GNC for rendezvous, dynamic capture and stabilization of spinning non-cooperative target

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What is the Clearspace-1 mission?

Context

Part of ESA ADRIOS program;

Rendezvous, capture and de-orbit a VESPA upper stage;

Objective

Demonstrate removal of VESPA from LEO with tentacles capture system

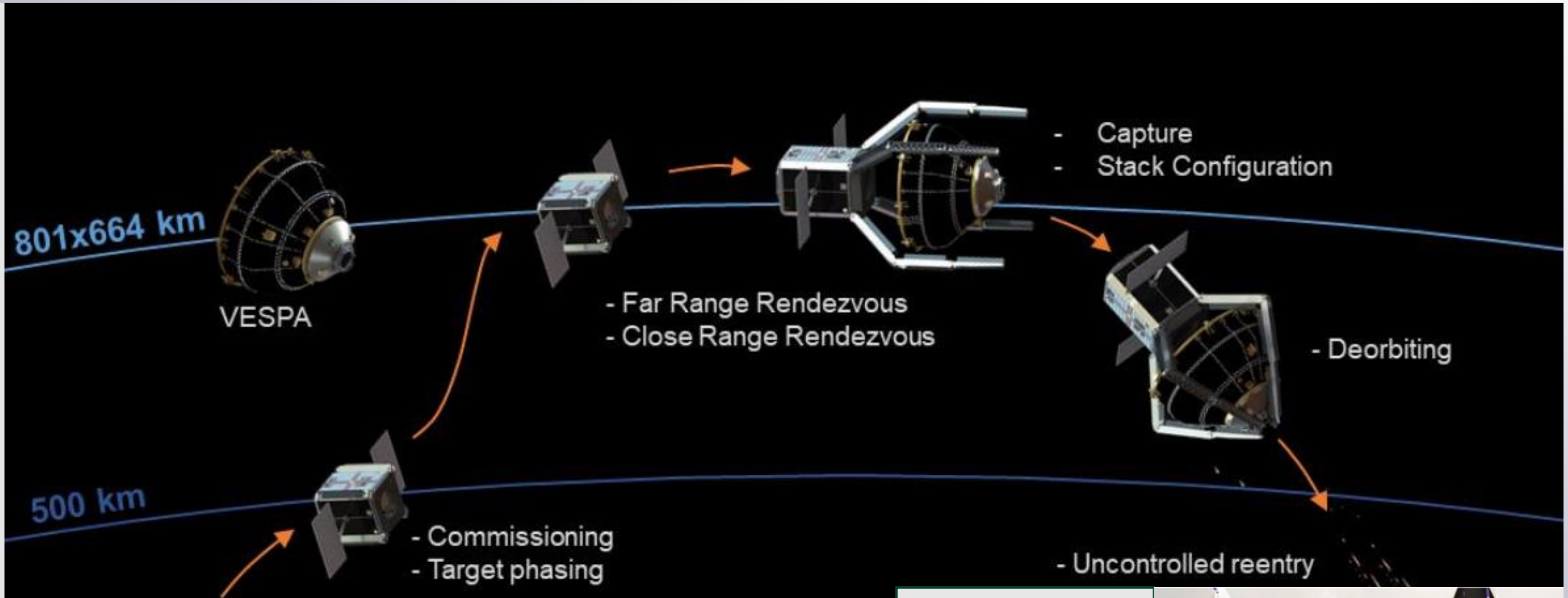
Develop building blocks for active debris removal (ADR) commercial missions.

Phases involved

- LEOP;
- Orbit Phasing;
- Closing;
- Fly-around;
- Proximity Operations.
- De-orbiting

Building blocks of ADR service

- uncooperative rendezvous (RV),
- motion synchronization,
- stack stabilization,
- stacked deorbiting,
- target release.



VESPA launched in May 2013 with VEGA Flight VV02 carrying Proba

Mission Phases

From Launch to Capture

deimos

clearspace . today

LEOP
- Correction of launcher injection errors
- Critical orbit and control manoeuvres until a safe orbit is reached

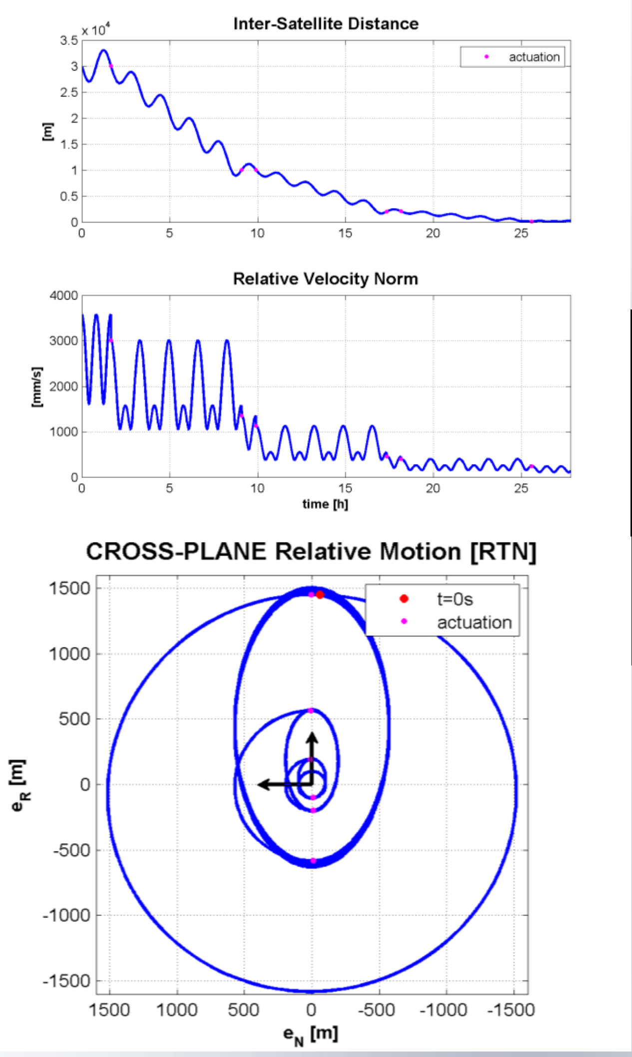
Commissioning
- Checking, sub-system by sub-system, its correct functioning
- “keys” handed over to operator at that point

Phasing
- Reduce the orbital phase angle between the chaser and the target
- Impulsive maneuvers at key points for minimising propellant usage.

