EROSS+ Phase A/B1 Guidance, Navigation and Control design for In-Orbit Servicing

Davide Casu [(1)], Vincent Dubanchet [(1)], Hervé Renault [(1)],
Anthea Comellini [(1)], Pierre Dandré [(1)]

[(1)] *Thales Alenia Space – 5 allée des Gabians, 06150 Cannes (France)*
name.surname@thalesaleniaspace.com

ABSTRACT

The H2020 project "EROSS+ Phase A/B1" has been carried out over 2021-2023 to mature a future demonstration of a robotic servicing mission with a highly-autonomous and coupled Guidance, Navigation and Control (GNC) architecture for both the satellite platform and its embedded robotic arm. EROSS+ project aims at deriving the system design of a robotic Servicer approaching, capturing and servicing a Client satellite with a strong focus on the avionics architecture hosting the GNC algorithms and logics. This architecture integrates and demonstrates the key European robotic building blocks developed over the last H2020 projects in space robotics by demonstrating their performances from Model in the Loop (MIL) tests to Hardware in the Loop (HIL) experiments. This article presents the work done at avionics level in the EROSS+ Phase A/B1 to derive a versatile GNC architecture applicable as much as possible to multi-orbit purposes from LEO to GEO, in order to minimize the delta-design impact and allowing a direct reuse for a future commercial application.

1 INTRODUCTION

The main use-case of EROSS+ project, standing for "European Robotic Orbital Support Services", is to demonstrate the capability of a Servicer spacecraft to perform medium and close-range rendezvous, before capturing and manipulating a Client satellite with a high degree of autonomy. The client satellite is considered cooperative and prepared for servicing operations such as refuelling and payload replacement. EROSS+ timeline is based on four main steps covering: the approach with an autonomous visual-based navigation using advanced processing and filtering techniques, the capture using state-of-the-art compliance control techniques to synchronize the robotic arm and its platform, the mating of the two spacecraft through a dedicated interface for refuelling, and then the robotic exchange of a replacement payload designed with standard interfaces. This project is built upon the previous developments of the Operational Grants led by the Strategic Research Cluster in Space Robotics funded by the European Commission since 2016. More specifically, this paper will focus on the GNC design and the Rendezvous (RDV) phase of the mission up until robotic operations take place.

Initially, a first section presents an overview of the main design drivers and requirements, both in terms of mission constraint (e.g., ground station visibility for communication and monitoring of critical operations, observability constraints) and safety requirements (e.g. exclusion zones, approach corridors, and GO/NO-GO decision at predefined hold points). In fact, the proposed RDV strategy has to be compliant to the ESA Safe Proximity Operation guidelines and the French Space Act (i.e., "Lois des Operations Spatiales"). A high level description of the CONcept of OPerationS (CONOPS) will also be provided, focusing on the rendezvous strategy from Phasing, Homing, Closing, Inspection, Approach and Capture. Subsequently, a detailed description is given on the GNC operational modes and phases to ensure the In-Orbit Servicing mission, firstly describing the high level architecture, which is oriented on the operational modes and the Hardware Matrix. The classical modes such as Stand-By Mode (SBM), Safe Hold Mode (SHM), Nominal Mode (NOM), and Orbit Control Mode (OCM) for absolute navigation, will be presented along with RDV-specific modes such as Capture mode, Collision Avoidance Mode, and others. This GNC architecture takes into account the typical challenges of RDV & Capture in terms of Hardware (HW) matrix (e.g., the presence of optical sensors for vision based navigation and image processing, the robotic arm control constraints for capture, and so on).

Eventually, the main GNC sizing and preliminary validation analyses are presented before closing the paper with a brief overview of the complete GNC workflow - from design to Validation and Verification (V&V) – being pursued in the on-going program "EROSS IOD" (i.e., In-Orbit Demonstration).

2 OVERVIEW OF EROSS MISSION AND CONOPS

EROSS mission has among other objectives, the one of demonstrating In-Orbit Servicing (IOS) capabilities through an In-Orbit Demonstration (IOD). In the frame of Phase B1, a Concept of Operations (ConOps) of the IOD has been derived. The IOD will demonstrate different Rendezvous (RDV) approach and departure strategies and capture strategies covering the two potential missions of application for cooperative and non-cooperative client vehicles.

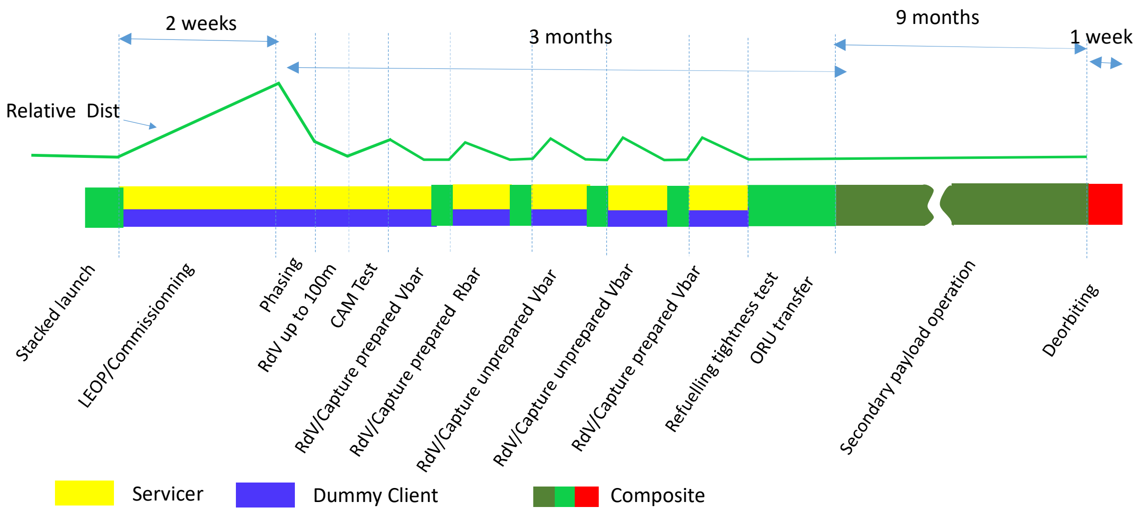

Figure 1: EROSS Mission Time Line

In the frame of EROSS In Orbit Demonstration mission, several types of final approaches will be tested. Figure 1 shows a high-level overall Mission Time Line (MTL). It is not intended to be a comprehensive timeline, as some phases could be reiterated. For instance several Rendezvous and capture rehearsals will be done to gather operational experience and to test different environment conditions such as solar illumination and its impact on the nominal visual navigation chain.

