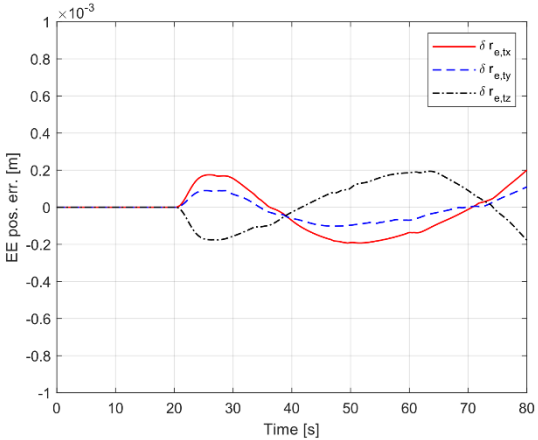
- Selection of weights on sensitivity and control moderation dependent on the scenario



Control synthesis
Results

- Multi-objective structured control synthesis with *MATLAB systune*
- Tuning considering rigid body uncertainties (mass, inertia)
- Better tracking performance with respect to unstructured controller
- Due to complexity of the uncertain model, post-synthesis robustness analysis considering additional effects like sloshing

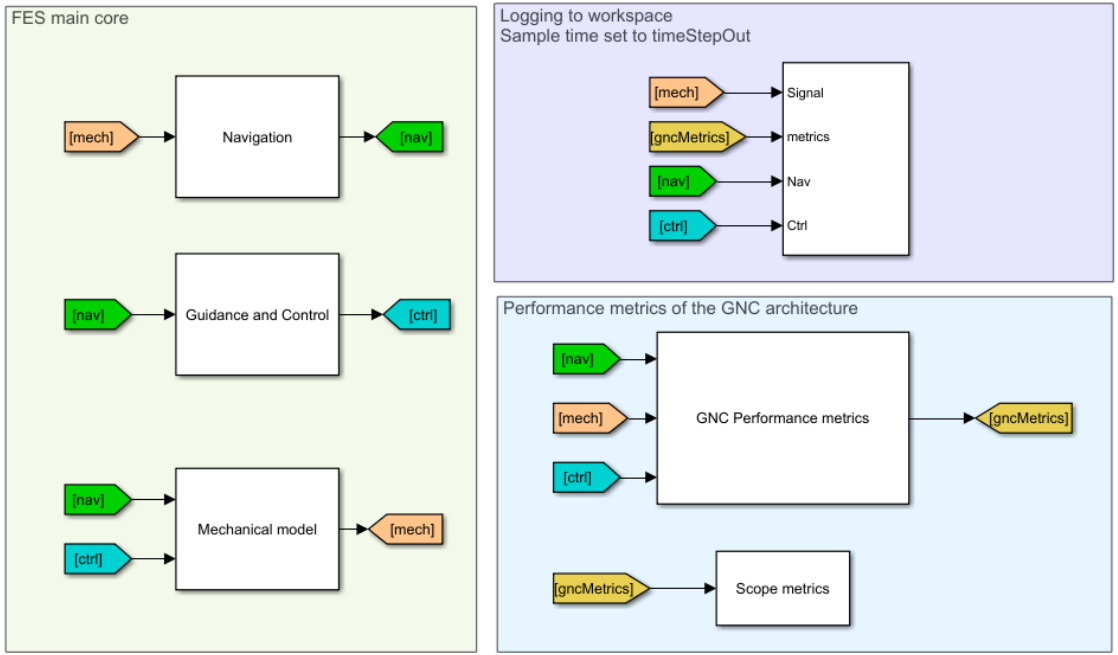




Functional Engineering Simulator

The second objective of the activity was to develop Functional Engineering Simulator to validate the GNC algorithms. The FES is an accurate and realistic simulation environment.