Far Range RV
- Starts at over 30 km from the target
- Relative dynamics are key to reduce energy consumption and ensure safety

Close Range RV
- Hundreds or tens of m from the target, down to capture
- Closed-loop control (6DoF), Flexible modes/sloshing are significant

Detumble & controlled reentry
- Reach, in a controlled manner, a perigee of ~50km
- A controlled reentry is the only one which ensure populations safety



Presentation scope

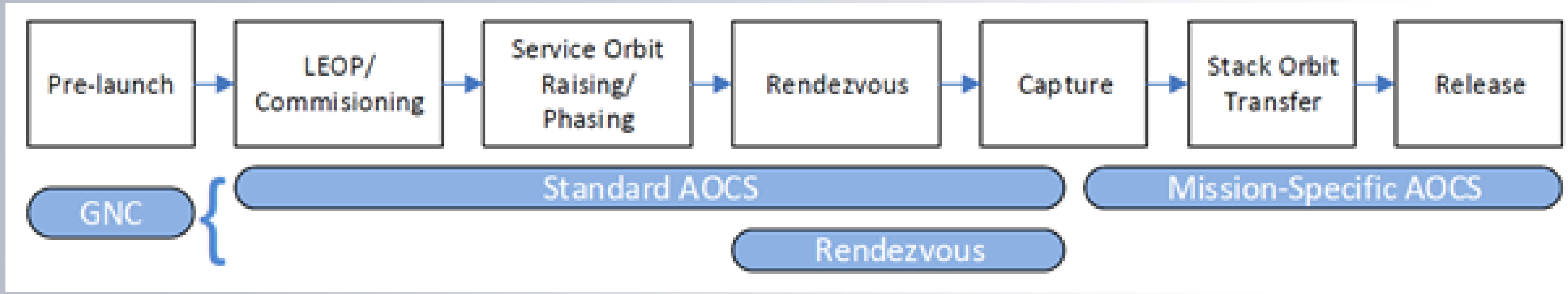
Demonstrate the several capabilities developed for the capture of space debris.

- Overall GNC architecture adopted;
- High fidelity functional engineering (FES) simulation facility for verification and validation of the developed solutions;
- Capability for on-line capture of the client:
  - Guidance for dynamic computation of approach trajectory;
  - Vision-based navigation solution
  - Control with performance robustness;
- Demonstration of very close proximity safety operations;

GNC architecture

GNC Architecture

GNC Subsystem during the different mission phases.



GNC subsystems

Attitude and Orbit Control System: dedicated to the absolute 6D motion;

Rendezvous GNC: dedicated the 6D motion relative to the target.

Rendezvous regions

Far range: switch from the absolute to the onboard relative navigation at a safe distance, with uncertainties due to ground-based relative navigation.

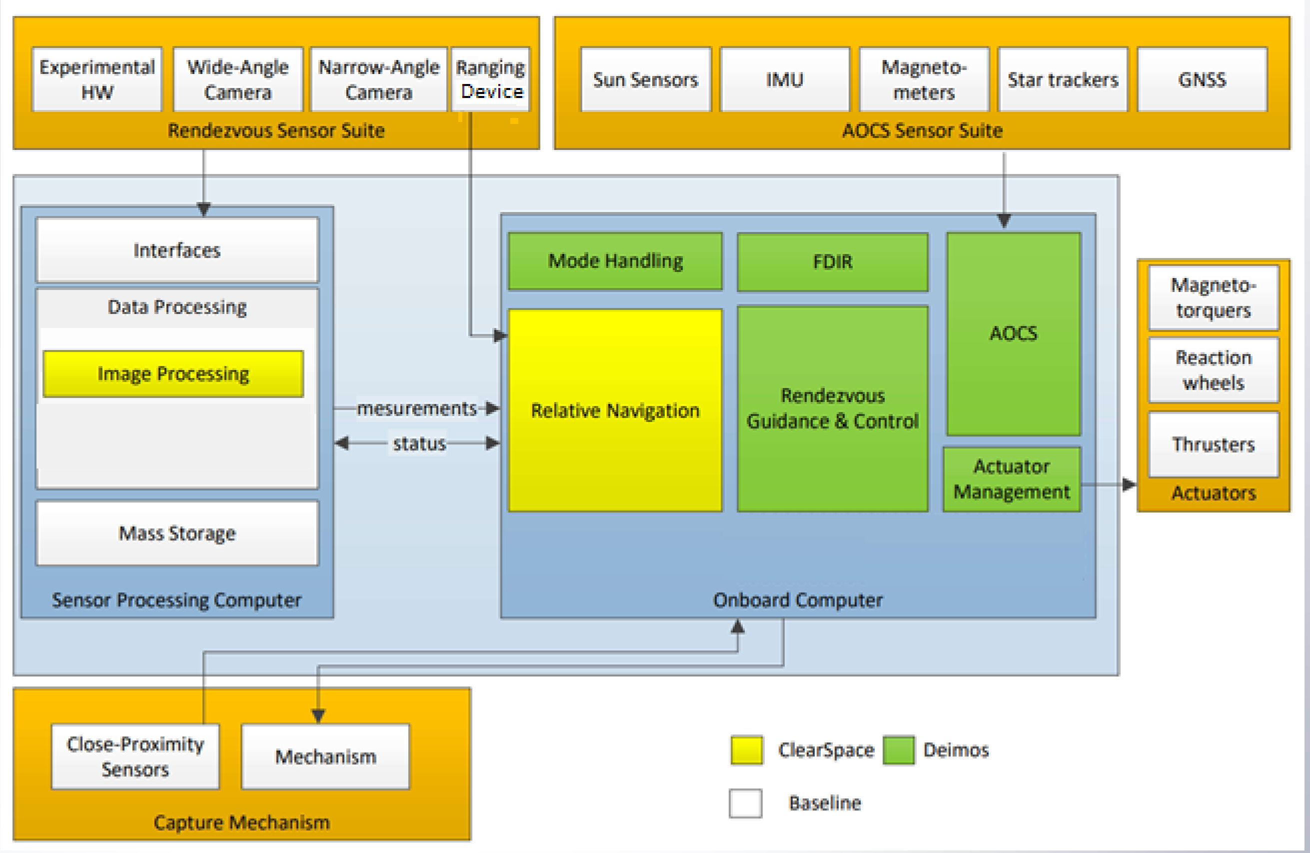
Mid range: before entering the close-range, safely perform the commissioning of the close range relative navigation.

