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EROSS-IOD GNC for a versatile Servicing Demonstration applicable to Prepared and Unprepared Client Spacecraft

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Abstract

This paper provides an overview of the Guidance, Navigation and Control (GNC) architecture of the Servicer vehicle developed in the scope of the EROSS IOD program to be bi-compatible with a prepared and unprepared Client vehicle. This key feature allows to anticipate the two current market trends to , first, service vehicles already in orbit without any specific feature or behaviour to support such servicing, and secondly, to mature the interfaces to integrate on the future spacecraft currently in the manufacturing process in order to ease future servicing and broaden their scope.

The resulting GNC architecture closely connects the Servicer design and the Concept of Operations (Conops) defined relatively to the Client Local Orbital Frame (LOF). The paper reviews (1) the mission Conops and key requirements or design drivers for such a new type of space mission. It covers as well (2) the Servicer and Client spacecraft design with a focus on the GNC architecture to handle these two use-cases for a prepared or an unprepared Client vehicle. Eventually, (3) the GNC simulator built to validate such a mission is reviewed and the obtained results are discussed per phase of the rendezvous from the GNC performance perspective.

From a navigation perspective, the relative sensors selection and their integration is also introduced in the paper to highlight the tight coupling with the GNC and especially the Navigation filter layer. Apart from the Conops, the sensors are the key components to handle the Client prepared/unprepared design with, as much as possible, a common system architecture. The end goal is to maintain a common Conops as safe and efficient as possible for these upcoming operational services in this new chapter of the space era.

Keywords: space servicing, space robotics, autonomy, formation flying, rendezvous

1. Introduction

The race for autonomous systems in space leads to the integration of advanced robotics and computer vision systems within the traditional spacecraft design. The scientific and industrial expectations are opening a new era of space systems more capable, more reconfigurable, more modular, and in the end also more sustainable by making a better usage of the resources available in orbit. The related developments over the last ten years gave a deep impulse into the space community by challenging established actors to apply differently their inherited knowledge on the traditional design and manufacturing of spacecraft, while giving birth to fast-growing start-ups specializing in this new types of mission with more agility.

New markets are emerging fast and the clients/providers actors landscape is truly booming with services such as On-Orbit Servicing (OOS) with station keeping or refuelling mission, or the autonomous In-Orbit Assembly (IOA) of large space structures addressing both scientific and telecommunication applications.

Past missions have paved the way for these OOS/IOA applications with the ETS-VII Japanese mission in 1997 and the Orbital Express American mission in 2007. The maturation of these systems autonomy and of the legal framework led later to the first OOS mission on February 26th, 2020 when Northrop Grumman successfully docked the Mission Extension Vehicle-1 (MEV-1) vehicle to the Intelsat 901 (IS-901) spacecraft to extend its life duration at a geostationary slot[*], and reiterated this service with MEV-2 vehicle on another Intelsat spacecraft IS-10-02[†] on April 12th , 2021 [4].

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[*] [last access: 12/07/2024] https://spacenews.com/northrop-grummans-mev-1-servicer-docks-with-intelsat-satellite/

[†] [last access: 12/07/2024] https://spacenews.com/mev-2-servicer-successfully-docks-to-live-intelsat-satellite/

In this context, Thales Alenia Space is currently leading the European flagship program called "European Robotic Orbital Support Services" (EROSS) and funded by the European Commission (EC) to demonstrate the European capabilities in terms of space servicing. Following the European Commission vision, the EROSS program, led over 2021-2023 for the phase A/B1 and over 2023-2025 for the phase B2/C, was initially called "EROSS+" and "EROSS-IOD" for In-Orbit Demonstration, and is now renamed "EROSS-SC" for Servicing Component. EROSS-SC program intends to validate and showcase European solutions for the Servicers and the Serviced LEO/GEO satellites, enabling a large range of efficient and safe orbital support services [5]. It will act as a building block of servicing and assembly in orbit to further serve the overall vision of a dynamic, modular, and reconfigurable space ecosystems envisioned by the EC.

Over the past 8 years, the Strategic Research Cluster (SRC) in Space Robotics from the EC provided funds to boost the maturity and the synergy of both industrial and academic European actors in this domain. Since 2016, four main suites of projects, also called "Operational Grant" (OG), have been led with a first set from OG1 to OG6 in 2016-2019 to develop robotic building blocks [6]-[10], and a second set from OG7 to OG11 to integrate them towards orbital/planetary missions from 2019 to 2021 [11]-[13]. Then phases A/B1 were led for the key orbital demonstrators with the last OG12-EROSS+, OG13-PERIOD and OG14-COROBX [14][14]. Within this Space Robotics SRC, Thales Alenia Space has led the OG4-I3DS on smart sensors development, the OG7-EROSS on the ground validation of a servicing mission, the OG12-EROSS+ to lead the system phase A/B1 towards an OOS mission of demonstration, and is now currently leading EROSS-IOD / EROSS-SC towards the flight demonstration, as part of the new "Horizon Europe" EC framework.

Along with the in-orbit demonstration of such a mission, one key aim of the EROSS-SC program is to prepare and carry out the last maturation & manufacturing of the critical technologies including space building blocks for robotics, computer vision, standard interfaces and autonomy. With a strong customer-driven approach, the proposed demonstration will enable access to the following market segments:

- In the short term, On-Orbit Servicing for unprepared clients: Inspection/surveillance, life extension (via station keeping, attitude and orbit control being taken over by the Servicer), change of orbit and end-of-life removal.
- In the mid-term, On-Orbit Servicing for prepared clients: life extension by refuelling (thus avoiding immobilisation of a servicer for several years), upgrade and potentially repair. This is where the proposed demonstration will position Europe in a leading position, as this requires a unique robotic dexterity and autonomy, as well as specific design features of the Client spacecraft soon to be standardized according to institutions roadmaps.
- In the long term, In-Orbit Assembly and Manufacturing: the technologies developed and showcased will prepare the change of paradigm in how the space infrastructures will be designed, produced and exploited in a more sustainable way.

