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Close-Proximity Operations Design, Analysis, and Validation for Non-Cooperative Targets with an Application to the ClearSpace-1 Mission

José Vasconcelos [1,*], Serena Gaggi [1], Tiago Amaral [1], Charles Bakouche [2], Adina Cotuna [3] and Ana Friaças [1]

[1] Deimos Engenharia, Av. Columbano Bordalo Pinheiro 75, 9 A1, 1070-061 Lisboa, Portugal; serena.gaggi@deimos.com.pt (S.G.)
[2] Clearspace, Rue de Lausanne 64, 1020 Renens, Switzerland; charles@clearspace.today
[3] European Space Agency, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands; adina.cotuna@esa.int
* Correspondence: jose.vasconcelos@deimos.com.pt

Abstract: This paper addresses the design, analysis, and validation of safe close-proximity operations around uncooperative targets, with an application to the ClearSpace-1 (CS-1) mission. It is focused on the areas of Guidance, Navigation, and Control (GNC), and Mission Analysis, due to their criticality for the success and safety of this kind of operation. The relevance of the concepts, of the GNC solutions, and their validation is demonstrated for the case study of CS-1, a reference mission for the rendezvous, capture, and de-orbiting of an uncooperative target (i.e., the VESPA payload adapter). It is shown how the design approach can be adopted for the Concept of Operations of CS-1, covering the definition of keep-out zones, corridors, and GO/NO GO criteria, for assessing the passive safety of trajectories, and for the incorporation of active safety strategies. The analysis is adopted for functional chains such as the Navigation and Control, and the combination of a prototyping and a high-fidelity simulator is adopted for directed Model-in-the-Loop Monte-Carlo campaigns. The outcomes are intended to support the industry in the development of Close-Proximity Operations similar to that of CS-1. These can be adopted in a wide variety of missions, including Active Debris Removal and In-Orbit Servicing. In particular, the adopted concepts are a key contribution to the standardization of Close-Proximity Operations for non-cooperative rendezvous missions, and act towards a sustainable and safe commercial application.

Keywords: GNC; Active Debris Removal; close-proximity operations; safety; verification and validation

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1. Introduction

In recent years, continuously increasing attention has been put on close-proximity operations (CPO) as they allow many fundamental actions for space sustainability, like refueling, inspection, and debris removal, among others. This rising interest has motivated the need for standard and internationally accepted requirements, so that the operations can fulfill their goal effectively and safely. Many activities are found within this scope: the International Rendezvous System Interoperability Standard (IRSIS) [1] was created to define standards for on-orbit crew operations, fully automated rendezvous and docking, and joint collaborative endeavors using different spacecraft; the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) [2–5] focuses on technical and operations standards for On-Orbit Servicing (OOS) and Rendezvous and Proximity Operations

(RPO), and the outcome can be found in the ISO 24330 document [6]; OOS was also the object of a French Space Operations Law (LOS) update issue [7,8]; and the Japan Aerospace Exploration Agency (JAXA) provided basic requirements for OOS, listed in the "Safety Standard for On-Orbit Servicing Missions (JERG-2-026(E))" [9]. All these documents can be compared and integrated into the European Space Agency (ESA) Guidelines on Safe Close-Proximity Operations [10].

The demonstration that the requirements and guidelines are well defined and fit for purpose is supported by the development and application of verification and validation (V&V) methods. The collection of guidelines abovementioned was thoroughly discussed, revised, and expanded in the study "Verification and Validation of Rendezvous and Proximity Operations Safety" [11], as a result of the collaboration of ESA and the industrial partners Thales Alenia Space, GMV, and Deimos. The aim of that study was to first derive CPO guidelines, then define verification and validation approaches, and finally demonstrate the V&V approaches for both a cooperative and a non-cooperative client.

Among the different applications of Close-Proximity Operations, this paper focuses on Active Debris Removal (ADR). In the ADR field, a large number of references can be found, covering the different aspects of this particular kind of mission. An extensive state-of-the-art review of ADR technologies is provided in [12], which gives an in-depth trade-off of different capture mechanisms while presenting the progress that has been made in the field since the 1990s. State-of-the-art space technologies are described therein. In particular, the use of robotic arms is widely discussed, highlighting applications with a single arm [13–15], dual arms [16], and multi arm [17,18]. Similar to robotic arms, the tentacles capture method is also covered [19]. Another presented capture mechanism makes use of a net shot from the active satellite that embraces the debris element, closes around it, and drags it to the desired position [15,20,21]. The harpoon method is also proposed due to its ease of testing and cost efficiency [15,22]. Then, the tether-gripper method is introduced [23]. Finally, other technologies are discussed, such as magnetic capture [24], and other ways to alter the trajectory of the debris and force their re-entry through laser systems [25] or space mist [26].

Regarding programs, it is worth mentioning ESA's e.Deorbit, which was born in 2012 with the objective of removing a single large ESA-owned space debris from the LEO protected zone [15]. Within this program, different technology development studies were conducted, focusing on both capture mechanisms, and GNC and avionics aspects. A notable ADR mission is RemoveDebris: launched in 2018, this mission was a low-cost in-orbit demonstration where a microsatellite was released and then successfully recaptured two debris targets with a net and a harpoon [21]. Another successfully conducted mission is ELSA-d, in which the target was captured using a magnetic docking technology in 2021 [24].

In general, the GNC aspects of ADR pose a significant challenge in the development of the mission, especially when considering a non-cooperative target, and hence the technical descriptions in industrial publications often do not provide a fine level of detail [15,21,24]. Nonetheless, there are some key elements that are commonly assumed in ADR operations. For mission design and guidance, the use of passively safe trajectories to approach the target is widely employed [24,27]. For navigation, angles-only navigation [28] is gaining increasing attention, especially for far-mid range phases, while visual-based navigation [21] is commonly used when approaching the target. Finally, for the control, a particular focus is put on the use of six Degrees-of-Freedom (6DOF) control and forced motion in the close-proximity phase [29].

This paper addresses the topic of close-proximity operation for non-cooperative targets, using, as reference, mission ClearSpace-1 (CS-1), whose importance is widely recognized, and focuses on the areas of design and validation of Guidance, Navigation, and Control

(GNC), and Mission Analysis (MA). The main contributions of the paper are the consolidated elaboration of Close-Proximity concepts and guidelines, stemming from [11], their application to the GNC/FDIR solutions considered for CS-1, and a positive demonstration of the V&V compliance by design, analysis, and testing. The GNC solutions and V&V approaches described in the paper have an application to ADR and IOS solutions in general, and can be standardized in aspects such as the following: vision-based navigation for close-range rendezvous with illumination constraints, robust control for performance and stability robustness of high-precision robotic capture, passively safe approach and target inspection through Relative Orbital Elements (ROE) guidance with vector collinearity, active safety with the Cancel and Collision Avoidance Maneuver (CAM), an efficient V&V of solutions through a combination of fast and of high-fidelity simulators, allowing us to identify properly the worst case conditions in the former, and a detailed analysis and confirmation of the results in the latter.

Whereas the requirements elaborated in [11] have a formal and self-contained formulation, in this paper they are embedded in the body of the text, to provide for context and improve readability. Likewise, the V&V, by design and by analysis, are addressed explicitly in [11], whereas in this paper these are inherently associated with the description of the design options and their analysis, respectively. Finally, the V&V by testing corresponds to the Monte Carlo campaign, as described in a dedicated section.

This paper is organized as follows: Section 2 outlines the CS-1 case study; Section 3 defines the CPO concepts and demonstrates their validity by design and analysis; Section 4 addresses the GNC/FDIR system validity, also by design and analysis; and Section 5 presents the validation by Model-in-the-Loop testing. Finally, Section 6 discusses the conclusions and the way forward of this work.