Close range: Close Proximity Operations rely on onboard, accurate 6DoF relative navigation.

GNC Architecture

- Rendezvous Sensor Processing Unit (RVSPU), processes the images collected by the cameras;
- Onboard computer (OBC) hosts the GNC algorithms for AOCS and rendezvous;
- Dedicated sensors & solutions for capture:
  - Image Processing algorithms
  - Narrow Angle Camera (NAC),
  - Wide Angle Camera (WAC),
  - Ranging device,
- Comprehensive set of FDIR capabilities due to criticality of the close-range operations.

High-level overview of the GNC system



GNC Architecture

Functionalities to support the rendezvous and capture

Control

- **Target pointing** to orient the relative sensors towards the target,
- **Stack detumbling and deorbiting** to control the stack,
- **Relative Control**. for regulating and tracking the S/C translational and rotational states around the guidance reference profiles,

Relative Navigation

- ***Angles-Only Navigation,*** detecting the target using centroids of the images taken with the Narrow-Angle Camera,
- ***3D Navigation*** combining direction to the target and a range measurement from the ranging device,
- ***Pose Estimation***, estimating pose when the image of the target is large enough,

Guidance

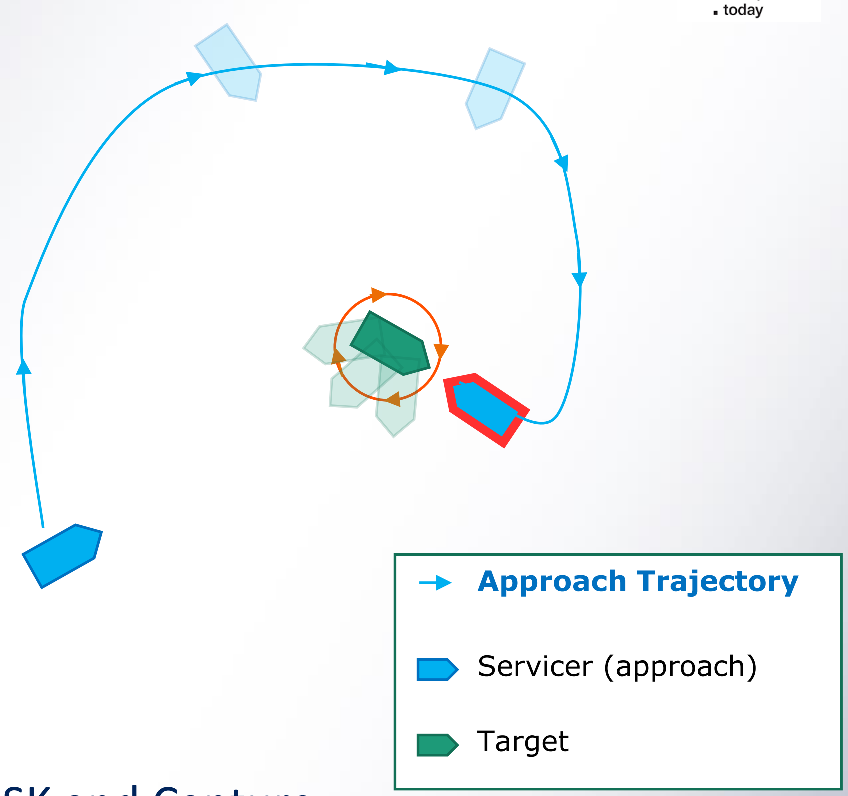
- ***Impulsive delta-V*** with passively safe trajectories based on natural dynamics for far- to mid-range,
- ***Forced motion*** to approach the target along its dynamic, tumbling motion.

6DoF Thrusters Manager Function translates the force and torque commands into Pulse Length commands

Guidance

Motion Sync Guidance

- Optimal and feasible trajectory for capture of the target
  - Minimizes fuel expenditure
  - Satisfies operational constraints (Target motion, Illumination, Ground)
- Deployment-oriented development
  - Auto-codable optimization algorithm,
  - Computational optimization towards real-time execution,
- Capability to recompute midcourse trajectory
  - compensates for errors in the estimation of target motion;
- Computation outcomes
  - Best capture time-instant for
    - good illumination conditions
    - ground pointing feasibility
  - Optimization of the translational/rotational trajectory between SK and Capture
    - Minimization of control energy
    - Satisfaction of path constraints.
    - Easily configurable dynamics, constraints, cost, etc.
    - Attitude/roll profile ending at the correct configuration (ground pointing)