- The FES is implemented in the MATLAB/Simulink Simscape environment
- A Simulink tool that interfaces with the synthetic image generator (PANGU) is integrated in the FES



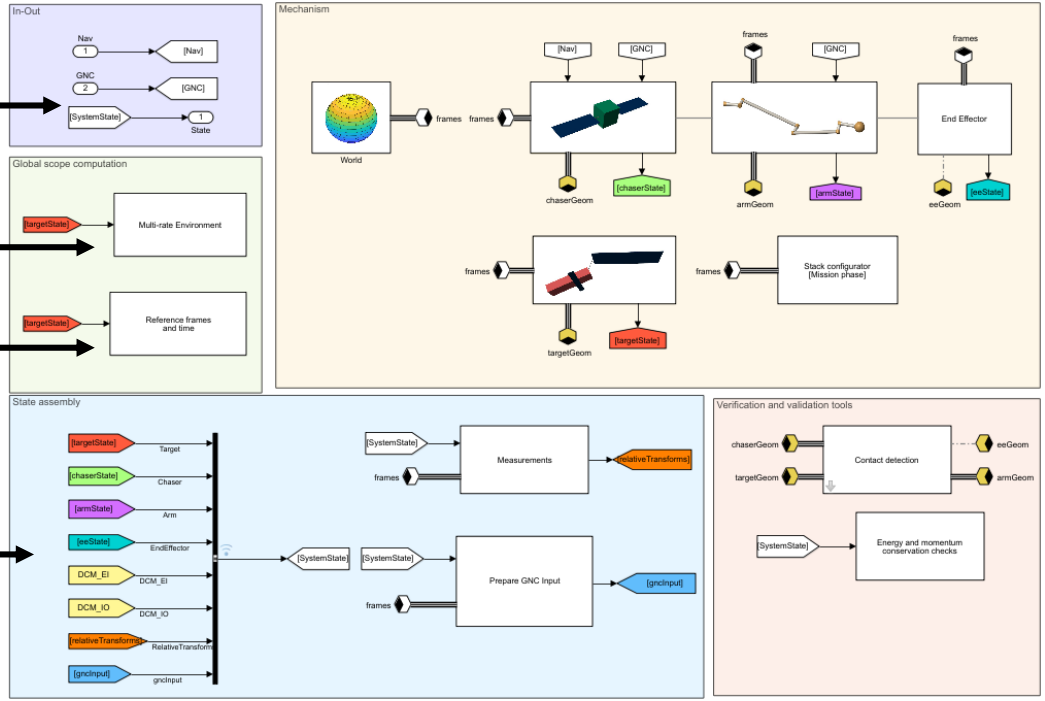
Mechanical model

GNC input

Environmental models

Reference frames

Signals manipulation



System dynamics w/ hardware models

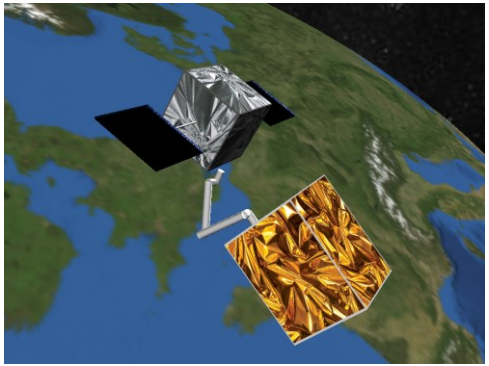
Contact detection tool

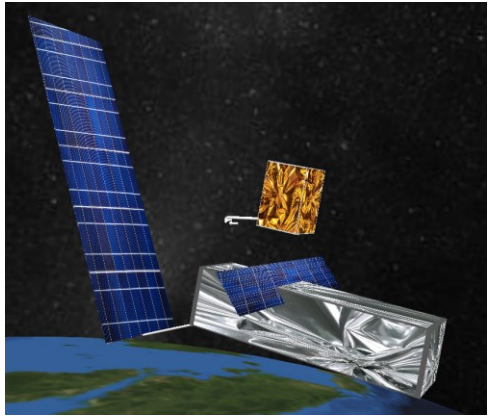
Energy and momentum conservation tool

Support functionalities

In addition to the core physics models required to simulate the system dynamics, several support functionalities are included:

- GNC performance tool
- Requirements guard tool
- Collision detection tool
- Phase transition tool
- Energy and momentum conservation tool
- Graphical User Interface
- Automatic report generation
- 3D rendering tool
- Monte Carlo





Nominal Simulations

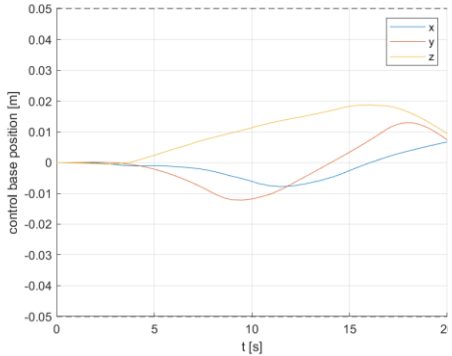
The goal of Nominal Simulations (NS) is to assess the performance of the system in design conditions: disturbances and system non-idealities are considered (i.e., environment, hardware, navigation, sloshing).