2. CS-1 Scenario and Rendezvous Phases

The primary objective of the ClearSpace-1 (CS-1) mission is to demonstrate the rendezvous, capture, and de-orbiting of the VESPA payload adapter, launched aboard VEGA in 2013.

Figure 1 provides an overview of the mission, showing the sequence of operations conducted, from the launch of the servicer to the deorbit of the stack configuration, including the key aspects of close-range rendezvous and target capture using a deployable robotic arm. In the bottom right of the figure, the target, the VESPA payload adapter, is shown.

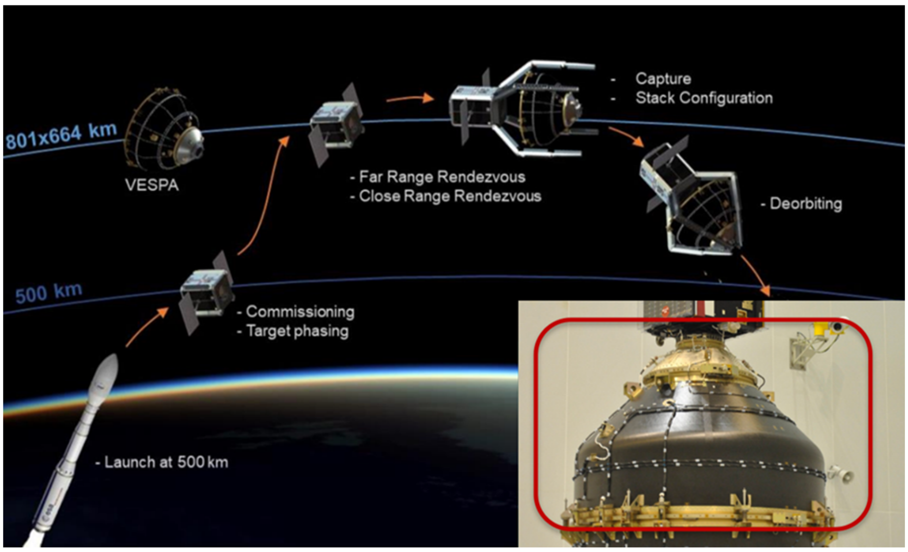


Figure 1. ClearSpace-1 mission overview.

Note that the figure presents a simplified overview of the CS-1 mission. The full mission includes strategies for efficient station keeping and advanced capture strategies (co-rotation) for high-angular target motion. This simplification is deliberate to focus the testing and demonstration of results on the main close-proximity phases.

Figure 2 shows the sequence of the CS-1 mission's phases, already illustrated in Figure 1, as well as the AOCS/GNC involved. A standard AOCS is combined with GNC for the rendezvous for the approach and capture; a mission-specific AOCS will be adopted for post-capture and de-orbiting. This paper focuses on the Rendezvous operations, that include Client Phasing, Far Rendezvous, Close Rendezvous, and Capture.

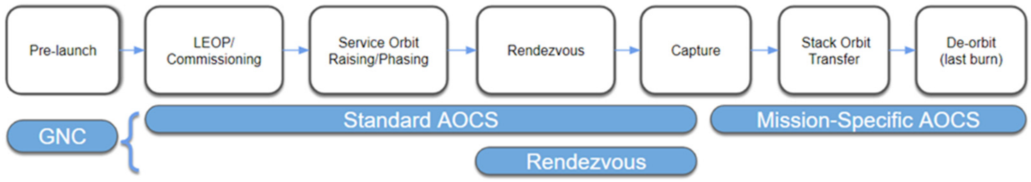


Figure 2. Phases of the ClearSpace-1 mission.

In particular, Client Phasing decreases the difference in the true anomaly of the servicer with respect to the client in a safe way, using the Relative Orbital Elements (ROEs) approach of walking safety ellipses [30,31]. A walking safety ellipse is a drifting out-of-plane elliptical periodic relative motion around the target that never crosses its velocity vector [32]. In this way, the chaser moves on the surface of a cylinder, approaching the target in a natural motion that avoids any collision with the target, as depicted in Figure 3. The technical details on ROEs are discussed in Section 4.3.

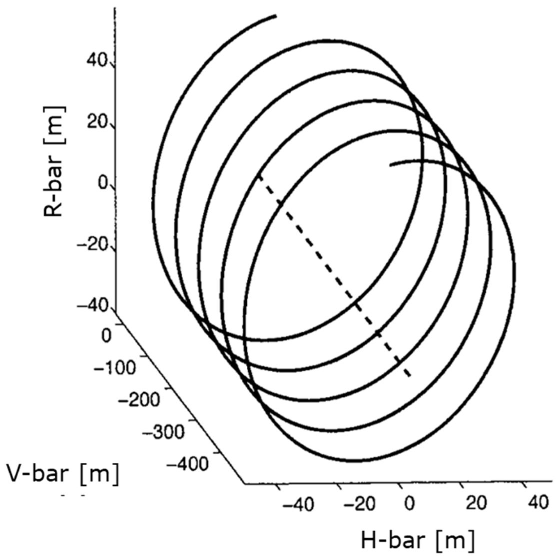


Figure 3. Illustrative example of relative motion with a walking safety ellipse [30]. Full line represents the chaser's motion, and the dashed line represents V-bar direction.

Then, in the Far Rendezvous phase, Fly-Around trajectories with impulsive control are used, allowing the servicer to get closer to the client, while also serving the purpose of inspecting it. Following the client inspection, the servicer transitions to forced motion control to reach a holding point known as the Formation Keeping Point (FKP), where the relative position is maintained until the next phase begins. Finally, during Close Rendezvous and Capture phases, six Degrees-of-Freedom (6DOF) forced motion guides the servicer towards the capture of the client.

3. Close-Proximity Concepts Design and Analysis

This section addresses the concepts that are adopted in developing safe Rendezvous and Close-Proximity Operations, and presents the solutions applied in CS-1. Such concepts provide a summary of the work presented in [11], and are compliant with ESA CPO guidelines [10]. This paper shows how the CS-1 mission is designed to comply with the concepts, complemented by an analysis of the desired properties.

The reference frame used throughout this work is the Local Vertical, Local Horizontal (LVLH), defined as follows: the origin is in the target, the Z-axis (R-bar) is aligned with the radial direction, pointing towards the Earth, the Y-axis (H-bar) is in the opposite direction of the angular momentum vector of the orbit, and the X-axis (V-bar) completes the orthogonal frame, following the right-hand rule [31].

3.1. Phases

A general Phase is defined as a predefined mission operations segment with an explicitly defined start. The phases of the Concept of Operations considered in this paper are Client Phasing (CP), Far Rendezvous (FR), Close Rendezvous (CR), and Capture (CAP). In the scope of the "Verification and Validation of Rendezvous and Proximity Operations Safety" project developed for ESA, the following definitions were proposed and adopted [11], as illustrated in Figure 4:

- Client Phasing Phase: The mission phase outside of the Approach Zone (AZ) where the orbital parameters of the client and servicer are brought closer to one another. This phase is usually led by the ground segment and ends at the GO for the AZ decision point (i.e., before the GO decision to enter the AZ).
- Far Rendezvous Phase: The first phase of the Close-Proximity Operations. This phase is initiated at the GO for the AZ decision point after a GO/NO-GO decision is taken with a positive result to enter the AZ, and ends at the GO for the Keep Out Zone (KOZ) decision point, i.e., before initiating the entry into the KOZ. As a higher level of on-board autonomy is required during CPO, the Far Rendezvous Phase usually corresponds to a handover from the Ground Segment to Space Segment.
- Close Rendezvous Phase: The mission phase that is initiated at the GO for the KOZ decision point after a GO/NO-GO decision is taken with a positive result to enter the KOZ through the Approach Corridor, and ends at the GO for the Capture decision point.