2.1 EROSS Rendezvous payload

The design of the servicer aims at segregating as much as possible the Platform hardware and software from the so-called "Payload" ones at the core of the flight demonstration. The payload is segregated as well into the Rendezvous and Robotic equipment and processing as they fulfil different functions of the mission. On one hand this approach allows for a maximum reuse of existing platforms and would also allow a better parallelization of the design and the integration, therefore helping to secure planning. On the other hand, direct reusability of the same Rendezvous and/or Robotic payloads to future commercial In-Orbit Servicing (IOS) mission is maximized.

The Rendezvous and Robotic payload (Figure 2) is mounted on a panel on top of the Servicer platform. It is constituted of :

- the robotic arm, stowed along a diagonal to optimize space for launcher compatibility;
- the Rendezvous sensors composed of 1x set of relative navigation cameras (i.e., Narrow Angle Camera (NAC), Wide Angle Camera (WAC) with their associated illumination device), along with a LIDAR;
- the capture gripper with interfaces for being handled by robotic arm and locked on servicer;
- a Refuelling interface to connect both spacecraft with a fluidic link;
- an Orbit Replaceable unit (ORU), to be transferred on the dummy client.

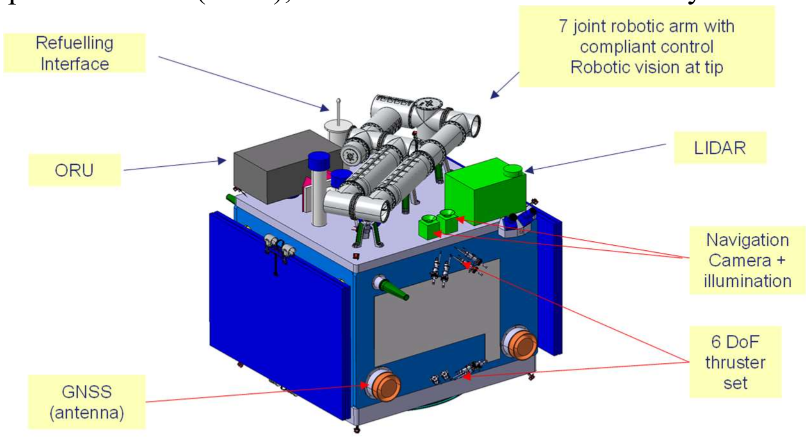

Figure 2: Robotic and Rendezvous payload

2.2 Mission Concept of Operations

Mission Analysis and GNC teams have worked closely with System engineering to derive the RDV strategies required to accomplish EROSS mission objectives while respecting all the mission constraints and especially ensuring the safety requirements through the approach trajectories.

Different RDV strategies have been derived, from the more classical in-plane approaches, to quasi-stationary orbits and 3D walking ellipses. All the derived approaches respect the same requirements to derive the RDV strategy, as follows:

- Phasing constraints and on-ground mission planning capabilities;
- Safety constraints and guidelines;
- Operational constraints, communication and visibility for critical operations;
- Relative navigation observability (e.g. illumination conditions, Sun Phase Angle)
- RDV equipment capabilities and overlap based on their range operability;
- Power constraints;
- Actuators and Control capability;
- Capture system constraints and clearance envelops;
- Attitude and pointing constraints;
- Client status (cooperative/non-cooperative, prepared/non-prepared);
- Time and delta-V cost.

All approaches are compliant with ESA Safe Proximity Operation guidelines and the French Space Act (i.e., “Lois des Operations Spatiales”). The main safety zones are:

- The **Approach Zone (AZ),** i.e. the zone from which relative position estimation is required for safety;
- The **Keep-Out Zone (KOZ)**, i.e. the zone from which relative 6DOF closed loop control is required for safety;
- The **Approach Corridor**, i.e. set of parameters including relative position, velocity, rate and attitude to be respected during manoeuvres inside the KOZ;

- The **Abort Corridor,** i.e. set of thresholds (defined inside the KOZ) including relative position, velocity, rate and attitude, whose violation result in the triggering of an Abort (i.e. the action to abort the rendezvous attempt that should lead to a recovery action leading to the exit of the AZ in a passively safe trajectory for at least 24h);

In Figure 3, a scheme presenting the previous zones is give, based on the example of "–Vbar RDV in-plane approach strategy". Several Hold Points have been defined to implement decision points in which a GO/NO-GO decision is required according to Safety guidelines and sent from the ground by TeleCommand (TC). The critical decision points are the following :

- H0, the **TC GO for Rendezvous Entry Point** is required;
- H1_V, the **TC GO for Approach Zone** is required;
- H3_V, the **TC GO for Keep-Out-Zone** is required;
- H6_V, the **TC GO for Capture** is required.

The following operational phases are defined according to the outcomes of the ESA Safe Proximity Operation guidelines described into more details in [4] :

- **Client Phasing Phase**, i.e. the operational phase encompassing operations and manoeuvres to reduce Client and Servicer relative orbital parameters up until the Far Rendezvous Phase;
- **Far Rendezvous Phase,** i.e. the operational phase starting with TC GO for AZ up until TC GO for KOZ;
- **Close Rendezvous Phase,** i.e. the operational phase starting with TC GO for KOZ up until TC GO for Capture;
- **Capture Phase,** i.e. the operational phase starting with TC GO for Capture up until physical connection (i.e. stabilized stack);
- **Separation Phase,** i.e. the operational phase from the TC GO for Separation, including physical release of the stack up to a predefined mission specific operational point from which Departure Phase can be initiated;
- **Departure Phase,** i.e. the operational phase initiated after separation, following a Departure Corridor to exit the KOZ, followed by a set of manoeuvres to reach a passively safe trajectory that does not involuntarily re-enter the AZ for at least 24h TBC;