From a Guidance, Navigation and Control (GNC) standpoint, these applications and missions require similar functions for moving safely around another object in space despite the internal and external disturbances, and the orbital mechanics constraints. Complete experimental ground setups have already been demonstrated in the past years to serve as proofs-of-concept for the final flight implementation currently on-going on EROSS-SC program. As an example, the ground experiments of the EROSS project covered rendezvous and robotic experiments with two mock-up at different scales to validate the long-range and short-range rendezvous [15]. In addition, three main test beds have been used to validate (a) the vision-based navigation approach in closed-loop on GMV's Platform-Art robotic bench; (b) the robotic controller compliance during the capture and contact on DLR's CAESAR robotic bench with a 0-gravity compensation system; (c) the avionics integration and autonomy loop on Thales Alenia Space's Avionics Test Bench (ATB) [16] whose GNC architecture is introduced in [17].

The current paper will focus on the on-going maturation of these Guidance, Navigation, and Control (GNC) algorithms to reach a flight maturity by the launch foreseen in 2026 [5]. A first section will recall the Mission Context and the Concept of Operations (Conops), and a second one will describe the GNC Architecture to handle such Conops. Then the GNC high-fidelity simulator is reviewed in a third section, before introducing the final results validating its architecture and concluding the paper in a fourth section. A final conclusion is given with the main challenges faced by the GNC integration for this servicing.

EROSS-IOD/EROSS-SC program is co-funded by European Union's Horizon Europe research and innovation program under grant agreement N°101082464 and is part of the Digital, Industry and Space programme. Thales Alenia Space leds this project in collaboration with DLR, GMV, PIAP Space, SENER Aerospacial, Space Applications Services, SINTEF AS, Kongsberg Defence & Space, Almatech, CSEM, NRB SA, and the dissemination support from TIPIK .

2. Mission & GNC Context

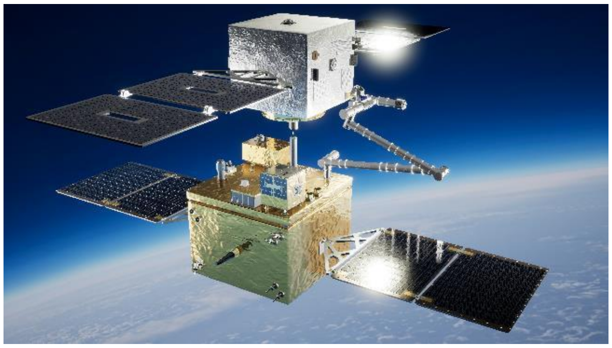

Figure 1 – Illustration of the EROSS-SC mission

2.1 Mission Summary

EROSS mission will demonstrate On-Orbit Servicing (OOS) capabilities and technologies through an In-Orbit Demonstration (IOD) over 1 year. The IOD will demonstrate different Rendezvous (RDV) approach and departure strategies, as well as and capture strategies covering the two potential missions of application for prepared and unprepared Client vehicles.

In the frame of EROSS SC, several types of final approaches will be tested. Figure 2 shows a high-level overall Mission Time Line (MTL). It is not intended to be a comprehensive timeline, as some phases could be reiterated, re-arranged, or even repeated. For instance several rendezvous and capture rehearsals will be done to gather operational experience and to test different environment conditions such as solar illumination, in order to assess its impact on the nominal visual navigation chain and the overall GNC performance.

Among the services to be demonstrated, the Servicer will cover the inspection, the AOCS take-over or station keeping including tugging for re-positioning or end-of-life management, the refuelling, and the orbital unit replacement with the robotic exchange of Orbital Replaceable Unit (ORU) between both vehicles.

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 Opérations Spatiales”).

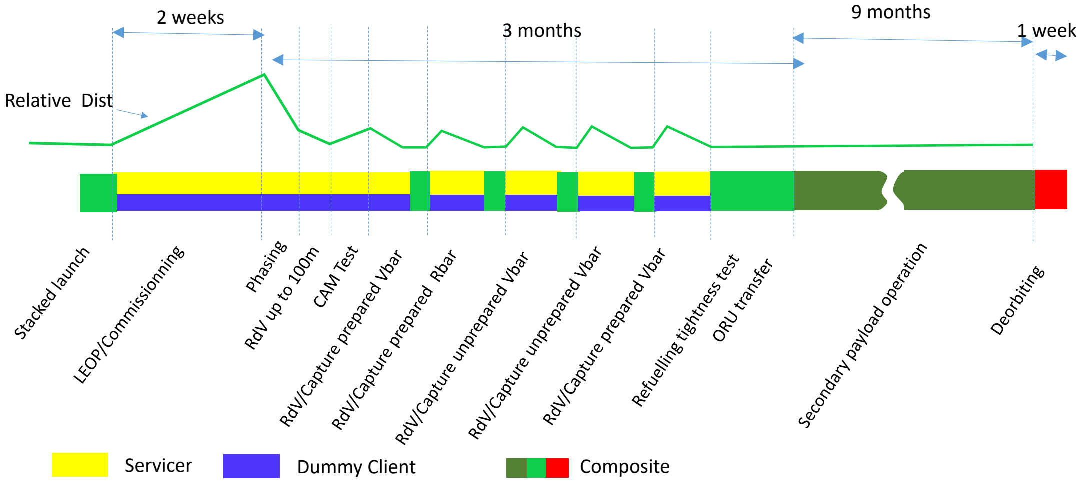

Figure 2 – EROSS SC Mission Time Line

According to these guidelines documents, the main safety zones are defined as follows:

- 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);

Figure 3 illustrates these zones based on the example of "–Vbar RDV in-plane approach strategy". Several Hold Points are 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 required to move from one zone to the next are defined as follows:

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

The following operational phases are defined according to the outcomes of the ESA Safe Proximity Operation guidelines :

- **Client Phasing Phase**, from TC GO for covering operations and manoeuvres to reduce Client and Servicer relative orbital parameters until next rendezvous phase;
- **Far Rendezvous Phase,** from TC GO to enter AZ, covering the impulsive manoeuvres through AZ until KOZ;
- **Close Rendezvous Phase,** from TC GO to enter KOZ, covering the continuous manoeuvres through KOZ until Capture;
- **Capture Phase,** from TC GO for Capture, covering the final meters motion combined between the platform and the robotic arm until physical and safe connection;
- **Separation Phase,** from TC GO for Separation, including physical release of the stack up to a predefined operational point from which Departure Phase can be initiated;
- **Departure Phase,** automatically triggered after the Separation, following a Departure Corridor to exit the KOZ, and then followed by a set of manoeuvres to reach a passively safe trajectory that does not involuntarily re-enter the AZ for at least 24h for safety

In the current baseline, a validation from Ground is also required to corroborate the on-board check points in order to proceed, in order to validate on-board the computed reference manoeuvre profiles, the sensors switching and major transitions by Ground.