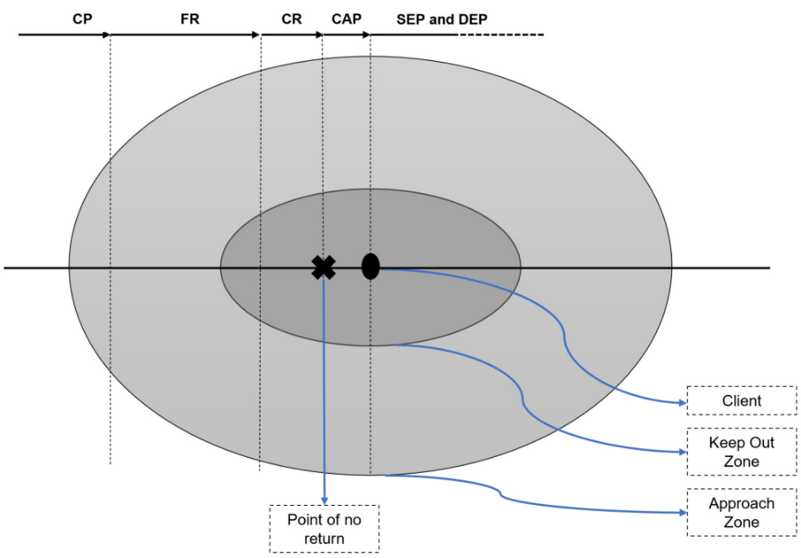


Figure 4. Illustration of the Mission Concept, extracted from [10].

For the sake of completeness, it should be mentioned that the capture phase is the mission phase that begins with the GO decision at the Capture decision point. After the GO, the maneuvers proceed beyond the Point of No Return, and a physical connection is initiated to accomplish a stable stack. The phase ends when the stack configuration is confirmed by the Servicer.

3.2. Zones

A zone is a predefined envelope (set of states, e.g., position and velocity) during the proximity operations mission timeline. The fundamental zones in this work are the following [11]:

- Approach Zone (AZ): The zone around the client that can be entered only if the servicer has on-board access to a continuous reliable estimate of the current relative client-servicer position to ensure mission safety. The parameters of the shape and size of this zone are mission specific.
- Keep Out Zone (KOZ): The zone around the client where a potential collision could occur. Inside the KOZ, the servicer must follow the Approach corridor (during the Close Rendezvous Phase). The shape and size of the zone are mission specific. In this zone, during the Close Rendezvous Phase, the servicer must ensure a 6DOF relative closed loop control.

The association of phases and zones is depicted in Figure 4. The requirements associated with the definition of such zones, the need for transition to be intentional, and the separation of AZ and KOZ are found in [11]. For readability and conciseness, these can be summarized as follows:

- The design of the servicer integrates the notion of the zones, in which the servicer enters only intentionally;
- The servicer is able to follow any trajectory within the AZ as long as such a trajectory does not enter the KOZ at any point during its execution.

These requirements can be verified and validated, firstly, by a proper definition and sizing of the zones:

- The Approach Zone is sized such that it defines an effective separation between closing trajectories (Client Phasing) and fly-around trajectories (Far Rendezvous), which are to be performed in the AZ itself.
- The Keep Out Zone design is based on the geometry of the client and the servicer: the KOZ is a sphere around the client, with a radius equal to the worst-case sum of the radii of the servicer and the client, with a 50% margin.

The zones are further validated by an extensive testing of the trajectories, presented in Section 5.

3.3. Decision Points

Decision points are operational points in which the mission timeline is progressed if a set of mission-dependent decision criteria is successfully met.

For the CS-1 case, the points are inherently placed at the entrance of the Approach Zone, at the entrance of the Keep Out Zone, and at Capture, as illustrated in Figure 5. The entry in these zones is subject to the positive assessment of GO/NO-GO conditions. If the GO conditions are not met, the entry into the zone does not proceed and, if needed, relevant actions are taken to ensure a safe relative trajectory.

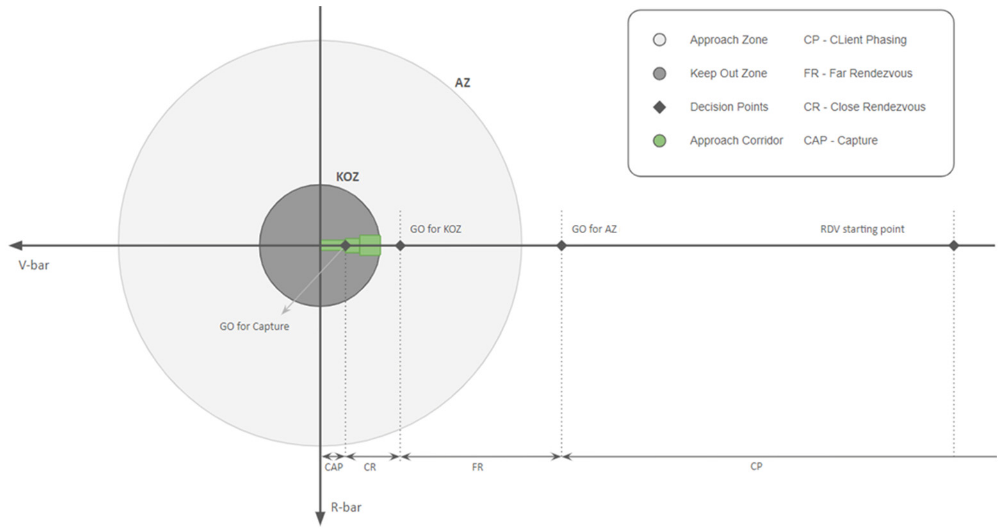


Figure 5. Illustrative summary of the zones and decision points of the CS-1 mission.

The CS-1 decision criteria are related to the operationality of all critical systems, and to the commissioning of the associated navigation and actuation systems, being defined as follows:

- GO for AZ—Commanded by Ground
  - All critical systems are operational (such as sensors, actuators, battery level, and having enough propellant);
  - Positive commissioning of a relative-state estimation;
  - Positive commissioning of impulsive maneuvers.
- GO for KOZ—Commanded by Ground
  - All critical systems are operational (such as sensors, actuators, battery level, and having enough propellant);
  - Positive inspection of the client;
  - Successful deployment and validation of the robotic arms;
  - Positive initialization and commissioning of 6DOF pose estimations;
  - Positive initialization and commissioning of combined forced motion and 6DOF navigation.
- GO for Capture—Autonomous
  - All critical systems are operational (such as sensors and actuators);
  - The 6DOF estimation and control are operational and reliable;
  - Servicer is compliant with the approach corridor (operational forced motion).

Before the GO for the KOZ is given, the correct functioning of the 6DOF navigation and control chain is tested with a station keeping at IPP. Note that, before the GO for KOZ, a forced motion, i.e., 6DOF control, is already performed to go from the Formation Keeping Point (FKP) to the Initial Proximity Point (IPP), as described in Section 4.3. However, such a transition is performed using 3DOF navigation (see Section 4.1 for details), and therefore cannot be considered as a reliable proof of the proper functioning of the 6DOF controller for the sensitive operation of entering the KOZ, as the tuning may differ.

The criteria to consider the chain to be successfully working are the following:

- Attitude control error.
- Position control error.
- 6DOF navigation filter covariance.
- Pose initialization tracking success.

- Pose tracking success rate.

All of these criteria are under pre-defined thresholds and checked by Ground teams.

To summarize, the servicer is permitted to enter a designated zone only after meeting a set of conditions that are verified at a decision point, thus validating the requirements associated with decision points.

3.4. Corridors

Corridors are spatial and dynamic envelopes to be followed by the servicer in a specific zone. Their definition and sizing are mission specific, and a violation triggers an active safety action. This safety action is associated with the concepts of Abort and Cancel, which are hereby defined as follows:

- Abort is the operation to safely terminate the operations if mission safety cannot be ensured. It consists of a maneuver that places the servicer in a passively safe trajectory.
- Cancel is the sequence of maneuvers that interrupts the operations if approach conditions are violated, and initiates a passively safe trajectory towards a safe state, from which the operations can be resumed.