Navigation

Relative Navigation Architecture

Navigation function

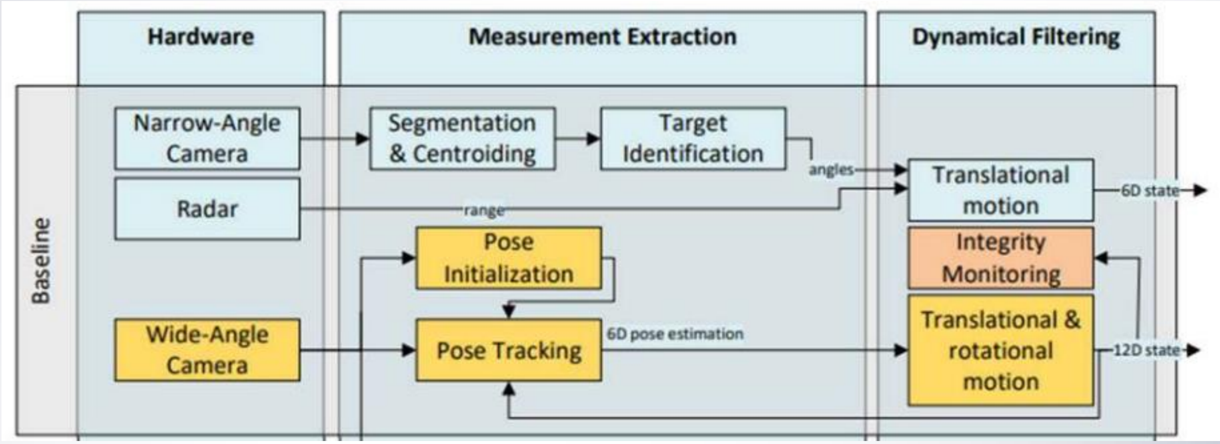
Goal of Navigation

- Provide an estimate of the Target's relative state (position and attitude)
- Target is passive and non-cooperative

Multiple regions approach

- Far Range : angles-only (line-of-sight) navigation with visible narrow-angle camera
- Mid Range : line-of-sight augmented by ranging device providing 3D position measurement
- Close Range : pose estimation of the Target using a visible wide-angle camera, providing 6D measurements of position and attitude

Navigation Architecture

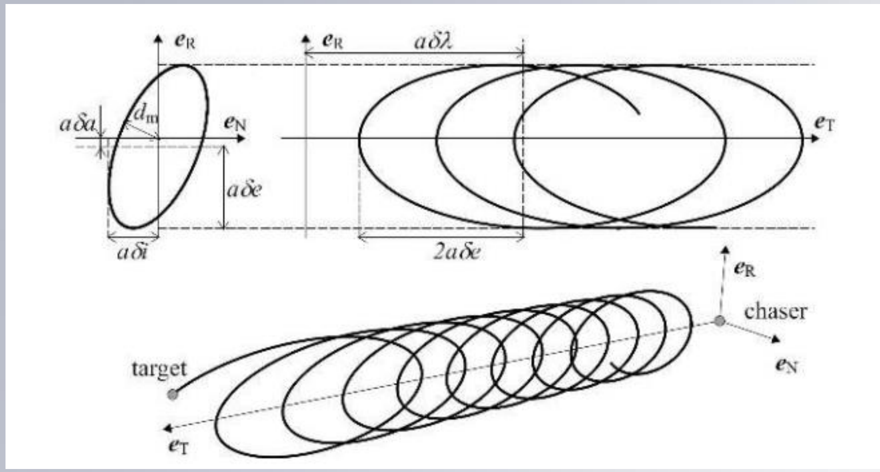


State Estimates

Far and Mid Range

Relative Orbital Elements formulation

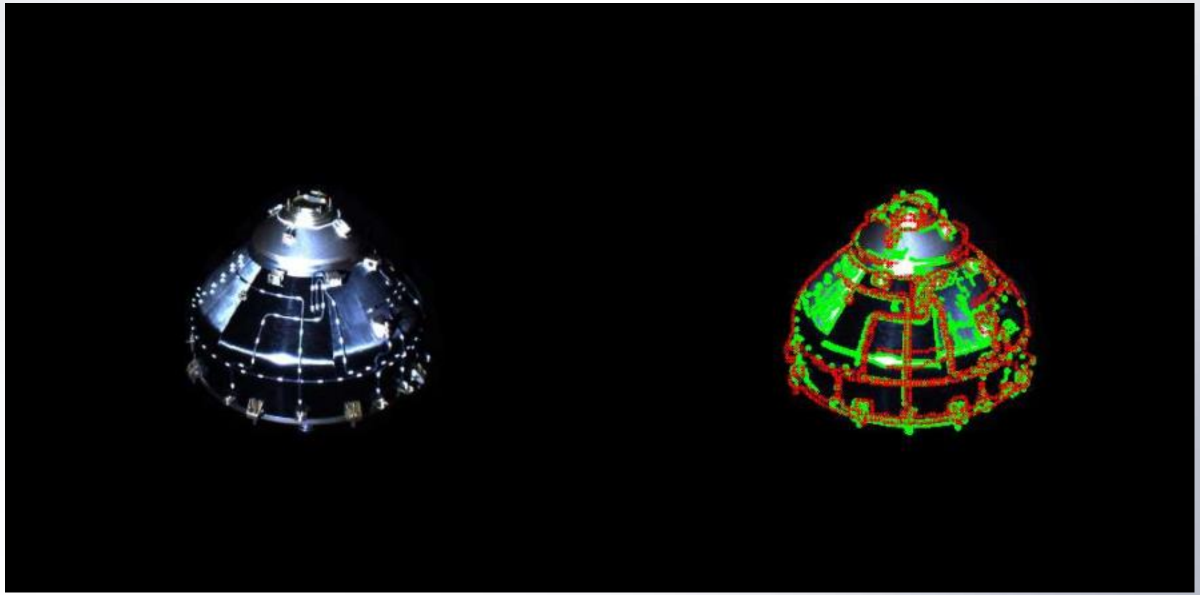
- Derivative of Keplerian elements
- Estimation through dynamic Kalman filter
- Suitable for approach through impulsive control
- Identification of states ensuring passive safety of trajectories