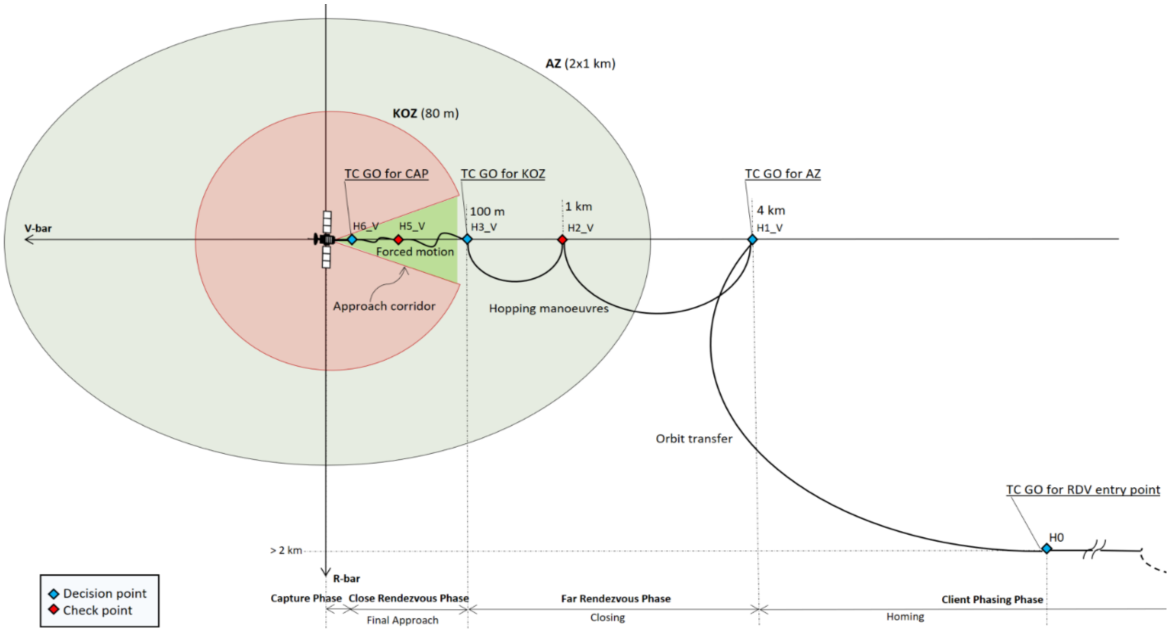

Figure 3 – LEO baseline RDV strategy for –Vbar approach

2.3 *Servicer and Client design*

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 illustrated in Figure 4 is mounted on a panel on top of the Servicer platform.

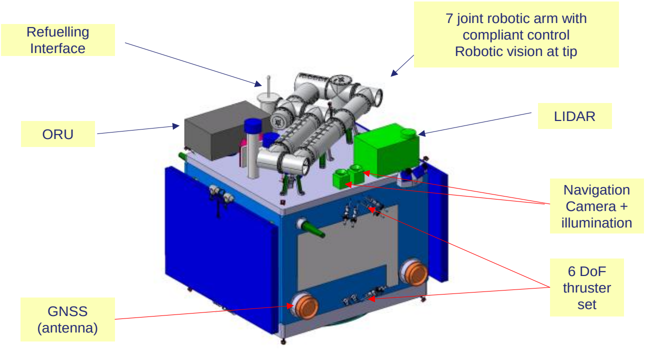

Figure 4 – Robotic and Rendezvous payload

It is constituted of :

- the **robotic arm**, stowed along a diagonal to optimize space for launcher compatibility;
- the **passive visual 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)
- the **active rendezvous sensor** composed of a LIDAR ranging and 3D mapping system;
- the **capture gripper tool** with interfaces for the robotic arm handling and for the storage;
- the **Refuelling interface** to connect both spacecraft with a fluidic link;
- the **Orbit Replaceable Units** (ORUs), to be transferred from the Servicer to the Client.

On the other hand, the Client vehicle design features two main panels to perform the rendezvous and capture demonstration with a prepared and unprepared sides. These panels are representative, respectively:

- **Unprepared panel:** a spacecraft already in-orbit without any specific fiducial marker or mechanical handle for the servicing, except a Launch Adaptor Ring (LAR) commonly used on most spacecrfaft;
- **Prepared panel**: a future spacecraft being designed to support servicing operations with minimal impact on the system design. The panel then features a specific mechanical handle bi-compatible with the LAR ring from the gripper perspective, along with specific markers to support the robotic vision.

Apart from the rendezvous and capture phases, the Client vehicle is also “prepared” for the subsequent servicing activities considering its specific interfaces for the refuelling or the exchange of the ORUs. But these interfaces are not necessarily concentrated on a single panel as for the rendezvous and capture phases introduced above.

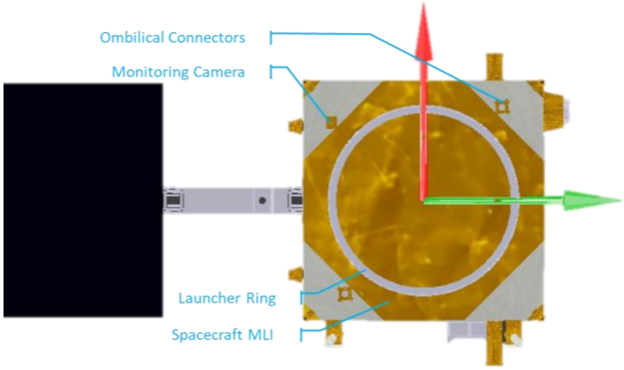

Figure 5 – Client Unprepared Panel

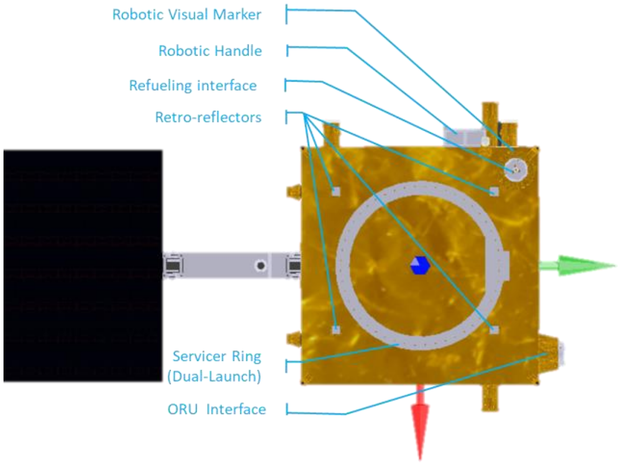

Figure 6 – Client Prepared Panel

3. GNC Architecture

This section introduces the main GNC design drivers and the main requirements fulfilled by the current architecture of modes.