Therefore, Abort is triggered when safety is at risk, being quite aggressive in terms of action, whereas Cancel is a retreat due to a non-hazardous violation of approach conditions, that still allows for a more controlled withdrawal. Any of these contingency maneuvers are designed to place the servicer in a reference point (Cancel) or in passively safe trajectories (Abort) from which recovery can be performed and nominal operations resumed.

The Abort and Approach corridors are closely related to the Abort and Cancel actions. For CS-1, an illustration of the Abort and Approach corridors' location within the KOZ is presented in Figure 6. The corridors were dimensioned in such a way to leave enough room for the servicer to control its position and attitude, and to accommodate a margin for the Cancel or Abort maneuvers to be performed without any physical contact with the client, as follows:

- Abort Corridor:
    - A Spatial and dynamical envelope within the KOZ, which ensures safety within its limits, and outside which mission safety is at risk (e.g., collision).
    - The Abort corridor covers distances between the entrance in the KOZ and up to the Point of No Return (PNR), after which it is no longer possible to trigger the Abort.
    - Violating this corridor results in an Abort, e.g., a Collision Avoidance Maneuver (CAM), driving the servicer to a safe trajectory, from which recovery can be initiated through a safe sequence.
- Approach Corridor:
    - A Spatial and dynamical envelope to be followed by the servicer, from the entry into the KOZ until the capture of the client, that ensures mission success.
    - Violating the Approach Corridor (blue area) within the Abort Corridor (green area in Figure 6), triggers a Cancel towards a recovery point, usually FKP. Otherwise, an Abort is initiated.

The fact that the Abort corridor does not extend to the Point of No Return for CS-1 can be explained though the nature of the Abort and Cancel maneuvers themselves. Indeed, as we get closer to the PNR, and thus to the target, the more aggressive the recovery maneuver needs to be. In the case of CS-1, the Cancel is considered not safe enough when very close to the PNR, and any violation of the approach corridor (blue area in Figure 6) leads to an Abort in that vicinity.

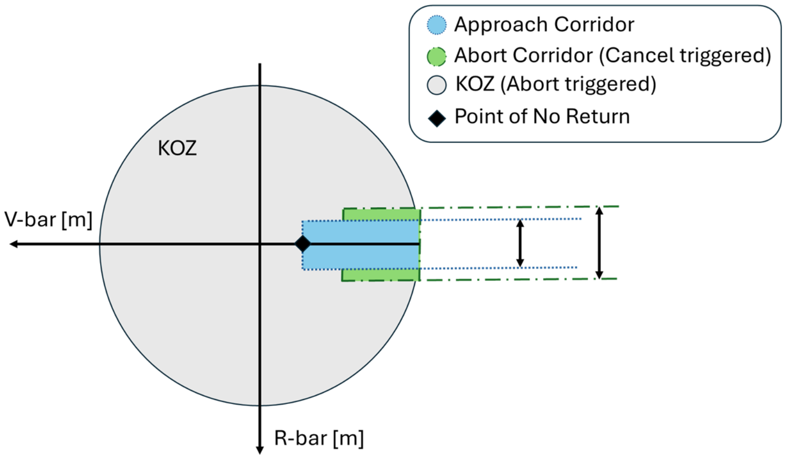


Figure 6. Abort and Approach corridors, defined within the KOZ. The gray area denotes where an Abort is triggered, the green area denotes where a Cancel is triggered, and the blue area is where no recovery action is needed.

It is relevant to remark that the design of the Abort and Cancel allows them to be commanded autonomously or by ground command, thus still meeting their purpose when triggered from within the corridors.

The zones are further validated with Monte Carlo results, as presented in Section 5.

4. GNC/FDIR System Design and Analysis

The following sections address the Navigation, Control, and Guidance subsystems, including the Fault Detection, Isolation, and Recovery (FDIR) functions. These are critical elements in the capture of non-cooperative targets, guaranteeing that the relative position and attitude are known and controlled for a proper servicing of the client.

4.1. Navigation

To ensure the general safe execution of close-proximity operations, the navigation needs to perform a relative position estimation even in the presence of environmental effects that may impact vision-based solutions, as formulated in [11], and summarized as follows:

- During the Far Rendezvous Phase and within the AZ (including in the KOZ), the servicer must have on-board access to a continuous reliable estimate of the current relative client-servicer position;
- Relative navigation solutions should perform in the presence of external or self-inflicted sources, such as the presence of Earth or other bodies in the background, and different rendezvous illumination conditions.

In CS-1, the Navigation system is designed to provide an accurate, continuous, and reliable estimate of the relative state of the servicer throughout all Rendezvous phases. The adopted architecture is depicted in Figure 7.

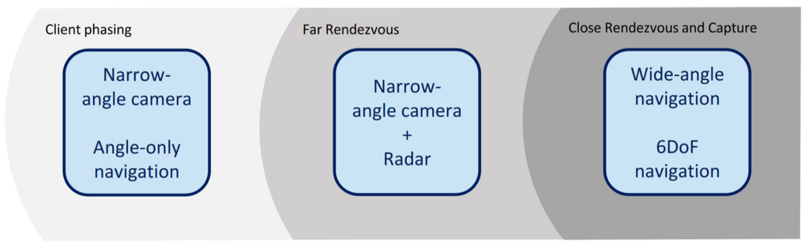


Figure 7. Navigation system architecture.

In particular, at far distances, a Narrow-Angle Camera (NAC) is used, facilitating angles-only navigation [28]. As the proximity to the client increases, radar measurements become available, augmenting navigation capabilities for an accurate 3D relative-state estimation. Finally, at close distance, the 6DOF navigation is initialized using a Wide-Angle Camera (WAC), that allows the system to provide both the relative position and relative attitude estimation. This initialization is performed at the IPP.

In Far Rendezvous, NAC line-of-sight measurements and Radar distance measurements are processed through a dynamical Kalman filter. The filter state definition is based on relative orbital elements [28], providing an estimate of the translational state.

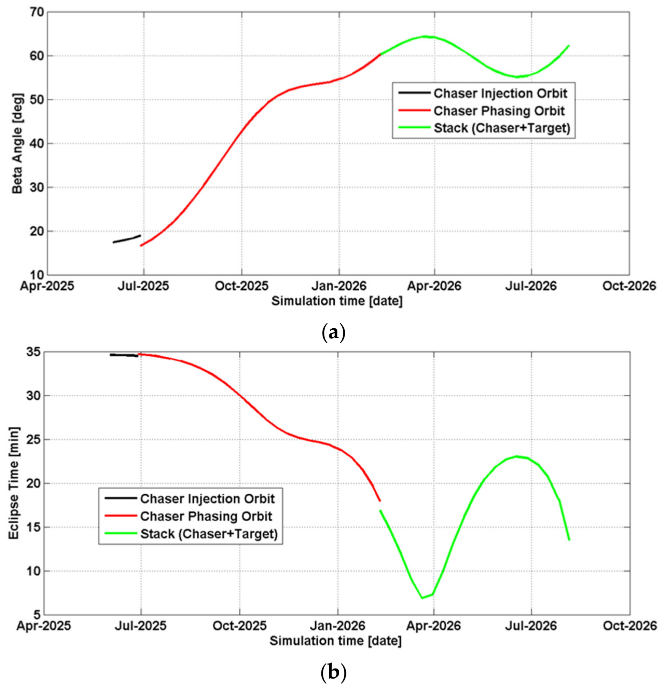
In Close Rendezvous, the WAC Pose Estimation provides 6D (relative position and attitude) measurements, processed through a second dynamical Kalman filter. The state definition of this second filter is adapted to short distances and is based on Clohessy–Wiltshire equations, which are a good approximation of the real relative dynamics in low eccentricity orbits [33].