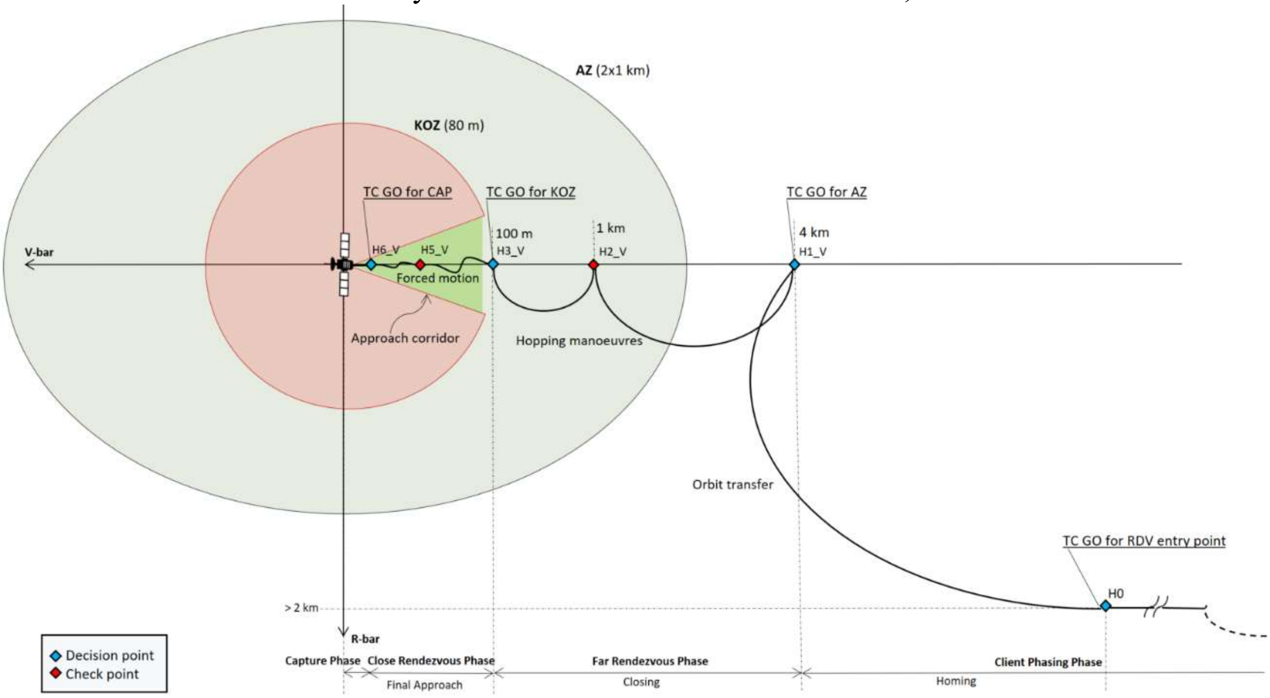

Figure 3: LEO baseline RDV strategy for –Vbar approach

In the current baseline, a validation from Ground is also required to corroborate the on-board check points in order to proceed further on. This will ensure on-board computed manoeuvre reference profiles, sensors switching and major transitions validation by Ground. The in-plane V-Bar approach is composed of Hopping manoeuvres which are open-loop radial boosts and mid-course correction manoeuvres to "jump" from on hold point to the other. These radial boost manoeuvres present a medium level of passive safety as no tangential drift is nominally impressed to the Servicer and in case of major propulsion system failure the Servicer does not naturally drift towards the Client in the short term. On the other hand, higher level of passive safety can be achieved with 3D walking ellipses manoeuvres. The, a closed loop forced motion is performed to enter the KOZ along the Approach Corridor to reach the Capture point. Relative station keeping is required at hold points as trajectory dispersions and perturbations cause a drift from the hold conditions over time.

3 GNC ARCHITECTURE

This section will firstly introduce the main GNC design drivers and the main requirements; then the GNC equipment for Rendezvous, followed by the presentation of the GNC modes logic and Hardware (HW) matrix.

3.1 GNC design drivers and requirements

As presented in the operational concept description, the platform GNC subsystem implements the conventional AOCS modes and the functionalities needed for relative navigation and control. The main high level design drivers of the GNC subsystem for Rendezvous operations are:

- To propose a LEO solution, with options to become compatible to GEO at minimum effort;
- Compliance of the RDV strategy with ESA's Safe Proximity Operation guidelines and with the French LOS;
- Cost reduction for a low-cost flight demonstration by maximizing the re-use of AOCS SW and HW inherited from the selected Platform avionics, while ensuring compatibility of the RDV payload and the GNC Software for RDV with the IOS product line needs and safety.

The main GNC requirements from System level are :

- The GNC subsystem shall be able to control the servicer to perform Delta-V in any direction in S/C frame by properly modulating the actuation of the reaction control set of thrusters;
- The GNC subsystem shall be able to control the servicer to perform large Delta-V using the main propulsion set while maintaining the attitude control;
- The GNC subsystem shall maintain the dummy client within the relative navigation sensor field of view at all time during the close proximity (including during boost);
- The GNC subsystem shall maintain a solar array pointing for power generation while performing the Far RDV, and to maximize it during the close proximity;
- The GNC subsystem shall be 1x failure tolerant;
- Upon FDIR or Ground triggering, the GNC shall be able to perform a predefined manoeuvre in local orbital frame (e.g., Collision Avoidance Manoeuvre/CAM), relying on inertial sensor and on a set of data uploaded by Ground and segregated from nominal operations;
- The CAM shall be sized to follow and reach passively safe trajectories (i.e., free of collisions) for a duration of at least 7 days;
- The GNC subsystem shall ensure an absolute pointing error better than 0.1 deg;
- The GNC subsystem shall perform 3-axis DV with an accuracy better than 4% using the reaction control set;
- The GNC subsystem shall perform large DV with an accuracy better than 4% using the main propulsion set.

The main GNC performances, extrapolated from the GNC Performance Budget for Rendezvous phase, at 3 sigma with a confidence level of 99.7% with temporal statistical interpretation, are presented in Table 1.

Table 1: Main GNC performances during Rendezvous phases

Relative navigation performances (3 axes)		
	Long Range (5km to 100m)	**Short Range (100m to 2m)**
Absolute Knowledge Error relative position	<1% of range	<1% of range
Absolute Knowledge Error client pointing	<0.01 deg	<0.1 deg
Guidance & Control performances (3 axes)		
	Long Range (5km to 100m)	**Short Range (100m to 2m)**
Absolute Control Error relative position	<2% of range	<2% of range
Absolute Pointing Error Client pointing	<0.1 deg	<1 deg

3.2 GNC Modes Description

Each mode implements one or more "phases", meaning the use of different guidance, navigation or control algorithms and/or their parameterization at phase level. Within a given mode, a main function is implemented to meet the mission goals, and is defined by a specific hardware matrix (i.e., the equipment used).

The mode/phase definition aims at maximizing re-use from previous programmes and commonalities between the servicer and the dummy client design for the demonstration mission. In this context, the safe and inertial modes are directly inherited from Thales Alenia Space previous programmes, while the phases and the GNC functions of the long and short range relative modes, the coordinated control relative mode, and the collision avoidance mode have already been prototyped and preliminary tested in simulation and in HIL tests at the robotic test bench in the frame of the R&D projects EROSS (OG7, 2019-2021, [1]) and EROSS+ (OG12, 2021-2023, [3]). The GNC mode logics is detailed in Figure 4, where their overall description can be summarized as follows:

Safe Hold Mode (SHM)

The Safe Hold Mode (SHM) is designed to recover the spacecraft from a *lost-in-space* condition and consists in reaching a pre-defined attitude pointing condition where the sun incidence on solar arrays is compatible with the power subsystem needs. This mode is inherited by LEO programmes.