Close Range

Cartesian coordinates formulation

- 12-D state of position, attitude, and differentiates
- Estimation through dynamic Kalman filter
- Suitable for close proximity operations using continuous control



Control Synthesis

Control Architecture

Control function

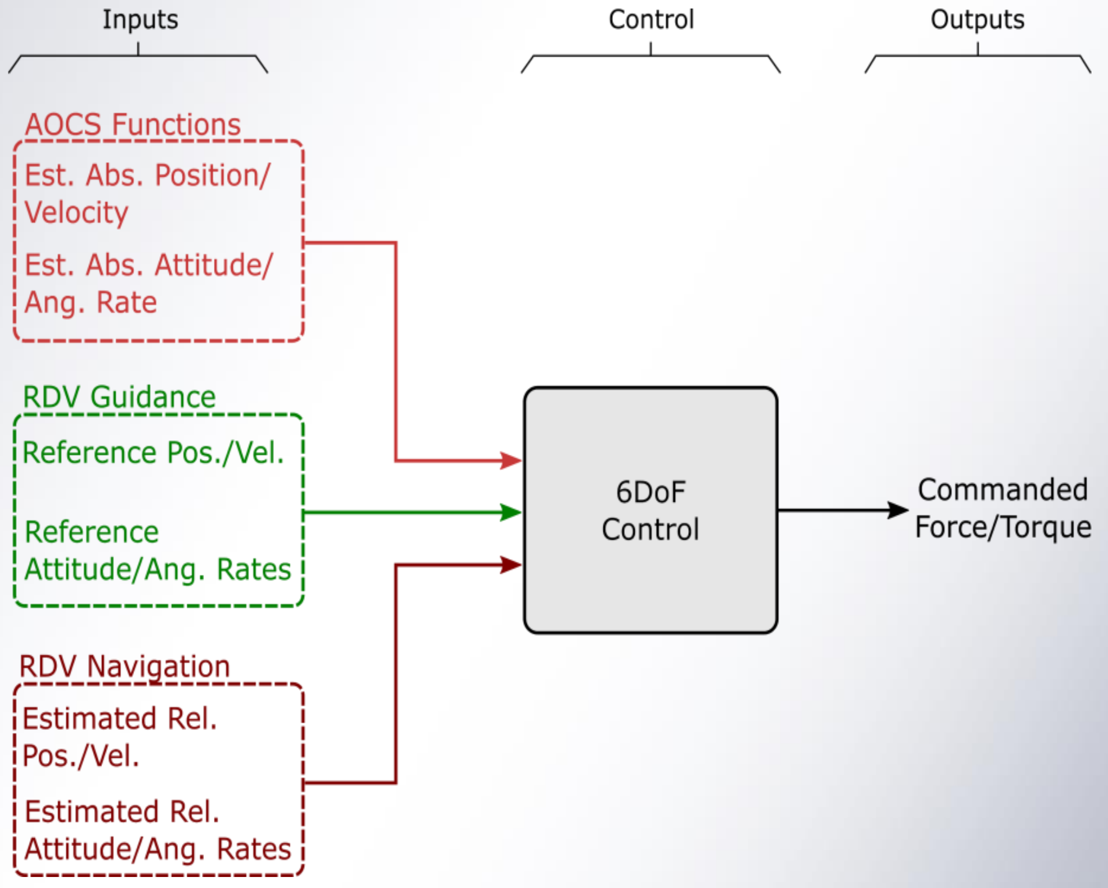
Control is robust to

- all significant actuator errors,
- navigation errors, including numerical inaccuracies,
- chaser (and stack) MCI uncertainties,
- modelling approximations such as in sloshing and flexible modes,
- environment disturbance and perturbations.