Therefore, the navigation solution has the necessary sensors to perform in the several operational conditions, to derive the relative position during client phasing, and to compute the relative estimate during Far and Close Rendezvous.

In CS-1, a robustness against environment perturbations is anticipated in Mission Analysis. Both the navigation initialization and the guidance trajectories should satisfy constraints such as illumination conditions and the avoidance of Earth in the cameras' field of view, so that 6DOF navigation is operational during the whole path towards the target.

To this end, the elevation of the Sun in the orbital plane, usually called Beta Angle, is analyzed, together with Eclipse evolution. With a good knowledge of the elevation of the Sun in the orbit plane (Beta Angle) and eclipses cycle, then it is possible to design a trajectory that is compliant with good illumination and that does not have the Earth behind the client, for optimal navigation functioning.

The analysis of the Beta Angle and of the Eclipse cycle is shown in Figure 8. The figure demonstrates that, for the capture time instant (the transition between the phasing red line and stack green line), the sun Beta Angle is high, and that the eclipse time is short enough to ensure that all capture operations are performed under proper illuminated conditions.



(a)

(b)

Figure 8. Evolution of the predicted beta angle (**a**) and eclipse duration (**b**).

The navigation operation within the complete GNC chain is tested through Monte Carlo campaigns in Section 5.

4.2. Control

The controller is another key element. Similar to navigation, it must be robust to factors that impact its performance and reliability, and guarantee a proper controllability of the pose.

In CS-1, the controller is designed with the H-infinity synthesis [34]. Within the adopted robust control design paradigm, the model is obtained by using the so-called Linear Fractional Transformation (LFT) framework. These LFTs allow for the representation of the system to control by means of the feedback connection of the nominal plant, $G(s)$, and a block-diagonal uncertainty, $\Delta(s)$, that gathers all the uncertain/time-varying parameters of the system, as illustrated in Figure 9.

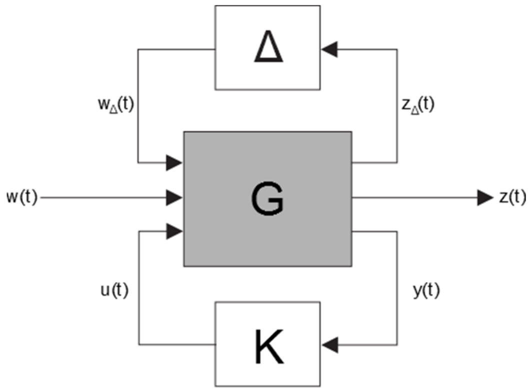


Figure 9. Control synthesis problem.

This framework ensures robustness by design against a selected set of uncertainties and non-idealities, namely the following:

- Actuation errors,
- Navigation errors,
- Servicer and stack Mass, Centre of mass, Inertia uncertainties,
- Disturbances like flexible modes and sloshing,
- Systems delays.

Concerning the exogenous disturbance and sensor noise, these are weighted by means of frequency domain filters, for the controller to reject disturbances in the desired range of frequencies and to penalize the controller sensitivity to sensor noise. On the other hand, design weights at the control outputs are used to bound the energy of the control signal, constraining the commands to the operational region of the actuator. Finally, to enforce closed-loop tracking performances, error performance weights are added to the synthesis problem, and the frequency response of the closed-loop plant is shaped in order to fulfil the performance requirements. Once the problem is posed, it is solved by using the iterative H-infinity synthesis methodology. More details on the adopted framework can be found in [35].

The effects of flexible modes can be considered with two main approaches. The first approach considers the flexible modes as a frequency domain disturbance, with a controller being synthesized for the rigid body. An analysis of the frequency response of the closed loop is performed, to guarantee that the sensitivity function from the flexible modes entry point to the attitude error indeed attenuates the effect of the disturbance at the impacted frequencies. A second approach can be adopted where the flexible modes are explicitly modelled, e.g., as described in [33], and incorporated in the plant adopted in the controller synthesis. The control optimization problem will have a higher degree of complexity, which may impact the convergence of the H-infinity iteration, but the resulting closed loop will naturally yield the desired attenuation of the flexible modes.

The resulting controller complies with the requirements formulated in [11], summarized as follows:

- An ability to control the position and attitude at any point during the mission;
- During all mission phases, compensation must take place for endogenous and exogenous perturbation forces and torques to the servicer, namely sloshing, flexible appendages, misalignment of the thrusters, thrust magnitude errors, solar pressure force, and torque;
- During the Close Rendezvous Phase and inside the KOZ, the 6DOF relative control ensures that the servicer stays within the Approach Corridor.

These properties are obtained by design and analysis. The V&V by testing is presented for the full GNC chain in Section 5.

4.3. Guidance and Passive Safety

In the application of Active Debris Removal, it is usually desirable to have an autonomous guidance system that can run independently of ground intervention. This guidance, being autonomous, is defined and validated prior to the flight.

In CS-1, the sanity of the guidance approach was performed by assessing the controllability of the approach trajectory. In particular, the sequence of operation is depicted in Figure 10 and can be summarized as the following:

- A station keeping at FKP, that is placed on the V-bar;
- Forced motion towards IPP;
- Station keeping at IPP;
- Forced motion towards the V-bar, to a point at the same distance of IPP;
- Station keeping;
- Forced motion until Capture.

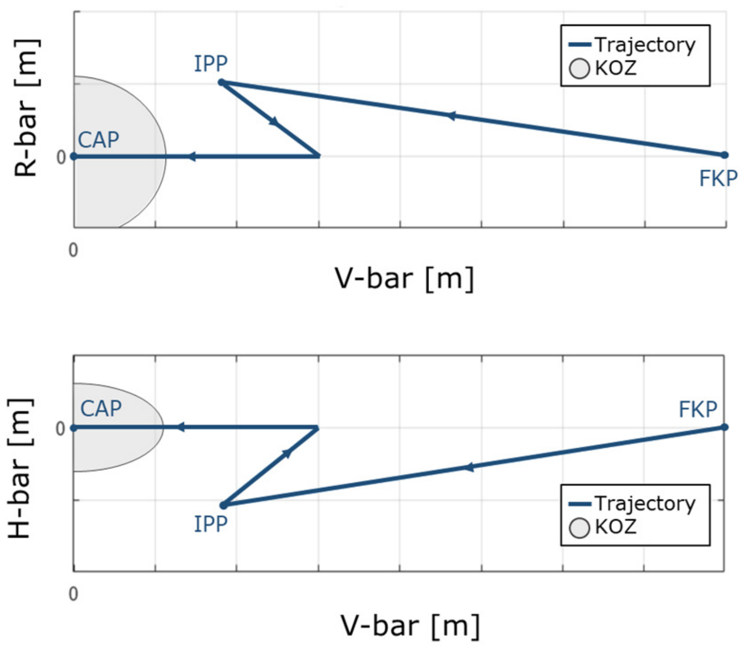


Figure 10. Close Rendezvous and Capture nominal trajectory in LVLH.

From the analysis of the relative position and velocity profiles in the LVLH frame, the required forces can be determined [31]. Namely, the time evolution of the position and velocity in LVLH coordinates can be translated into a thruster command force as described in [31]. Regarding attitude, target pointing defines the angular position and velocity as functions of the linear position and velocity. Therefore, the time evolution of angular coordinates can be computed as a function of linear coordinates. Finally, the required torques are obtained from the attitude and angular velocity using Euler's rotation equations [33].

These are illustrated in Figure 11. Note that this yields a nominal profile for the forces and torques, and hence an authority margin should be considered in order to compensate for errors and dispersions. The nominal profile is within the maximum control authority, with an 80% margin. This defines a necessary condition for the servicer to control its position and attitude pointing during the mission. If the maximum control authority is exceeded within the KOZ, then an Abort or Cancel are commanded, as defined in Section 3.4; if this happens outside the KOZ, then a Cancel is initiated towards a recovery point, usually FKP.