Inertial Modes (NOM and OCM)

Two inertial modes are foreseen, the Normal Operation Mode (NOM) and the Orbit Control Mode (OCM). The Normal Operation Mode aims at maintaining a stable attitude pointing compatible with operational requirements. The Orbit Control Mode is used to modify the orbital position of the spacecraft (i.e. orbit raising, phasing, deorbitation). The main boosts are executed by the Main Propulsion System (MPS) which consists of thrusters accommodated to perform large delta-V along the Z_{sc} axis, while the Reaction Control System (RCS) controls the attitude and the thrust axis alignment. These modes are inherited by LEO programmes.

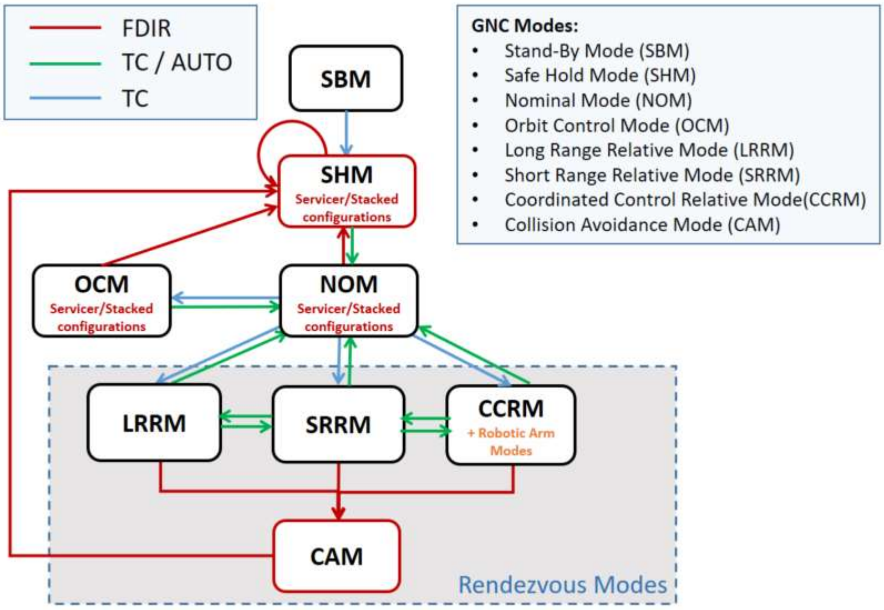

Figure 4: GNC Modes logic

Rendezvous modes (LRRM, SRRM, CCRM, CAM)

The rendezvous modes are designed to control the servicing spacecraft during proximity operations in a range from few kilometres until few metres to the client. Four modes (with multiple phases) are implemented to cope with functional, performance, operational and safety requirements:

- **Long Range Relative Mode (LRRM):** used to navigate semi-autonomously at long range by impulsive manoeuvers, and using relative sensors like NAC and relative orbit propagators fed with absolute GNSS and Client orbit propagator. The LRRM mode computes autonomously attitude and trajectory target guidance validated by ground at predefined hold points where the S/C is maintained in a stable and safe condition before executing open loop main boosts and correction manoeuvres to reach the subsequent hold point or trajectory;
- **Short Range Relative Mode (SRRM):** used to navigate autonomously at short range by continuous manoeuvres, and using relative sensors like WAC. This SRRM mode generates autonomously the guidance on-board (R-bar and V-bar straight line approaches, forced fly-around) and the thrusters are used in closed loop for 6DoF forced motions. It must ensure that the spacecraft is operated in a stable, safe condition before engaging the final phases of rendezvous with the deployment and operation of the robotic arm;
- **Coordinated Control Relative Mode (CCRM):** used to operate the robotic arm for the early deployment (independently), or for the client capture (with an active coordinated control of the platform). Tis CCRM mode actively controls the platform in a "free-flying" way using its actuators fed by a feedforward command from the robotic arm while moving relatively slowly. Depending on the robotic arm strategy, the CCRM also allow to leave the platform passive with a "free-floating" control when no feedforward commands are sent by the robotic arm. The main goal and challenge of the CCRM remains to capture the client using state-of-the-art compliant control methods while minimizing the platform depointing;

  Note: After reaching berthing conditions, the robotic arm capture is triggered, and the control supervision is handed over to the robotic arm control SW through its own sub-modes developed in synergy with the GNC SW.

- **Collision Avoidance Mode:** used for contingency operations, it execute manoeuvres to avoid collision and reach a safe position/orbit. This mode make use only of inertial sensors, thrusters and open-loop relative propagator, segregated from the nominal navigation & decision chains.

EROSS IOD Flight Segment shall perform autonomous Rendezvous, from initialization to capture completion, without Ground intervention except for GO/NOGO commands required for proximity operation in order to monitor the overall safety. In case of contingency, the Servicer Segment shall be able to continue to operate safely without Ground intervention. Ground shall check that the on-board computed manoeuvres are correct before sending a TC GO. Ground can intervene at any time to command a retraction/stop/abort manoeuvre overriding any automatic transition.

3.3 GNC Hardware matrix

Table 2 presents the main GNC equipment used in each mode. A preliminary analysis of the functional and performance needs for the demonstration mission has allowed to consolidate a preliminary definition of the previous modes, along with a selection of the most suited GNC HW equipment in the following baseline. The rationale behind the choice of several classical AOCS equipment is strongly determined by the Platform choice for the EROSS IOD mission.

Table 2: Baseline GNC HW Matrix with redundancy strategy

Equipment	Baseline	Main Use
Main Propulsion System (MPS)	1+1 THRs	Inertial orbit control (raising/phasing/deorbitation),
Reaction Control System (RCS)	8+8 THRs	RDV torque-free manoeuvres Attitude control in OCM Emergency detumbling
Reaction Wheels Assembly (RWS)	4 RWs	Attitude control and pointing for nominal and RDV operations
Magneto-torquer Bars (MTB)	3 MTBs	Attitude control in Safe Mode and RWS desaturation
Magneto-meter (MAG)	1+1 unit (3 axes)	Mainly for Safe Mode
Coarse Sun Sensors (CSS)	8 units	Mainly for Safe Mode
Gyroscope	1+1	Robustness to STR blindings
Star Tracker (STR)	3 OHs	Absolute Attitude estimation
GNSS	1+1	Absolute Servicer orbit update
Narrow Angle Camera (NAC)	1+1 Visible	Long Range navigation
Wide Angle Camera (WAC)	1 Visible + Illumination device	Short range navigation
Robotic Arm Camera	1 + 1 Visible + Illumination device	Robotic Capture Navigation and Servicing monitoring
LIDAR	1 unit	Monitoring and functional redundancy
IMU	1 + 1 unit	Manoeuvres Monitoring

For the relative navigation during the Rendezvous phase, relative sensors capable of autonomously detect the Client and estimate the relative state are required. To this end, the following scheme in Figure 5 presents the main RDV equipment operational ranges and their deployment along the RDV approach. On the top of the figure, the GNC mode used along the approach is showed to correlate with the HW matrix introduced above.