3.1 GNC main 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 law;
- 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 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 RDV

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 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 [15][11] and EROSS+ [16]. The GNC mode logics is detailed in [17], 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 + 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.

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 <u>open loop main boosts and correction manoeuvres</u> 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;

- **Collision Avoidance Mode (CAM):** 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.

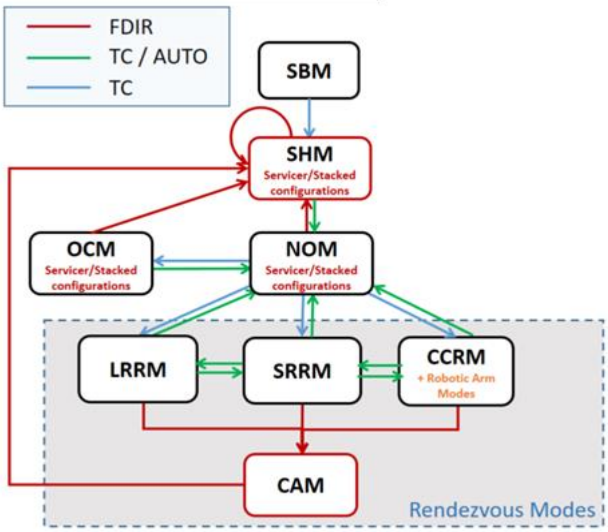

Figure 7 – GNC Modes logic

4. GNC Simulator

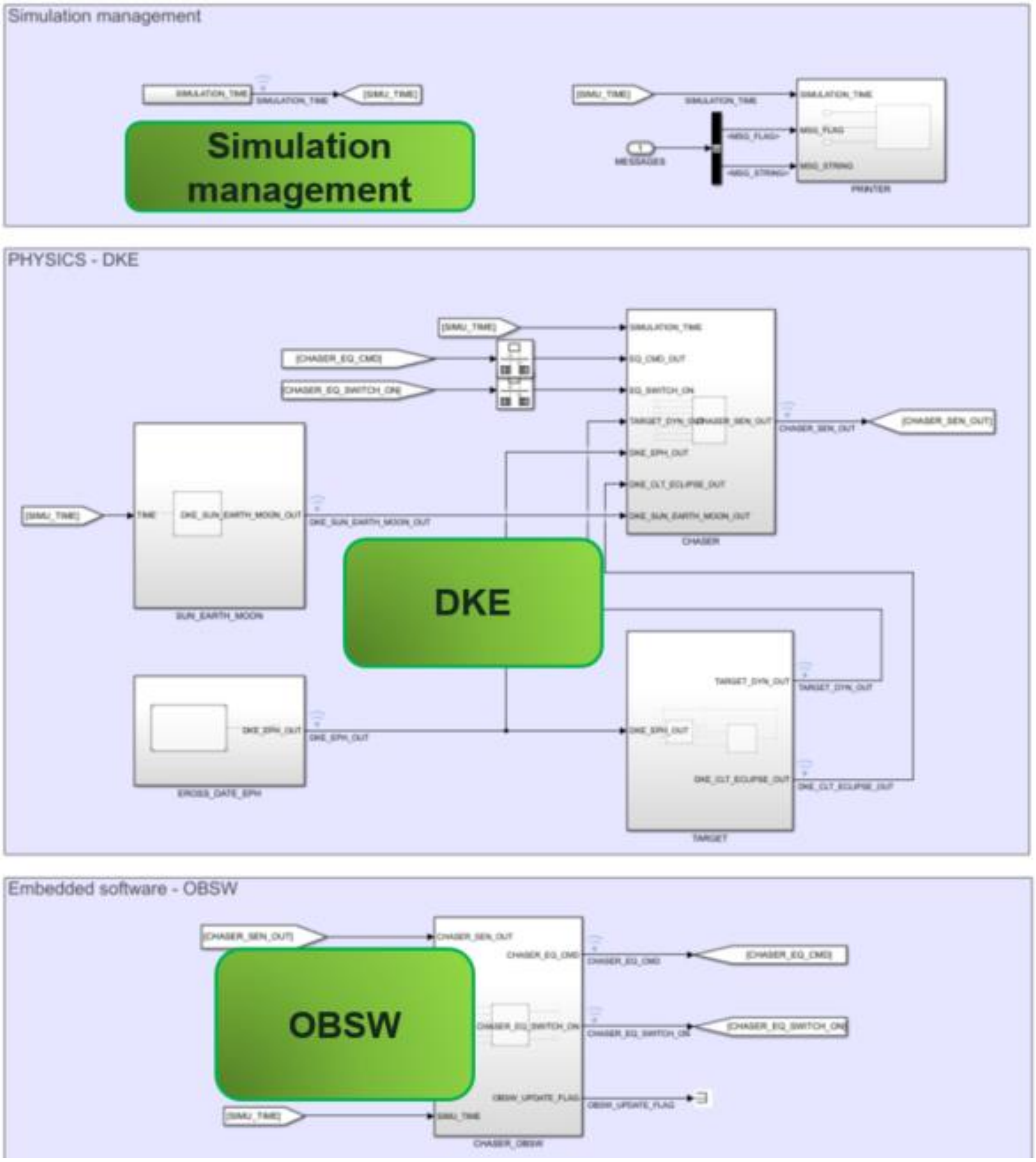

Figure 8 – EROSS IOD GNC simulator overview

The GNC Functional Engineering Simulator (FES) is the AOCS/GNC high fidelity simulator and is realized in Matlab and Simulink. As it can be seen in the image above it includes three main parts: the On-board Software (OBSW) and the Dynamics, Kinematics and Environment (DKE) models and, in addition to those a Simulation Management section which simply gives the simulation time and prints the messages relative to time elapsed, TC sent, GNC modes and phases switch. In GNC FES the active vehicle is named CHASER while the passive vehicle is named TARGET due to internal naming heritage, but in the EROSS SC scenario naming the CHASER designates the Servicer active vehicle, while the TARGET passive vehicle is the Client one.