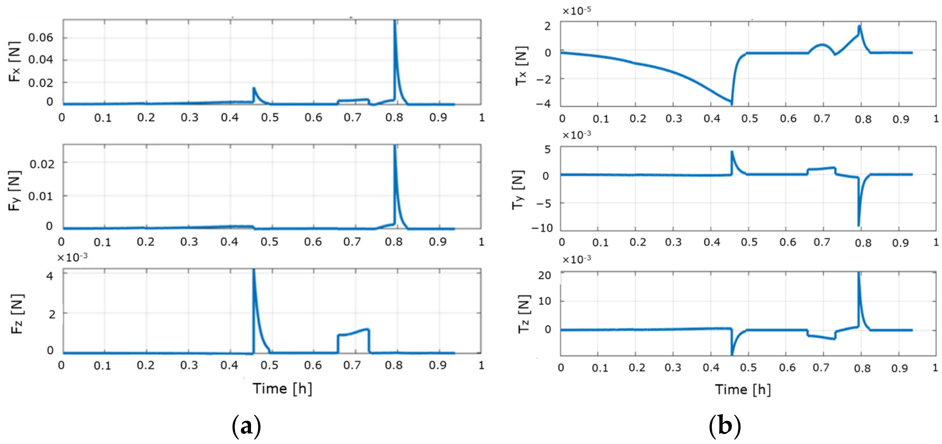


Figure 11. Actuation required to perform the forced motion of the rendezvous profile: force (**a**) and torque (**b**) profiles. The lines show the body axes where the quantities are applied vs. time.

Another important aspect defined in [11] is that, prior to any rendezvous and/or capture operations, the servicer is capable of performing an inspection of the capture point of the client. This is satisfied by the design of the approach trajectories, described by ROEs [36].

For the sake of clarity, Relative Orbital Elements are defined as follows:

$$\delta\alpha = \begin{pmatrix} \delta a \\ \delta\lambda \\ \delta e_x \\ \delta e_y \\ \delta i_x \\ \delta i_y \end{pmatrix} = \begin{pmatrix} (a_c - a)/a \\ (u_c - u) + (\Omega_c - \Omega)\cos i \\ e_{x_c} - e_x \\ e_{y_c} - e_y \\ i_c - i \\ (\Omega_c - \Omega)\sin i \end{pmatrix}$$

and are based on the well-known Keplerian (absolute) orbital elements as follows

- a: semi-major axis,
- e: eccentricity,
- i: inclination,
- Ω: right ascension of the ascending node,
- ω: argument of periapsis,

- ϑ: true anomaly,
- M: mean anomaly.

Note that subscript c denotes the chaser, or servicer, and no subscript denotes the target elements. Moreover, $u = \omega + M$ is the mean argument of latitude. Finally, e_x and e_y are defined as $e\cos\omega$ and $e\sin\omega$, respectively. An example of trajectory, defined through ROEs, is depicted in Figure 12, assuming a circular target orbit and $\delta a = 0$, which results in a closed ellipse centered in the V-bar. The notation in Figure 12 assumes

$$\delta \boldsymbol{e} = \begin{pmatrix} \delta e_x \\ \delta e_y \end{pmatrix}, \; \delta \boldsymbol{i} = \begin{pmatrix} \delta i_x \\ \delta i_y \end{pmatrix}.$$

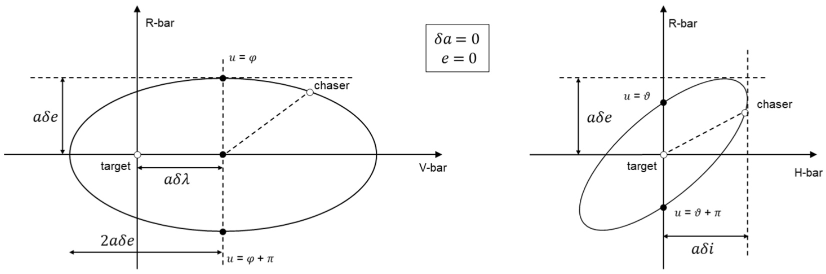


Figure 12. Example of ROE trajectory.

In particular, inspection is performed with a fly-around trajectory with a constant ROE. The drivers for choosing this over a more dedicated type of trajectory are the following:

- Passive safety, which is ensured through a proper definition of ROE, as better explained later;
- Fuel consumption, which is lower than any forced motion trajectory.

This strategy allows inspection over the full orientation of the target if it is tumbling, which is a reasonable assumption in the ADR case.

The ROE trajectories' extensive testing is performed in Monte Carlo campaigns, as discussed later in Section 5.

As mentioned, another aspect ensured by ROEs is the passive safety of the trajectory when the relative eccentricity and the relative inclination vectors are collinear [37,38], as depicted in Figure 13. In passively safe trajectories, the relative trajectory of the servicer with respect to the client ensures that the servicer does not enter a safety envelope around the client, even in the case of a total loss of the controllability of the servicer, with no specific action needed to avoid a collision.

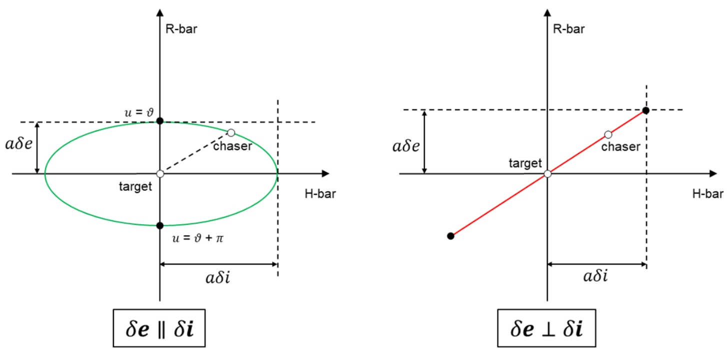
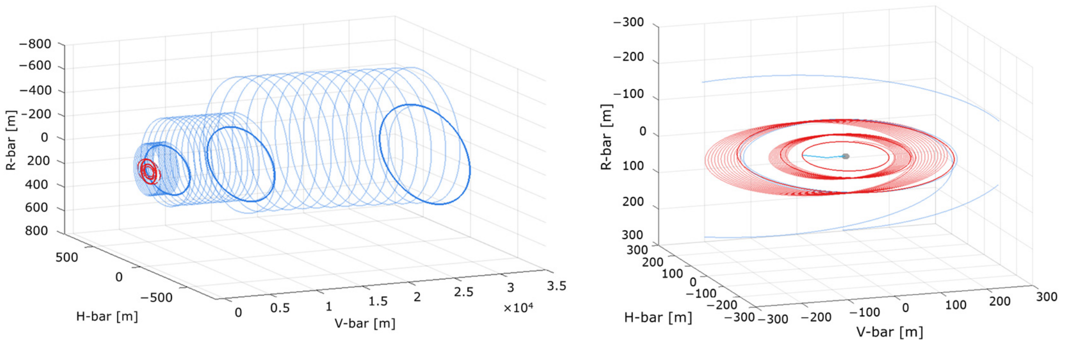


Figure 13. Passive safety with ROEs. Collinear relative eccentricity and inclination result in a passively safe trajectory (**a**), while perpendicular relative inclination and eccentricity result in an unsafe trajectory (**b**) that crosses the target trajectory (V-bar).

A well-known property of ROEs is that they remain within the same region, in terms of radial and normal separation (see Figure 3), if no actuation is performed and assuming no perturbations, thus satisfying the exclusion of zones. Note that a walking safety ellipse can be obtained with $\delta a \neq 0$.

The nominal trajectories for Client Phasing and Far Rendezvous are shown in Figure 14.