Two types of NS have been executed:

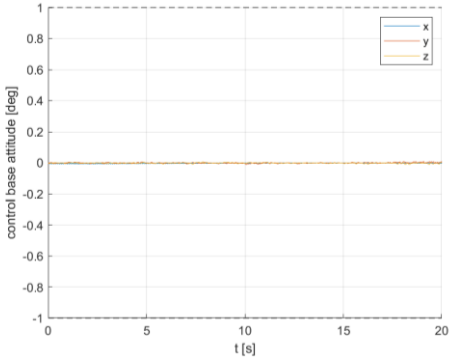
1. Rigid nominal simulations → neglecting the dynamics of flexible bodies
2. Flexible nominal simulations → considering the dynamics of flexible bodies

Nominal Simulations – SC2

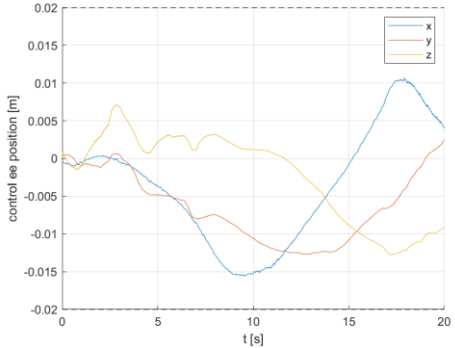
A



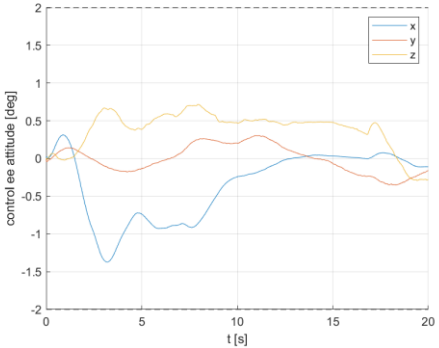
Position error of chaser body



Attitude error of chaser body

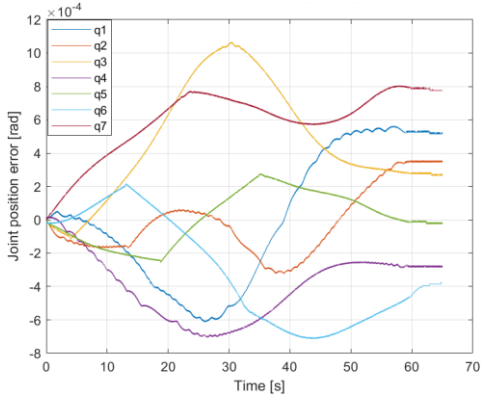


Position error of EE



Attitude error of EE

B



Joints position errors (Phase B)

Error Budget – SC2 phase A

The goal of the Error Budget analysis is to determine the contribution of each potential error source to the overall GNC error of the system.

Done by identifying error sources and executing semi-ideal simulations with all error sources inactive, except for the one under study. The GNC error obtained is a function of the error source considered.