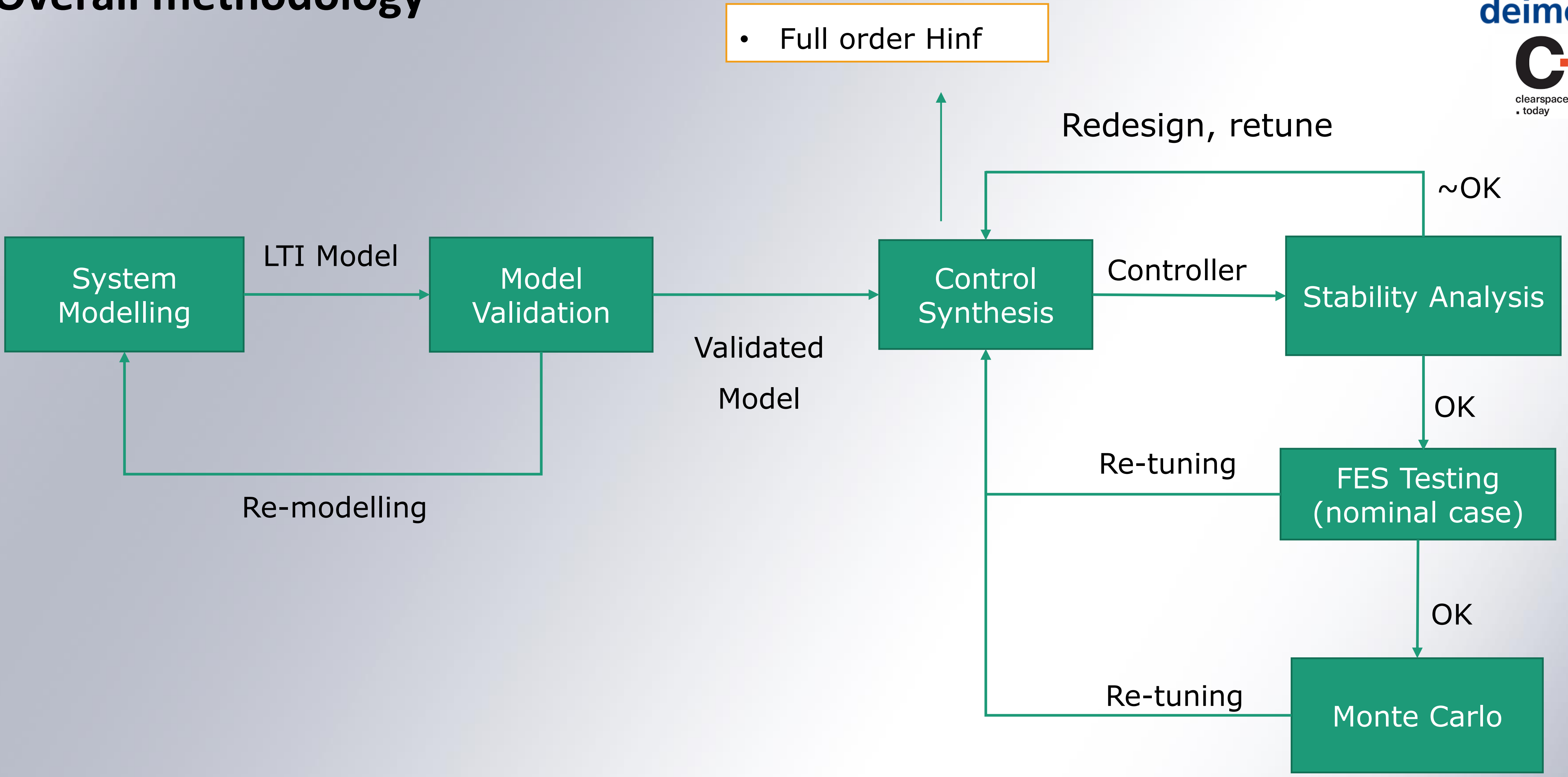
Control synthesis methodology is

- Modelling: derivation of a reliable model for robust control design;
- Synthesis: tuning the optimization parameters to attain the desired closed-loop performance and stability robustness;
- Analysis: analytical and numerical evaluation of the controller properties.