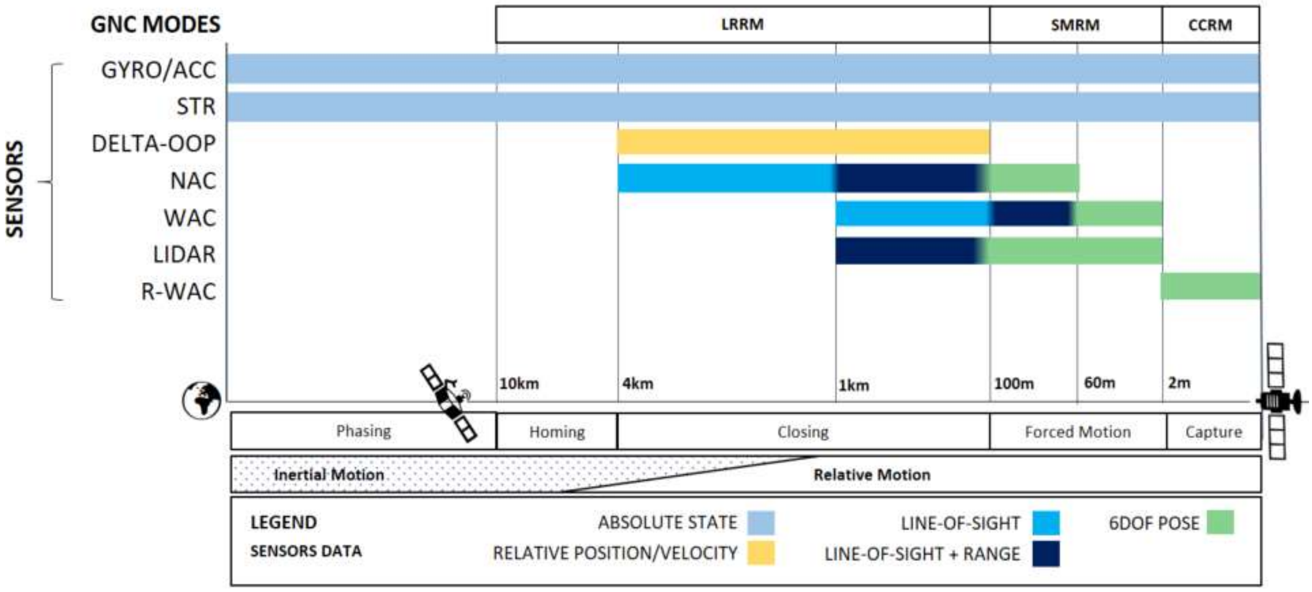

Figure 5: RDV GNC equipment per mode/mission phase

Relative position estimation during long range navigation is based on GNSS and a Client orbit propagator, coupled with a NAC capable of providing Line-Of-Sight information during good illumination conditions (i.e. when Sun Phase Angle constraint is met and out of eclipses). Once the range becomes observable by the NAC images and model-based technique, the relative dynamics can be estimated more accurately on board. At 1km, the LIDAR will be used as a parallel navigation chain to feed the monitoring function. At 100m, SRRM will be triggered and 6DoF forced motion manoeuvres will be performed to reach the capture point in V-Bar or R-bar. The full pose estimation capability will ensure detection of Client sudden involuntary movement that could trigger an autonomous CAM.

At the current preliminary design stage, a NAC of 5° of FoV (Field of View) and a WAC of 30° of FoV seem to better fit the mission needs. The on-going RFP (Request For Purchase) process selection of cameras will allow to finalize the trade-off and potentially review the current baseline of their FoV. The GNC architecture is however robust to accommodate different kind of navigation sensors capabilities thanks to the advanced filtering implemented and to the flexible ConOps, if it is needed to cope with different sensors performances and interfaces.

4 GNC Preliminary Analyses

This section will presents some examples of the main preliminary sizing and validation analyses made in the frame of Phase B1.

4.1 Far Rendezvous analyses

During the Far RDV phase, open-loop boost manoeuvres are performed to move from one hold point to the other. Once an Hold Point is reached, phases of active relative station keeping and drift are performed upon a logic based on entry/exit conditions of the control box around the hold point. Free-drift, which is allowed only at stable hold points (i.e. point along V-Bar), is preferred when relative dynamics observability is not ensured (e.g. during eclipse) and navigation on differential on-board absolute dynamics propagators of Client and Servicer is not accurate enough. The actual drift is not much if the prepositioning is accurate enough. Preliminary analyses have been performed to assess feasibility using the GNC Functional Engineering Simulator (FES).
All main disturbances in LEO are taken into account but most importantly, refined models of the entire actuation chain are considered with the control, commanding, and actuation models. From the operational scenario point of view, different realistic waiting times from the main maneuver computation to the execution have been tested. These hypotheses are coherent with actual realistic operational timelines (i.e. syncronisation of vibility windows from ground stations and illumination conditions). NAC-based line-of-sight and range measurements are not available during eclipses or bad illumination conditions (i.e. Sun Phase Angle constraints are not met), and mid-course correction maneuvers execution is allowed only during predifined time slots and only if relative measurements are available. The model used to simulate the relative measurements in Far Range is a model based on representative errors of the NAC LoS and relative range estimation, obtained from open-loop validation campains of a representative model of the Image Processing functions (see [3] for more details).
The relative Kalman filter at the core of the Navigation function fuse these relative measurements when they are available (e.g., different rate, delay, availability). Considering all these factors, in some conditions, the need to exectute two correction maneuvers is not excluded. In fact, in order to meet acceptable arrival conditions (e.g. not crossing the Keep-Out Zone), a second correction maneuver allow to follow more accurately the guidance reference profile. Figure 6 shows a run test example performed with 5% of range error in initial state (i.e. +/- 50m in all directions) before hopping maneuver execution.