(**a**) (**b**)

Figure 14. Nominal ROE trajectories for Client Phasing—blue (**a**) and Far Rendezvous—red (**b**).

The ROE trajectories are modified through impulsive maneuvers. The instantaneous change of ROEs $\Delta\delta\boldsymbol{\alpha}$ due to the impulsive change in the chaser velocity $\delta\boldsymbol{v}$ in LVLH can be derived from Gauss' Variational equations under the assumptions $a_c \simeq a$ and $e = 0$ [36]:

$$\Delta\delta\boldsymbol{\alpha} = \Gamma\delta\boldsymbol{v},\ \Gamma = \frac{1}{na}\begin{bmatrix} 2 & 0 & 0 \\ 0 & 0 & 2 \\ 2\cos u & 0 & -\sin u \\ 2\sin u & 0 & \cos u \\ 0 & -\cos u & 0 \\ 0 & -\sin u & 0 \end{bmatrix},\ \delta\boldsymbol{v} = \begin{pmatrix} \delta v_V \\ \delta v_H \\ \delta v_R \end{pmatrix}.$$

where n is the mean anomaly of the target orbit. A minimum number of three maneuvers along a V-bar are required to achieve an arbitrary reconfiguration in the plane defined by R-bar and V-bar. Therefore, the final ROEs $\delta\boldsymbol{\alpha}_F$ after the maneuvers are computed as the following:

$$\delta\boldsymbol{\alpha}_F = \Phi_{0,F}\delta\boldsymbol{\alpha}_0 + \begin{bmatrix} \Phi_{1,F}\Gamma_1 & \Phi_{2,F}\Gamma_2 & \Phi_{3,F}\Gamma_3 \end{bmatrix} \begin{bmatrix} \delta v_1 \\ \delta v_2 \\ \delta v_3 \end{bmatrix}$$

where $\Phi_{i,F}, i = 0,1,2,3$, is the state transition matrix computed between the ith time instant and the final time F. This equation is analytically solved, when the final ROEs are fixed, to find the maneuvers' magnitude and their timing [36].

As formulated in [11], the ROEs are dimensioned to include margins for navigation errors, actuation errors, and orbit perturbations, for a predefined amount of time that ensures the implementation of corrective actions from an external entity. In complement, the validation of passive safety is performed in Monte Carlo simulations, as presented in the following section.

4.4. Active Safety

This section addresses the active safety aspects. As illustrated in Figure 15, active safety complements the passively safe phases by guaranteeing that corrective actions, such Collision Avoidance Maneuvers, are taken in the event of a fault that could otherwise lead to undesirable effects, such as impact. Whereas passive safety is guaranteed for Far Range by ROEs application with the collinearity of a relative eccentricity and inclination vector, as explained in Section 4.3, the passive safety cannot be guaranteed for the Close Rendezvous phase due to the small distances between the servicer and the client spacecraft. In this phase, the FDIR functions take over and ensure no collision can occur between the two spacecraft, thus providing overall safety.

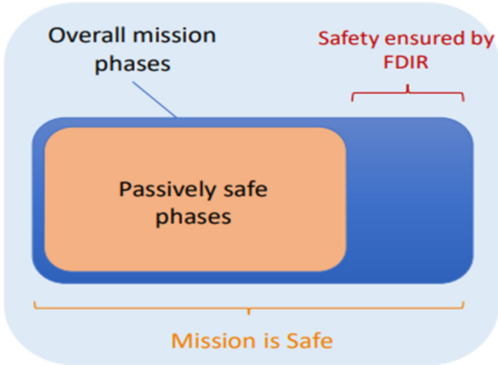


Figure 15. Safety strategy for CS-1.

The active safety implements the concepts of Approach and Abort corridors, described in Section 3.4, and the associated actions of Abort and Cancel. As illustrated in Figure 16, the Cancel trajectory is designed such that the boost will reach a point where operations can be resumed (left), and the sequence of Abort boosts is designed to attain a trajectory that diverges from the target (right). The solutions are designed such that they can be triggered at any point inside or outside the corridor.

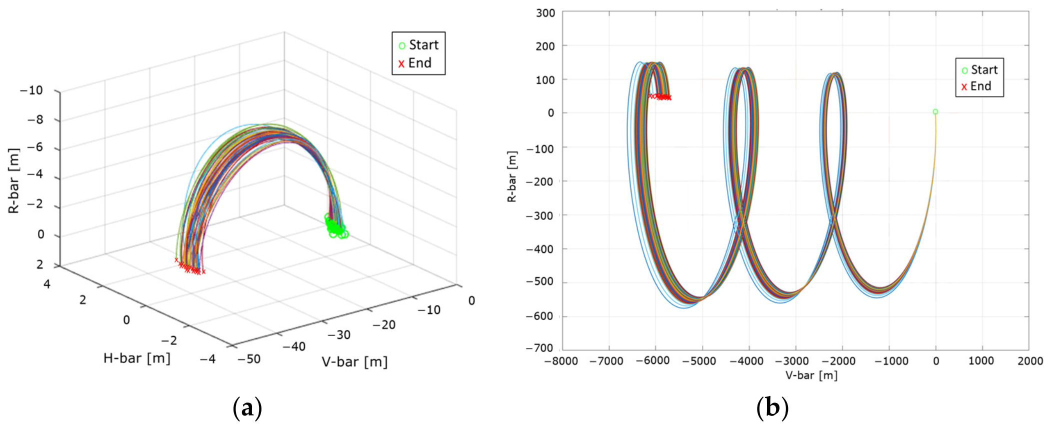


Figure 16. Cancel simulation with a stop at FKP (**a**) and an Abort simulation demonstrating that the passive safety trajectory is safe by design (**b**).

5. Model-in-the-Loop Testing

This section covers the V&V that employed extensive Model-in-the-Loop (MIL) Monte Carlo (MC) campaigns, complementing the information provided in previous sections.

The effects considered in the simulation environment were quite comprehensive, including the following:

- Dispersion of Mass, Center of Mass, and Inertia,
- Modelling and dispersion of sensor and actuator non-idealities,
- Modelling of flexible modes and fuel sloshing,
- Modelling of orbital perturbations,
- Dispersion of illumination conditions.

The MC campaign is conducted for all Rendezvous phases.

5.1. Client Phasing

The MC campaign results, shown in Figure 17, confirm that the GNC chain operates as intended. The controllability of the position and attitude at any point is demonstrated, achieving the Control design guidelines formulated in Section 4.2, with the Navigation system being able to provide relative-position estimation between the servicer and the client using the Narrow-Angle Camera. The results also indicate that the ROE approach for the rendezvous is working correctly, with all orbits being passively safe between transitions and corrections. The simulations also show that no trajectory from the MC campaign unintentionally enters the Approach Zone, which has a radius of 1km, as mentioned in Section 3.2.

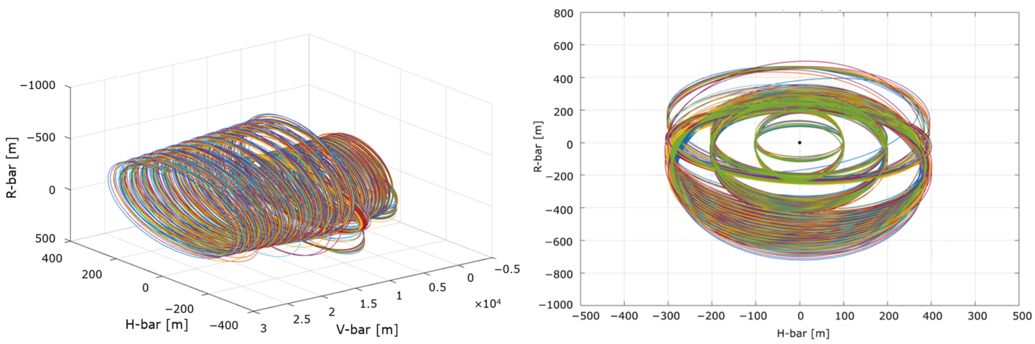


Figure 17. Client Phasing trajectories in LVLH.