The OBSW includes the Embedded Software applications. Only Servicer OBSW, named CHASER OBSW due to the aforementioned naming conventions, is implemented in this sub-block. On the other hand, a simplified Client GNC application is integrated in the TARGET DKE block.

The CHASER_OBSW block includes the GNC application of the Servicer and is under the responsibility of the GNC team from design, validation until the automatic code generation of the GNC application for OBSW integration in the On-Board Computer (OBC).

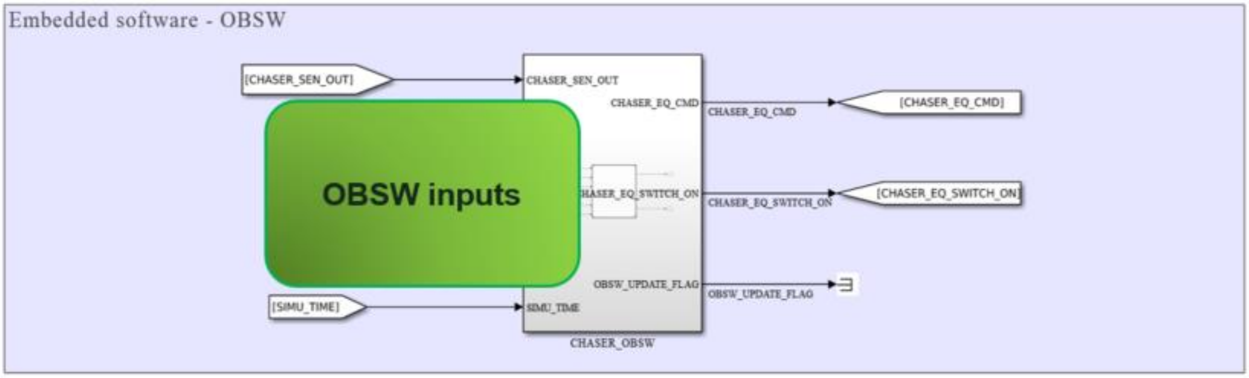

Figure 9 – Servicer OBSW

The GNC application includes different modules: the GNC manager to manage the TC, the modes and the scheduling of the algorithms, the SDP (Signal Data Processing) to perform the data processing of the raw data coming from the equipment, the NAV (Navigation) module which includes all the algorithms for Navigation, the CTL (control) which includes all the control functions for the inertial and relative motion, the GDC (Guidance) which manages all the guidance laws and algorithms and the CMD (command) with the commanding of the actuators coming from the embedded software. All these functions are extended from the traditional inertial versions for a single spacecraft, to meet the formation flying requirements in the rendezvous scenario.

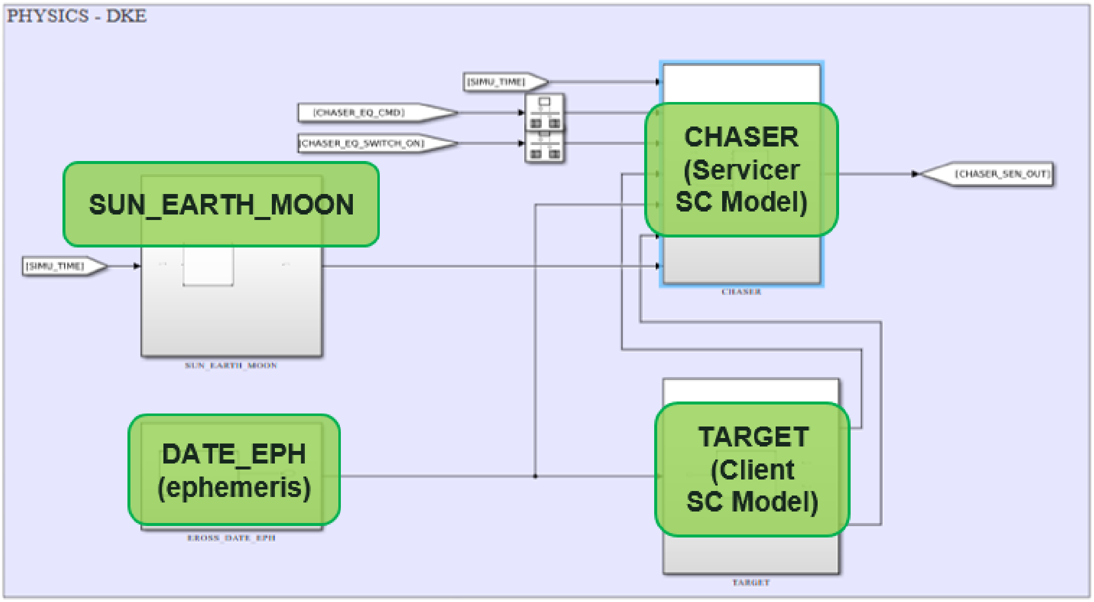

Figure 10 - EROSS DKE models

The DKE includes four main blocks: SUN_EARTH_MOON, DATE_EPH, CHASER and TARGET. The two first blocks compute the ephemerides of the celestial bodies and the date and time references, while in the Servicer and Client blocks the full Dynamics, Kinematics and Environment of the two vehicles is modelled.

The Servicer and Client models on the one hand both include the modelling of the 6DoF rigid body dynamics and the characterization of the external environment and disturbances which are modelled with an internal library written in ADA for execution efficiency with multibody systems mixed with long orbital scenarios. The environment modules simulate the features of the space environment such as eclipses, atmospheric density, Earth magnetic field and gravity, while the disturbance module includes air drag, solar radiation pressure and the magnetic torque. The dynamics module calculates the propagation of the spacecraft position and orientation considering the external forces coming from the environment and from the actuators. This module also calculates the internal forces between mobile parts of the spacecraft and updates the position and orientation of the local frames used for each component.