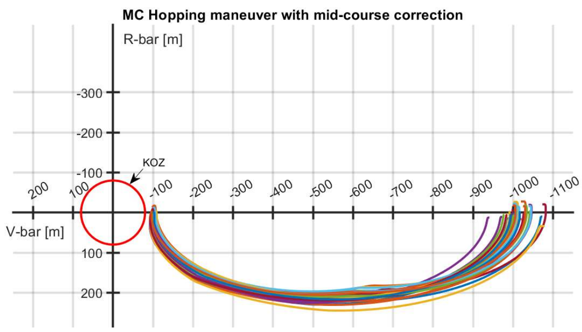

Figure 6: Reduced MC analyses of hopping manoeuvre (1km-100m) with mid-course correction manoeuvre.

Preliminary analyses shown that the baseline Far Range ConOps is feasible but a throrough robustness campaign shall be performed in the next phases to validate the approach and all the GNC functions involved. Position error at arrival is below 5% of range wich is the performance budget allocation for position error at station keeping entry. Thresholds to trigger a CAM should be accurately tuned to ensure Safety while minimizing false alarm rate. These preliminary analyses allowed to capture the evolution of the main observables for the trajectories in Far Range.

4.2 Close Rendezvous analyses

Close rendezvous phases have been preliminary tested in MIL/SIL/HIL (Model/Software/ Hardware-In-the-Loop) during the previous EROSS H2020 project [1] and during EROSS+ [3]. For this latter, additional functionalities have been developed and tested in simulation and in HIL testing at the robotic test bench. Both V-bar and R-bar LEO and GEO straight line approaches, inspection orbits and forced fly-around approaches have been developed and tested. The navigation performance improves as the Servicer moves towards the Client as expected. The measurement model employed in the FES (Functional Engineering Simulator) for short range approaches has been built based on an offline open-loop validation of image processing algorithms with synthetic images (i.e., using the in-house SpiCAM rendering tool by Thales Alenia Space), while a final correlation of this model with the experimental results is on-going for the EROSS IOD program.
From an operational point of view, the observability constraint is relaxed once the client is within the operational range of the illumination device, allowing the visible WAC camera to be robust to eclipses and bad illumination. Figure **7** shows an example of close rendezvous final approach. A V-bar straight line approach enables the servicer to reach -20m. Then a forced fly-around manoeuvre is executed to reach R-bar axis at -20m. An R-Bar approach follows up until -2m from the Client. During this forced motion, 5% of range error specification, which is the performance budget allocation in position error inside the approach corridor, is met.

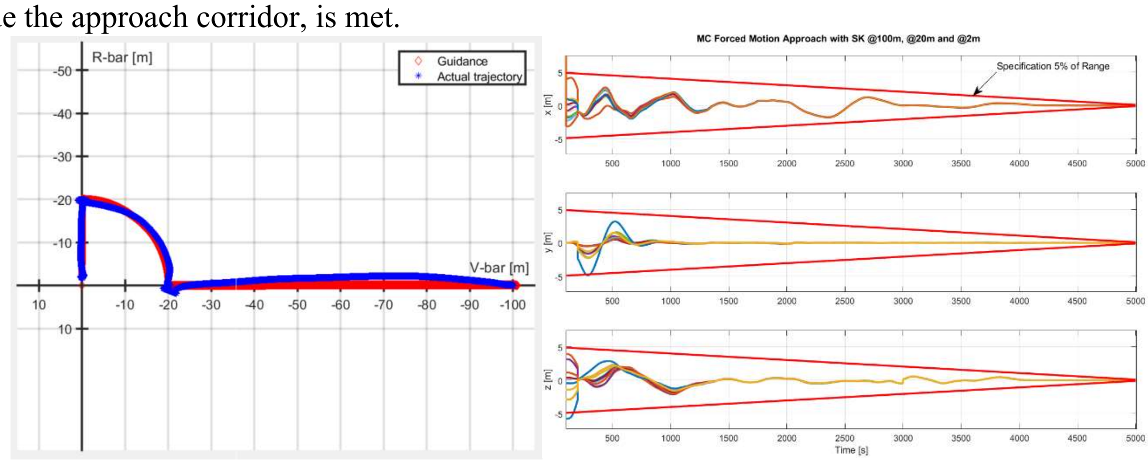

Figure 7: Final approach example in V-Bar/R-Bar plane (left), in LVLH frame (right).

Several approach trajectories have been tested during Phase B1. The current architecture is capable of executing V-Bar and R-Bar straight lines, forced and natural fly-around, and ellipse of inspection. During inspections or natural fly-around, an out-of-plane components can be added to avoid causing interference in the Client-Ground communication. Part of these manoeuvres has been tested also at the robotic test bench in HIL tests, as presented in [3].

4.3 Controllability analysis and RCS accommodation

The Reaction Control System (RCS) is composed of 8+8 1N THRs. This system shall ensure a torque-free and force-free capabilities and 6 Degree of Freedom (DoF) control of the Servicer in order to generate forces and torques independently along any inertial axis. These capabilities are achievable with 8-THRs configuration whose accommodation allows for torque and force along all axis. The accommodation shall also minimize plume-impingement on the Client mainly, but also on the Servicer itself (e.g., appendages like solar array or robotic arm). The main functions of the RCS are:

- Ensure torque-free translational control during RDV;
- Attitude/Torque control during OCM;
- Emergency desaturation and rate damping;
- Collision avoidance manoeuvres.

A thorough controllability analysis have been performed in order to find the optimal accommodation and validate controllability performance. Dispersion analysis for different CoM position (including worst cases) considering uncertainty on the Force/Torque matrix distribution and thrust magnitude and directions have been carried out in the FES simulator through a Monte Carlo (MC) analysis. A Thruster Management Function (TMF) computing the opening of each of the 8 THRs leading to a torque-free behaviour in forced motion is used for these analyses. It is inherited from past projects and is already integrated at FES level. In Figure 8, an example of the results obtained is showed (in Blue the mean value, in Red the Standard deviation).