- *Top*
- *High*
- *Medium*
- *Low*

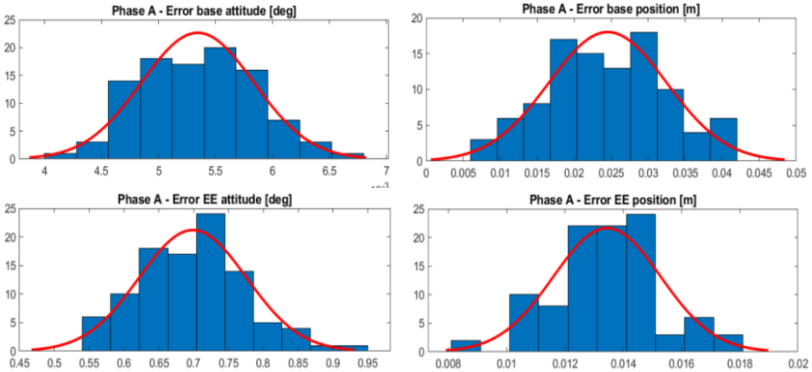
	Thruster	MED	BLDC	GNSS	Star Tracker	IMU	Optical encoder	Sloshing	Grav. Harm.	Geomag. Field	SRP	Grav. Gradient	Third Body	Nav. Error	Ch. Mass uncert.	Ta. Mass uncert.	Ch. Inertia uncert.	Ta. Inertia uncert.	Ch. CoM uncert.	T. CoM uncert	Ch. Sloshing uncert.	Ta. Sloshing uncert.
Chaser body position error [m]	Top	Low	Low	High	High	High	Low	Medium	Low	Low	Low	Low	Low	High	Low	Low	Low	Low	Low	Low	Medium	Medium
Chaser body velocity error [m/s]	Top	Low	Low	High	High	High	Low	Medium	Low	Low	Low	Low	Low	High	Low	Low	Low	Low	Low	Low	Medium	Medium
Chaser body attitude error [deg]	Low	Low	Low	Medium	Top	Medium	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Chaser body rate error [deg/s]	Top	Medium	Low	High	High	High	Low	Medium	Low	Low	Low	Low	Low	High	Low	Low	Low	Low	Low	Low	Medium	Medium
EE position error [m]	Top	Low	Low	High	High	High	Low	Medium	Low	Low	Low	Low	Low	High	Low	Low	Low	Low	Medium	Medium	Medium	Medium
EE velocity error [m/s]	High	Low	Low	High	Top	Top	Low	Low	Low	Low	Low	Low	Low	High	Low	Low	Low	Low	Medium	Medium	Low	Low
EE attitude error [deg]	Medium	Low	Low	High	Top	High	Low	Low	Low	Low	Low	Low	Low	High	Low	Low	Low	Low	High	Medium	Low	Low
EE rate error [deg/s]	Medium	Low	Low	High	Top	High	Low	Low	Low	Low	Low	Low	Low	High	Low	Low	Low	Low	Medium	Low	Low	Low

Monte Carlo analysis

A preliminary Monte Carlo analysis (100 simulations) has been conducted by considering the variability of uncertain parameters within realistic ranges. The goal is to assess the robustness of the GNC algorithms.

Example for SC2:

distributions of mean values of performance metrics (averaged over simulation time). The mean and std of these distributions are used to assess robustness.

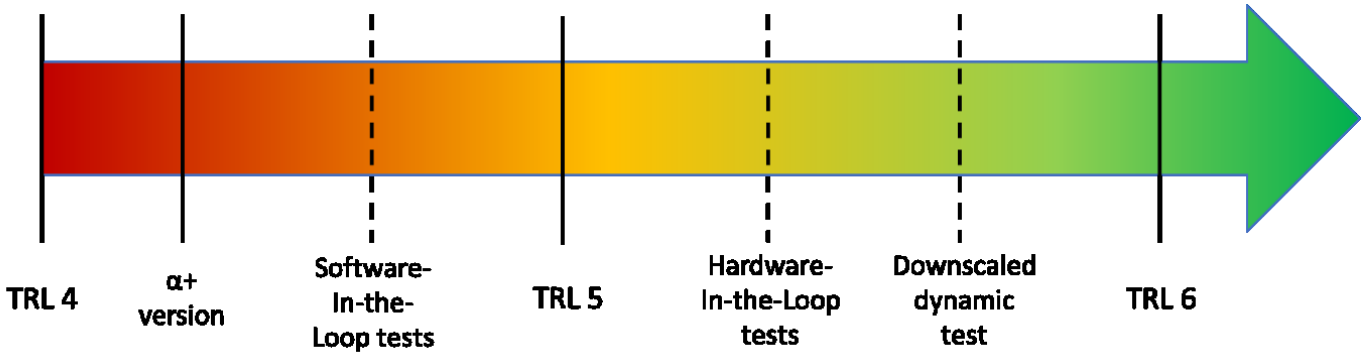


Performance Metric	SC2
Chaser body position error	✓
Chaser body velocity error	✓
Chaser body attitude error	✓
Chaser body attitude rate error	✓
EE position error	✗
EE velocity error	✓
EE attitude error	✓
EE attitude rate error	✓

Roadmap to TRL 6

Steps required to reach TRL 6:

- Development of alpha+ version of the software by solving critical aspects encountered
- Coding of standalone GNC software in compliance with standards
- Software-In-the-Loop tests with updated simulation environment
- Hardware-In-the-Loop tests with deployment on representative hardware
- Downscaled dynamic tests (open-loop and closed-loop)



Thank you for your attention!