As already mentioned before the Client model includes a simplified GNC application enabling Local Orbital Frame pointing of Client axes.

In the Servicer physical model the equipment performance models are included. These models are realized based on the technical documentation and characterization of the specific equipment and are hereafter listed.

- Actuators models:
    - Reaction Wheels cluster (x4),
    - Thrusters set (x8),
- Inertial sensors:
    - Star tracker,
    - IMU unit,
    - GNSS;
- Relative sensors:
    - LIDAR,
    - SVS ("Servicer Vision System") with Narrow and Wide Angle Cameras.

The performance models of the relative sensors (both LIDAR and SVS NAC/WAC cameras) allow to represent the performance on prepared and unprepared client cases based on different parameterization of the block. In the prepared case the client is equipped with retro-reflectors and markers which support the relative sensors and increase their operational range and their accuracy. On the other hand, in the unprepared case, these supports are missing and the resulting performances are poorer.

According to the two scenarios the performances of the sensors are different, however the models are fully tuneable and all the features can be set according to the performance provided by the supplier based on analytical knowledge of their unit, or based on experiments performed with mock-up.

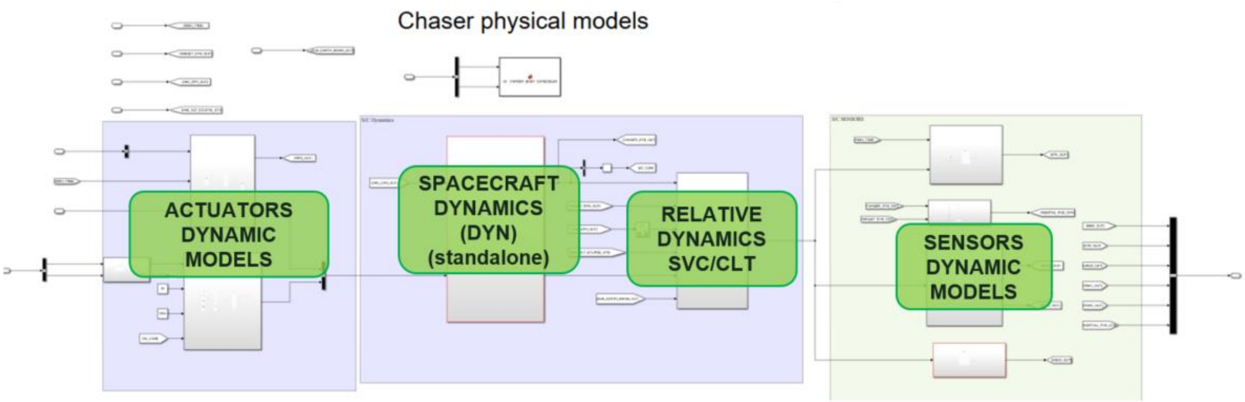

Figure 11 - Servicer physical models

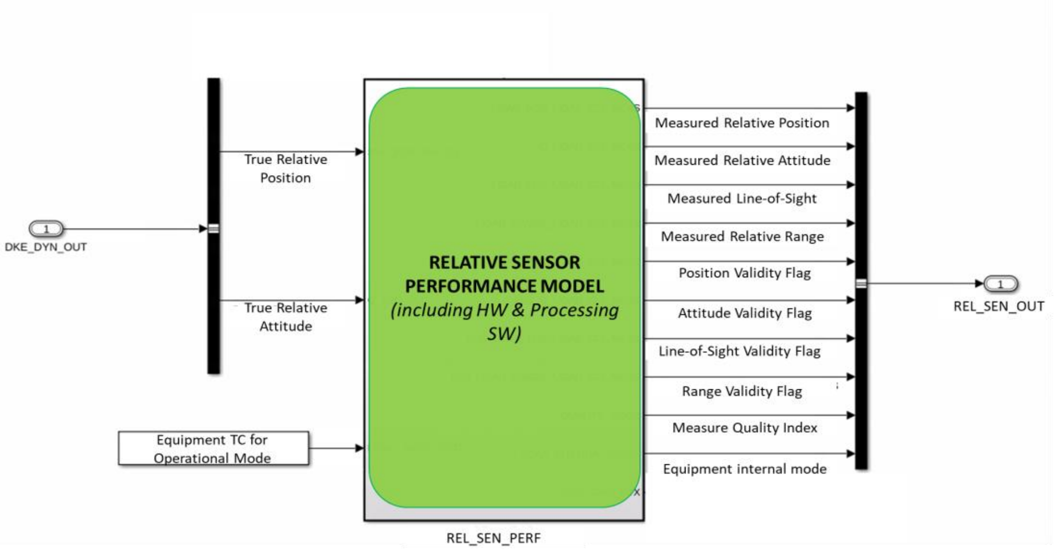

Figure 12 - LIDAR and NAC/WAC performance model architecture

Into more details, a 3σ noise is applied on the Line-of-Sight (LoS), on the relative range and on the 6DoF relative states in position and attitude, in order to output the 1/2/3/6DoF states measured in the current operational mode. This is modelled in such a way that the performances are dynamically dependent on the real range between the Servicer and the Client. Likewise, the relative distance at which a new type of measurement is available can be parametrized, as well as the minimum range to receive measure and their dependency upon the illumination conditions of the Client.

Performance models of the sensors also provide validity flag of the measures to support the GNC and FDIR implementation within the OBSW. All the sensors measurements are then collected in the bus REL_SEN_OUT and directed toward the OBSW.

In the image above the I/O of the relative sensors models is shown. As it can be seen, in addition to each measure (LoS, range, relative position in the sensor frame and attitude of the client with respect to the sensor frame), there is the corresponding quality or covariance computed by the sensor's algorithms implemented in the performance model such that this information can be exploited by the GNC application and filtering stage.

The GNC application has an architecture which is independent from the current main relative sensor used in the control loop and switch from one to the other as long as the states remains sufficiently continuous.