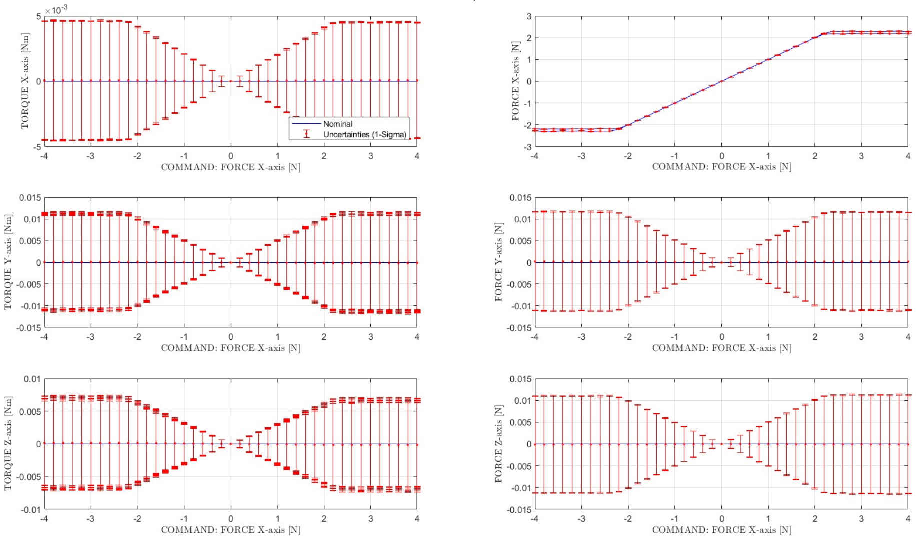

Figure 8: Force/Torque induced perturbation for commanded force along X_{sc} axis

Meanwhile, the attitude control is ensured by RWS desaturated by MTB in order to lower relative pointing error and enhancing stability. The limitation is due to the induced thrust disturbance that should remain below an acceptable threshold to maintain torque free/force free decoupling. Residual torques are lower than 10^{-4} Nm during a torque-free forced motion actuation, ensuring a torque free behaviour allowing for 3D translation actuation capability of up to 1.5 N. RCS accommodation has then been validated in the FES with closed-loop monte-carlo simulations.

4.4 Control Tuning Trade-Off

Particular attention is given to forced motions control as it drives the THR selection which is based on COTS system without delta-qualification. As a consequence, it then drives the GNC usage of the THR with the Ton/Toff cycles. In pulsed mode, each 1N THR shall be at least commanded at its qualified minimum *on-time* every command period, or usually a waiting *off-time* of few dozenzs of seconds shall be respected before commanding another pulse (i.e. red zone constraint). Thus, during close range when red-zone actuation constraints could be dangerous as they limit control reactiveness, the pulsed mode usage leads to a fuel consumption significantly greater than without. This leads to a trade-off to select a compromise for the command period.

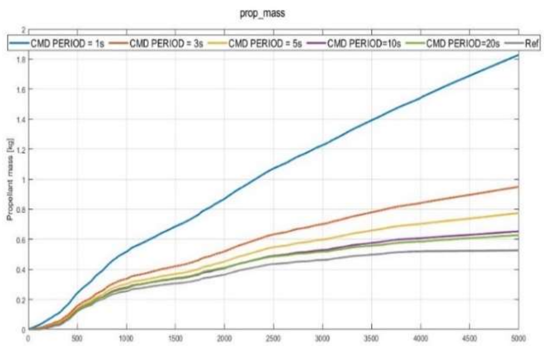

Figure 9: Propellant mass consumed during a forced motion for different command periods

The command period shall be sufficiently high to ensure enough thrust resolution for a given mimimum on-time and minimize fuel consuption during pulsed mode, but not too high in order to not

compromise the control loop stability and reactiveness. Robust performance and stability must be always ensured. Figure 9 presents a sensitivity analysis during a forced motion approach as function of the command period. Command periods must be carefully tuned to meet the required performances (e.g., as shown in Figure 7), with enough reactiveness while still limiting fuel consumption. Fuel consumption for Far Rendezvous and for Close Rendezvous has been computed as direct output of the FES simulations for charactectistic duration time for each planned type of maneuvers. For a complete nominal Rendezvous V-bar approach in the LEO baseline orbit, the total required delta-V is in order of less than 5 m/s.
To meet the full list of requirements and constraints, robust control techniques of Multi-Input Multi-Output structured H-infinity [2] have been used to synthetize a minimal set of controllers capable of ensuring robust performance and optimize fuel consumption. Preliminary uncertain Linear Fractional Transformation (LFT) models have been derived to verify also in the frequential domain that control requirements are respected.

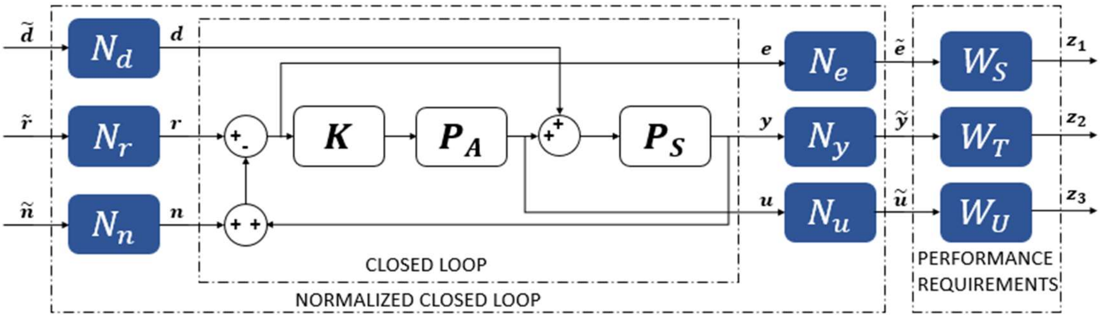

Figure 10: Control Synthesis Model

Figure 10 presents the model used to syntehsize the robust controllers, while Figure 11 shows an example of frequential analyses for MIMO case with simplified uncertain LFT model. Monte Carlo non-linear temporal analyses validate the performance and the robustness of the control loop.

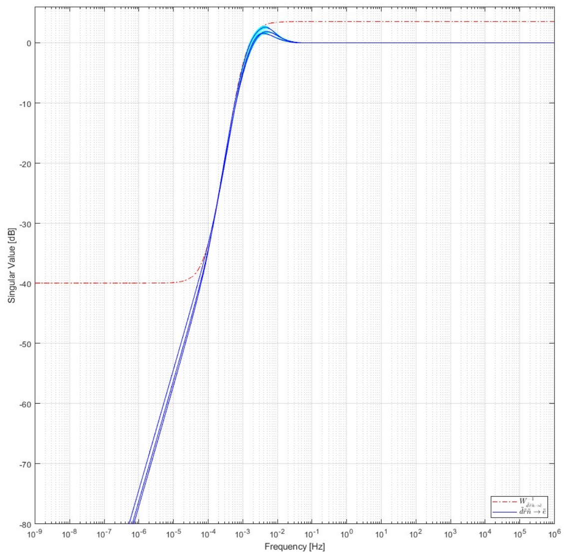

Figure 11: Examples of MIMO frequential analysis (singular values of inputs to the control error)

These trade-off analyses have allowed to identify a range of Component-Off-The-Shelf (COTS) qualified thrusters suited for the EROSS IOD mission, which are now being traded-off in terms of qualification range with deeper applicability and GNC analyses at avionics level.