Control Architecture

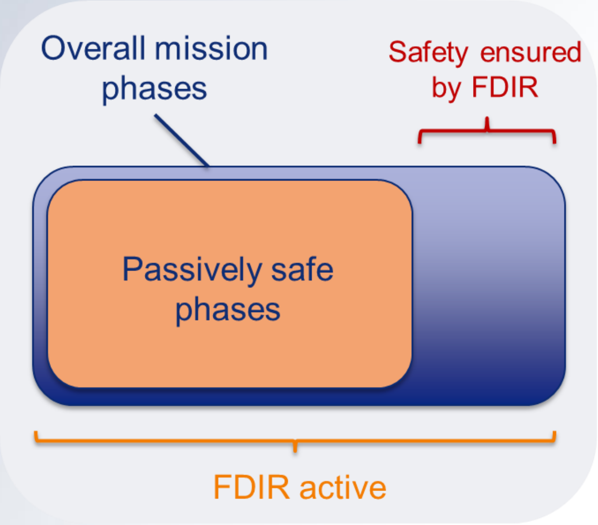


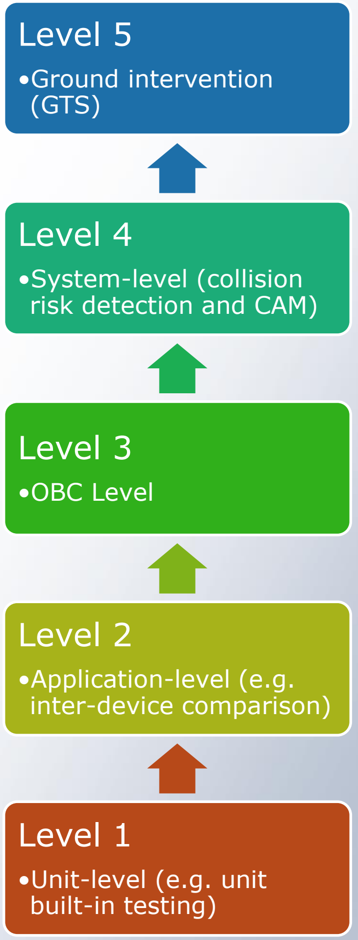
Overall methodology



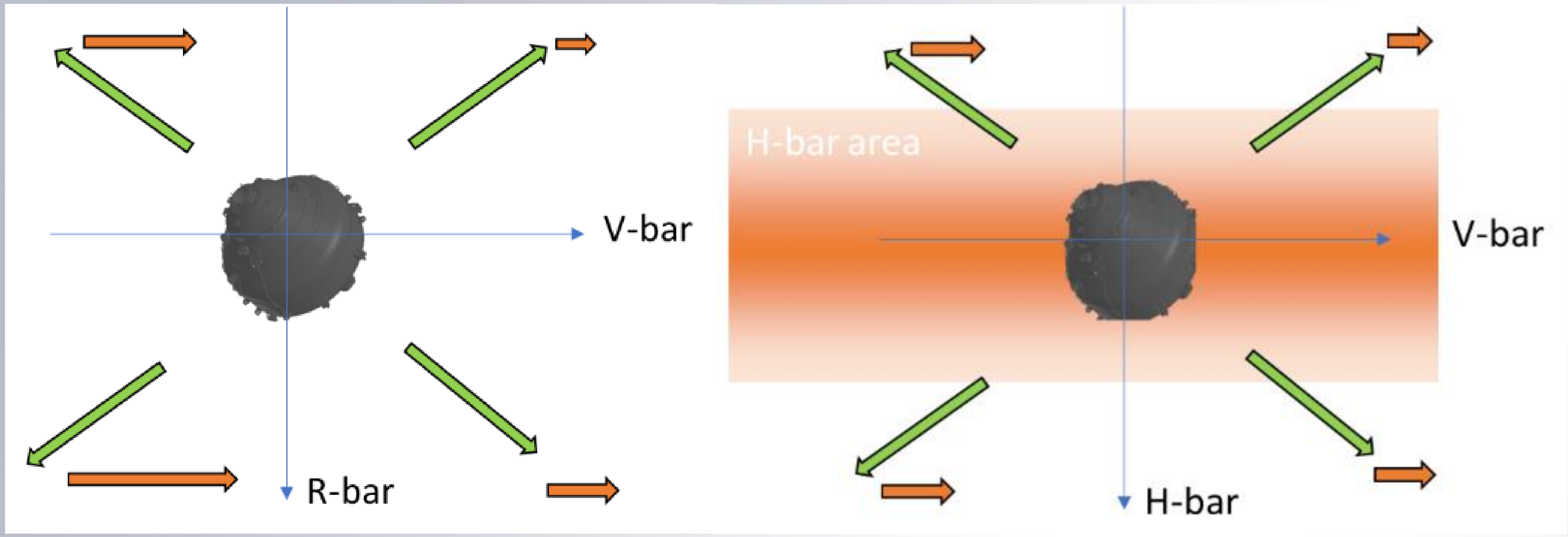
FDIR

- Failure Detection, Isolation and Recovery (FDIR) needs to ensure (up to the extent possible) no collisions and to extend mission feasibility.
- Passive safety is the baseline approach, ensured by the correct design of the relative trajectories.
- CAMs are used for cases where passive safety is not ensured. A single CAM will ensure absence of collision over a given period.



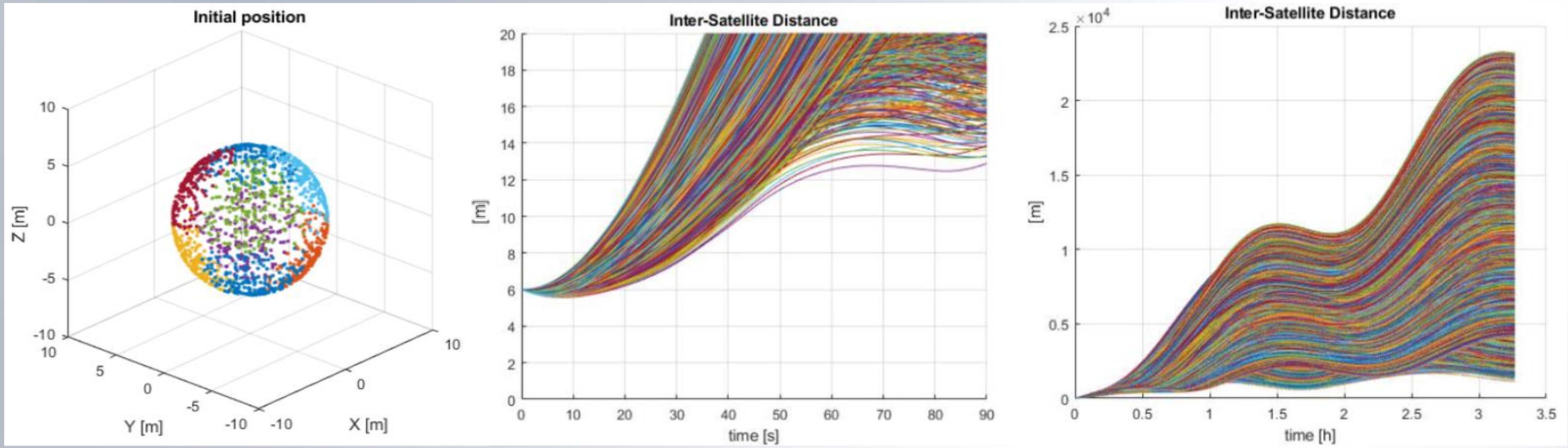


Collision Avoidance Maneuver



- CAM strategy designed for simplicity and reliability;
  - 1st boost to move away from the target (short term safety)
  - 2nd boost to acquire positive V-bar velocity (long term safety)
- Retreats to a passively safe orbit;
- Guarantees minimum drift in negative V-bar;
- Minimum knowledge of S/C state required (only rough quadrant location)

Collision Avoidance Maneuver



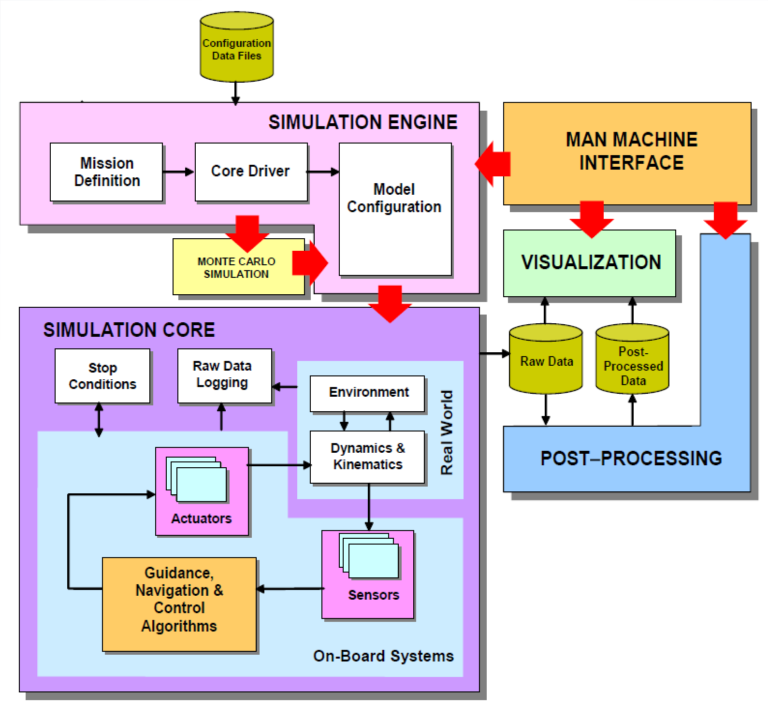
Sizing case with:
- Initial positions in all quadrants around the target with worst-case relative-velocity.
- Non-ideal effects (sensors, actuators, flexible modes)
- 4 sigma dispersions in the parameters of the Motion Sync campaign (IMU, RCS, MCI)

Outcome:
- Positive validation in both light-weight simulator and high-fidelity environment.
- Strategy is safe for all cases, both in short and long term, with small displacements towards the target.