A Signal Data Processing function receives as input the measures coming from all the relative sensors and, according to the information of the relative sensor selected, it provides to the relative navigation filter the measures of the selected sensor in the control loop along with the covariance matrices and the validity flags of the measures. With these inputs combined with the inertial sensors also modelled (Start tracker, IMU, GNSS), the GNC NAV Mode is able to correctly perform the estimation of the relative Client-Servicer position and velocity, and even to reconstruct the Client inertial states to further feed the Guidance and Control stages. All the GNC and Sensors setup can be tuned, and the main relative sensor used in the loop, or the Navigation mode can be changed by TC.

The GNC architecture introduced earlier has been implemented in the OBSW block of the GNC simulator, and then the GNC simulator has been used to demonstrate the validity and performances of the different algorithms along the overall rendezvous Conops. These results are shared in the next section.

5. Simulation Results

This section covers the simulation results obtained though the overall Conops, from the Hoping phases in Far-range rendezvous, until the Forced motion used to cover the short-range rendezvous until the Client capture. A final paragraph reviews the main GNC challenges faced and to be solved for the final flight implementation.

5.1 Simulation Scope

Simulation campaign objectives were to validate the robust control design and the Conops strategy. Spacecraft properties such as mass, centering, inertia, flexible modes characteristics, actuators and sensors accommodation and performance were scattered to cover both design and in-orbit uncertainties.

Orbital parameters and mission date were scattered as well to cover all possible mission environment.

Simulation scenarios cover all Conops phases introduced above from the long-range phase to the robotic capture. Into more details they encompass:

- Station-Keeping at Hold-Point 2,
- Hopping from Hold Point 2 to 3,
- Station-Keeping at Hold-Point 3,
- Forced-Motion from Hold-Point 3 to 4,
- Station-Keeping at Hold-Point 4,
- Forced-Motion from Hold-Point 4 to 5,
- Station-Keeping at Hold-Point 5,

Nota bene: The final robotic capture phase is not simulated in this GNC validation work but is studied separately along with the robotic partner DLR.

The following results show typical runs with a robust tuning to the previous listed uncertainties and external disturbances. For sake of completeness, only a subset of all results is introduced and the main GNC challenges are summarized.

5.2 Main results

5.2.1 Station Keeping

For propellant consumption optimization, the Station Keeping strategy is based on a 5% spherical control box in which the servicer remains in free drift. The manoeuvers are performed when the servicer is reaching the boundaries of this box. Doing so, it maintains the spacecraft mostly in free drift instead of performing a consuming continuous control which would more accurate but much more consuming in terms of fuel

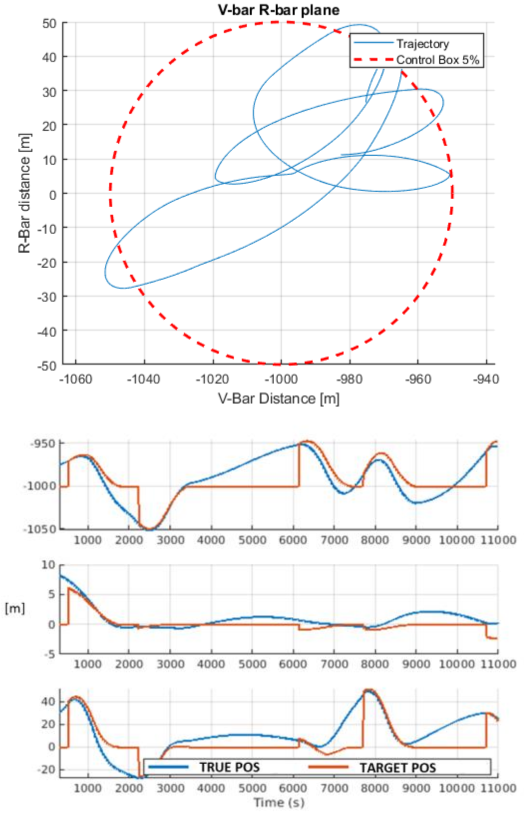

Figure 13: Station-Keeping trajectory in V-bar/R-bar plane (up) and Relative Position in Client LOF (bottom)

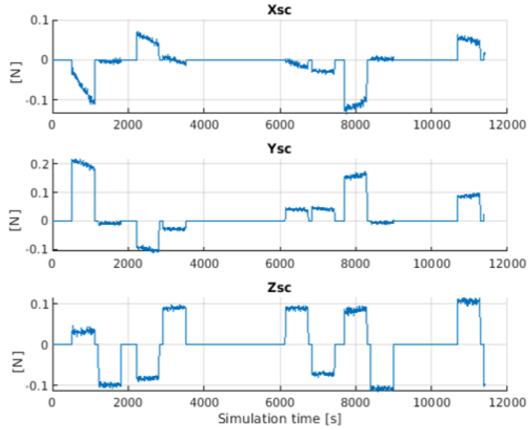

Figure 14: Resulting Thrusters Force in Station Keeping

5.2.2 Hoping

The next plots shows the Hoping manoeuver followed by station keeping phase. This manoeuvre is near impulsive in order to minimize the fuel consumption as well [18]. It is later followed by a correction manoeuvre to reach the control box of the next Hold Point with maximum safety and accuracy

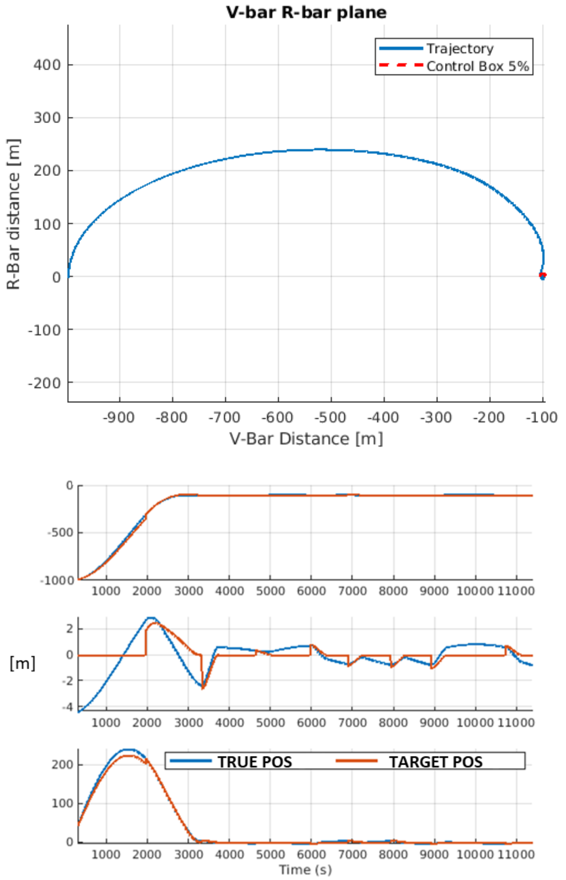

Figure 15: Hoping trajectory in V-bar/R-bar plane (up) and Relative Position in Client LOF (bottom)