5 GNC V&V APPROACH

The following section will present the overall Verification & Validation (V&V) for the GNC system with a focus on the GNC SW application. The V&V process is allowing fast prototyping from building blocks development to flight software, thanks to the autocode framework and early integration of the GNC software in representative space hardware (see [5] for more details), to assess the required computational budgets and confirm early preliminary algorithms profiling. Early testing of several hardware elements has taken place during the Hardware-In-the-Loop experiments with vision systems testing in robotic test benches in order to corroborate the Processor-In-the-Loop, Model-In-the-Loop, and Software-In-the-Loop preliminary tests in closed-loop.

5.1 Functional Engineering Simulator simulations

Preliminary GNC analyses have been performed with the FES. An automatized workflow has been established allowing to run multiple tests on the FES simulator and facilitating the post-processing of the results. The process is described in Figure 12. The reference runs consist only of a pre-defined scenario (i.e., a sequence of telecommands emulating the flight plan) and the typical configuration of the servicer satellite (MCI features, sensors and actuators layout, initial conditions). For the robustness campaign an additional plug-in is used to introduce scattered parameters overwriting those of the typical configuration. The tests performed on the GNC allow to completely validate the GNC architecture for the nominal and contingency scenarios. The main performance requirements are satisfied for the nominal scenario on realistic cases.

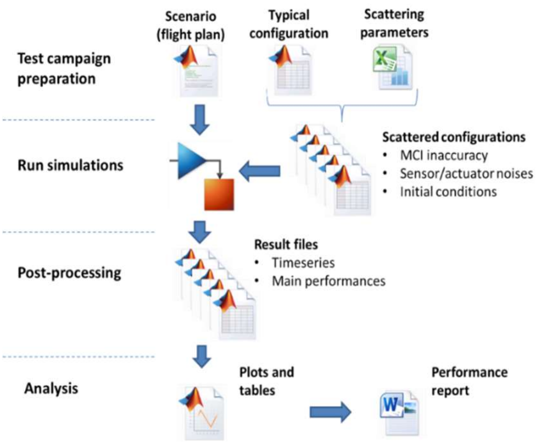

Figure 12: Workflow for running tests on FES simulator

5.2 Development, Validation and Verification process for the OBSW GNC application

From 2016 on, any new program of Thales Alenia Space applies automatic code generation at the highest level, including full applications [5]. This means that the GNC mode logics, the satellite data base and many other functional requirements are modelled in the Matlab simulator and then directly exported to flight code. This has been possible thanks to the experience acquired in previous programs where code generation has been applied on simpler perimeters. Concerning the validation facilities, there are still the same elements as per the conventional process, including the FES simulator, along with the Software Verification Facility (SVF) and Avionic Test Bench (ATB). The introduction of automatic code generation allows to use the FES functional simulator with the full or partial AOCS/GNC subsystem in SIL, which could be introduced as an intermediate step between the FES and SVF validation perimeters.

The previous figure presents the V-cycle combined with internal “Agile” loops to take advantage of the automatic code generation process. It is worth noting that the Agile philosophy is specially well suited to support this development scheme enabling the possibility of developing and validating incrementally the flight software of the AOCS/GNC application, once a fast and efficient software delivery process is in place. A more detailed V&V process pipeline, implemented in the EROSS IOD programme is presented in [4].

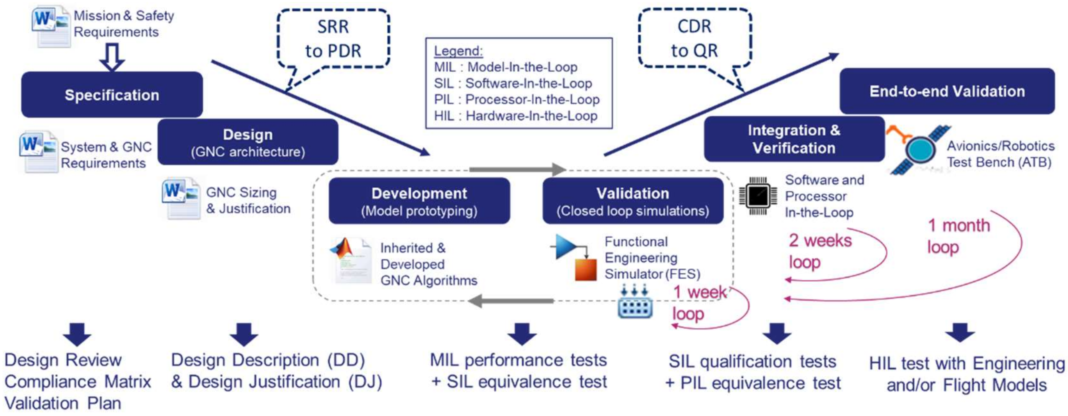

Figure 13: V-cycle for the AOCS/GNC development process with automatic code generation

6 CONCLUSIONS

The current paper presents the main results of the H2020 EROSS+ Phase A/B1 with a strong focus on the GNC design and sizing analyses. In parallel of this Phase B1 and of the GNC architecture activities, early derisking and integration HIL testing has been also performed and the main results are presented in [3] to correlate the current architecture with ground results. The EROSS+ project concludes its Phase B1 early in 2023 and has switched to the EROSS IOD mission since then. The core GNC software is claimed to be at TRL5 at the end of this Phase B1 thanks to the implementation in a representative flight avionics. Currently in Phase B2, the EROSS IOD programme will achieved PDR by January 2024 and CDR is foreseen for January 2025, while launch is targeted for 2026.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] Dubanchet, V., Andiappane, S., Negro, P. L., Casu, D., Giovannini, A., Durand, G., & D'Amico, J., "Validation and demonstration of EROSS project: The european robotic orbital support services", in *Proceedings of the International Astronautical Congress (IAC)*, Virtual Edition, 2020.
[2] Kemin, Z. H. O. U., and JOHN C. Doyle. "Essential of Robust Control", 1995.
[3] Dubanchet V., Casu D., Comellini A., Giglio A., Bejar Romero J.A., Torralbo Dezainde S., Alonso M. , "EROSS+ ground demonstrations from Model to Hardware in the Loop validation", in *Processing of the ESA GNC-ICATT conference*, Sopot, Poland, 2023.
[4] Comellini A., Casu D., Dubanchet V., Renault H., Bitetti L., Dandré P. , "Safety in GNC systems design for In-Orbit Servicing during close proximity operations", in *Proceedings of the ESA GNC-ICATT conference*, Sopot, Poland, 2023.
[5] P. Dandré, et. al., "AIMONS, Validation & Verification process update of GNC OBSW application", in P*roceedings of the ESA GNC-ICATT conference*, Sopot, Poland, 2023.