Simulation and Validation

GNC V&V approach

- Incremental validation over different test benches of increasing fidelity: MIL/SIL -> SVF -> FSS -> FlatSat -> PFM
- The FES is specifically designed to support the GNC design and verification:
  - Flight dynamics model
  - Space environment model
  - Open-loop and closed loop simulation
  - MIL and SIL simulation
  - Monte-Carlo simulation
  - Failure injection
  - Automatic post-processing
  - Automatic report generation

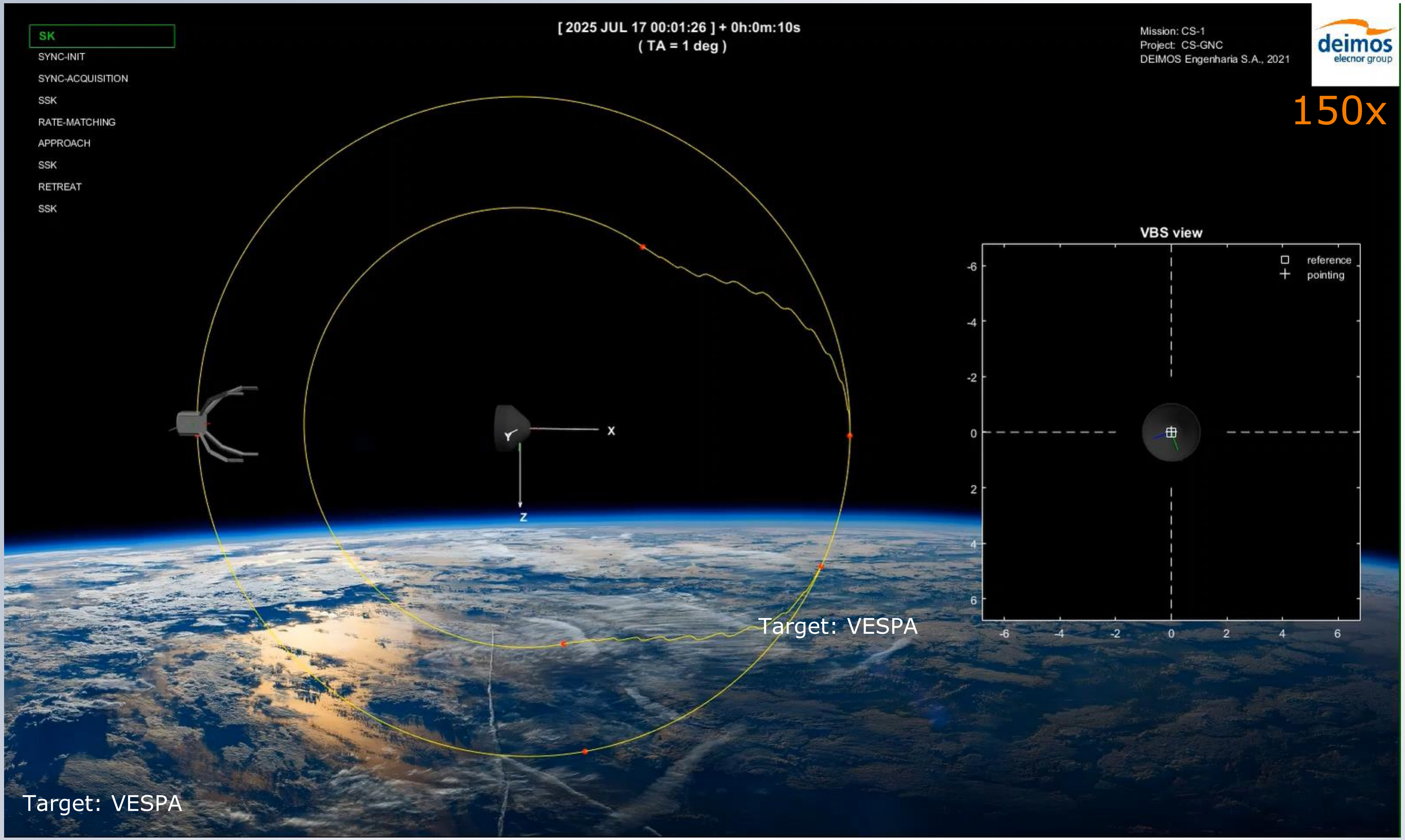


Validation of GNC system

- Configuration of several effects and dispersions:
  - Flexible modes with very low damping and dispersion of parameters (frequencies and damping)
  - Fuel Sloshing
  - Dispersion of several Sensor and Actuator non-idealities (all relevant performance parameters, positions alignments)
  - Dispersion of Orbital Parameters
  - Dispersion of Chaser spacecraft MCI parameters
  - Dispersion of target parameters (MCI, angular velocity norm, direction and initial attitude)
- Execution of MC campaign, with number of shots determined by required confidence level of requirements.

Mission Phases
Close Range Rendezvous Manoeuvres

Motion Synchronisation – Illustration only



Conclusion

Conclusions

- This presentation addressed a series of aspects to consider when defining an in-orbit service, and particular those regarding the development of the GNC subsystem.
- The status of target/client spacecraft plays a key role in defining the GNC requirements, architecture and hardware baseline.
- Non-cooperative targets with uncontrolled motion require the implementation of sophisticated GNC capable of executing the proximity operations leading up to capture.
- Collision safety is the major concern for the mission. Passive safety approach is used whenever possible, complemented with active safety measures when needed.
- GNC Development entering the detailed design phase. Will be making extensive use of high-fidelity simulation facilities for validation, before advancing to PIL and HIL test benches.

Thank You!

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