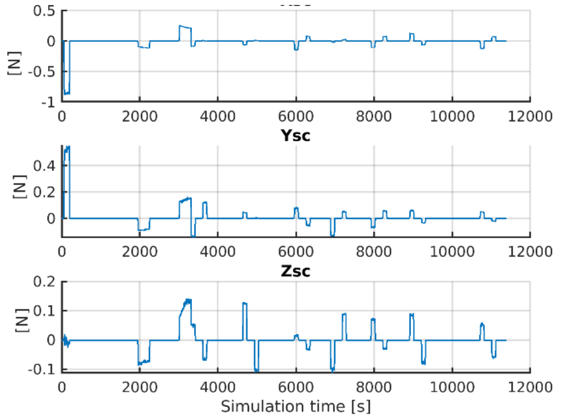

Figure 16: Resulting Thrusters Force in Hoping

5.2.3 Forced motion

The Forced-motion manoeuvre are performed continuously by a closed loop control in relative position in order to approach safely the client within the Keep Out Zone. This requirement is mandatory from the ESA Guidelines mentioned earlier. Position and attitude of the servicer spacecraft are continuously controlled during this phase by using the relative sensors relative states measurements in both position and attitude.

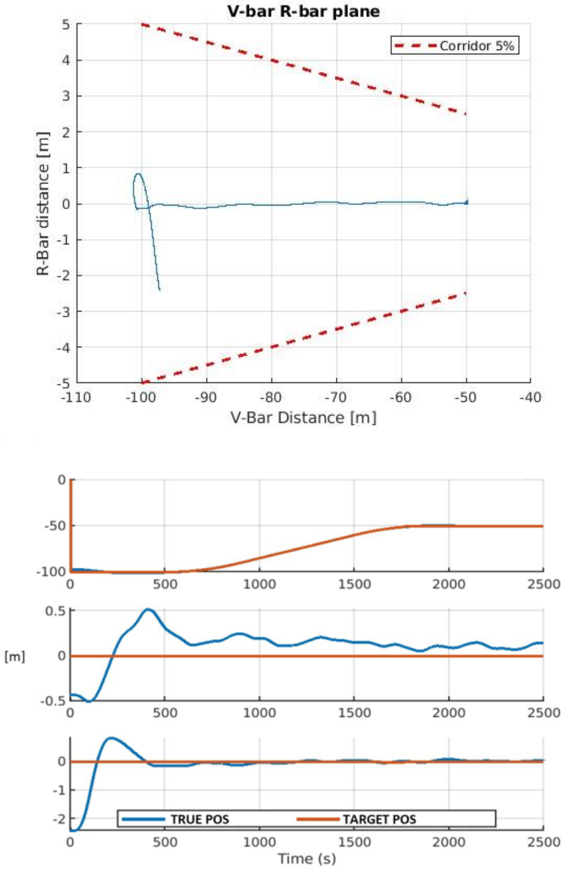

Figure 17: Forced motion trajectory in V-bar/R-bar plane (up) and Relative Position in Client LOF (bottom)

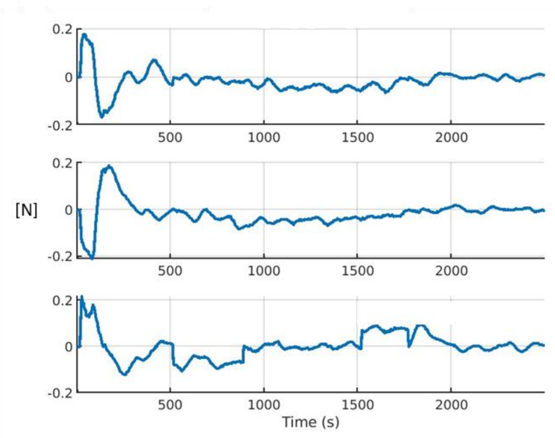

Figure 18: Resulting Thrusters Force in Forced Motion

5.3 Results discussion

This simulation campaign has demonstrated the robustness of the overall GNC design with respect to chosen rendezvous strategy and despite the applicable uncertainties. It thus validate the Conops approach used in the EROSS SC program.

Into more details, the robustness test campaign carried out highlighted the following GNC challenges for the flight implementation:

- Arrival covariance at initial Hold Point is very high and must be closely synchronized with the relative sensors operational range to correct this relative position error;
- On-board corrections for the different Hoping are crucial for the accurate retargeting of the hoping end point;
- These hoping correction manoeuvres can be extremely fuel-consuming when the manoeuvres execution accuracy or the external disturbances amplitude are tuned to the worst cases values;
- The usage of an active relative sensor like a LIDAR leads to a successful rendezvous in terms of accuracy and Conops approach;
- The usage of a passive relative sensor like the NAC/WAC cameras impacts strongly the autonomous manoeuvres accuracy due to the navigation performance degradation with the sun light variation. Conops adaptations are mandatory to cope with this accuracy deviation.
- The rendezvous has been successfully demonstrated with the LIDAR for the prepared and unprepared Client panels using different performance models of the relative sensors.

6. Conclusion

Overall the current paper has provided a quick overview of the GNC robustness campaign results obtained in the scope of the EROSS IOD / EROSS SC program. The GNC architecture is based on a dual relative sensor chain with active and passive sensors in order to evaluate different sensor configuration for the future operational missions. As well, the Client design with prepared and unprepared panels allows to mature the impact of embedding specific features for the future spacecraft in order to maximize the safety and accuracy of their future servicing.

The next stage of the program is to reach the Critical Design Review and to target a launch in 2026 for the in-flight demonstration of these operational concepts and equipment.

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