5.2. Far Rendezvous

The MC results for Far Rendezvous, presented in Figure 18, show that the fly-around trajectories are contained within the region of the Approach Zone, and that the trajectories never cross the KOZ, which has a radius of 6 m, as expressed in Section 3.2. The trajectories ensure that the servicer maintains a safe distance from the client, in the presence of navigation, actuation, and perturbation errors, without requiring active control interventions, i.e., being passively safe as per the design described in Section 4.3. Moreover, it shows that fly-around trajectories provide comprehensive coverage for inspecting the client.

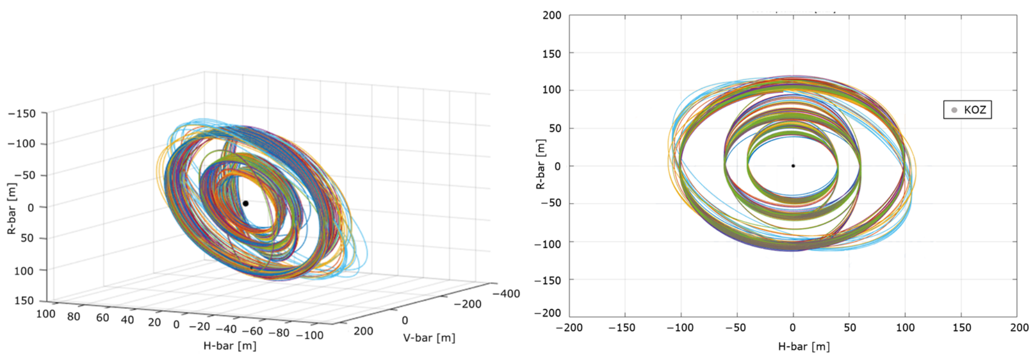


Figure 18. Far Rendezvous trajectories in LVLH. All the trajectories are contained within the AZ (1 km radius from the target) and never cross the KOZ (a 6 m radius from the target, not clearly visible in the plot).

5.3. Close Rendezvous and Capture

The profile for the close-range rendezvous is depicted in Figure 19. It represents the high-fidelity simulation of the GNC performance in the execution of the approach profile previously depicted in Figure 10. A station keeping is started at FKP (top left of Figure 19), where an initial dispersion around this point is stabilized by the Control and Navigation. The servicer performs a forced motion to the IPP outside the V-bar, where a suitable Beta angle allows for a 6DOF relative Navigation initialization. After this point, the conditions formulated in Section 3.3 are assessed and, if satisfied, the GO for capture is commanded. The servicer returns to the V-bar and approaches the target along this direction, entering the approach corridor.

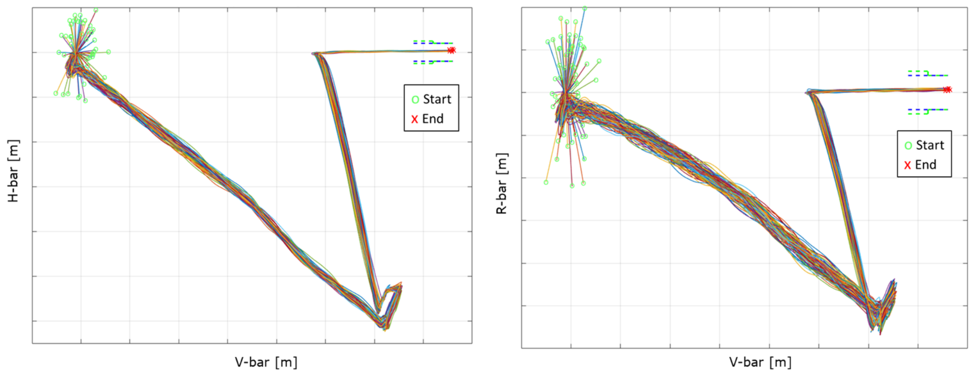


Figure 19. Close Rendezvous trajectories in LVLH.

The results demonstrate that the Navigation and Control systems can provide robust solutions to meet mission requirements since, for all cases in the MC campaign, the servicer successfully controlled its position and attitude while navigating towards the client within the KOZ. These results confirm the servicer's capability to perform 6DOF control and to use forced motion to safely approach the client, as intended by the design described in Section 4.2.

The navigation assessment is complemented by test campaigns that made use of synthetic image generation with the scattering of relevant optical parameters, and an optical test bench at GRAALS with a target mockup and a camera model, demonstrating that the navigation coped with the effects of external sources such as Earth in Field of View (FoV) and with illumination conditions, as mentioned in Section 4.1, and that it effectively computed the relative estimates.

The Abort corridor, presented in Section 3.4, is well defined and the trajectory is contained within this region with a considerable margin, as shown in Figure 20. In addition, the Navigation system operates correctly for all the phases, and in the presence of external sources and for different operating conditions, in accordance with the design described in Section 4.1.

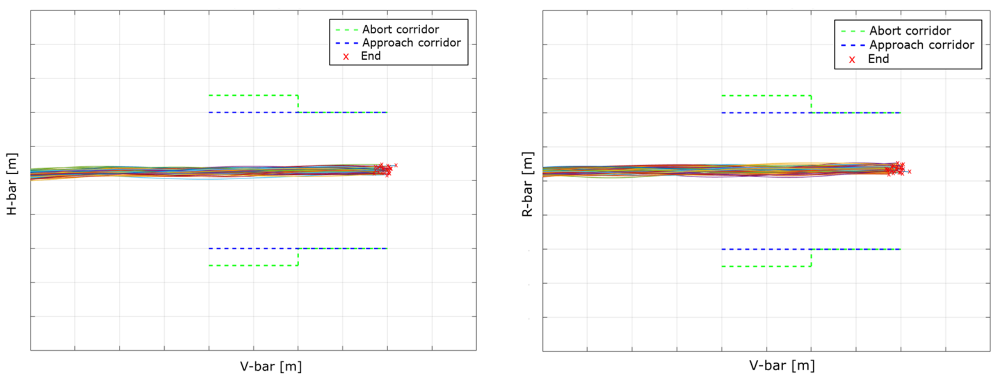
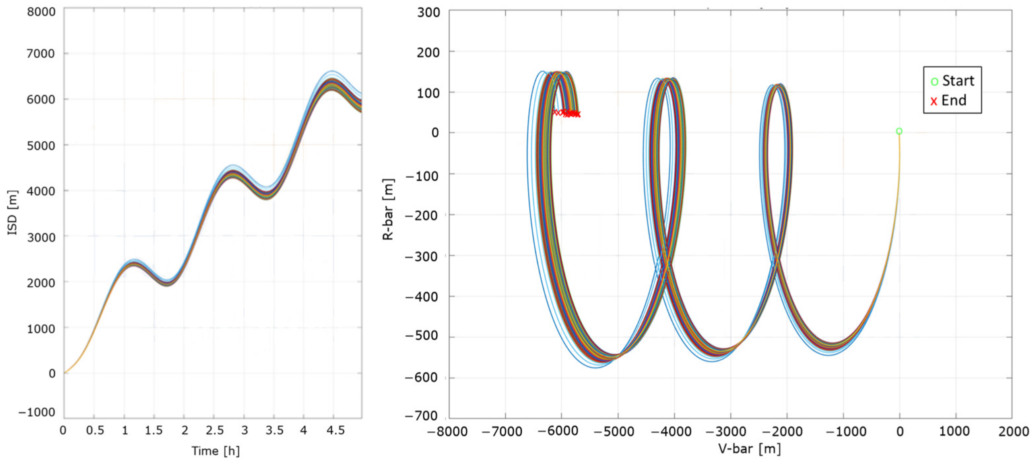


Figure 20. Capture trajectories in LVLH.

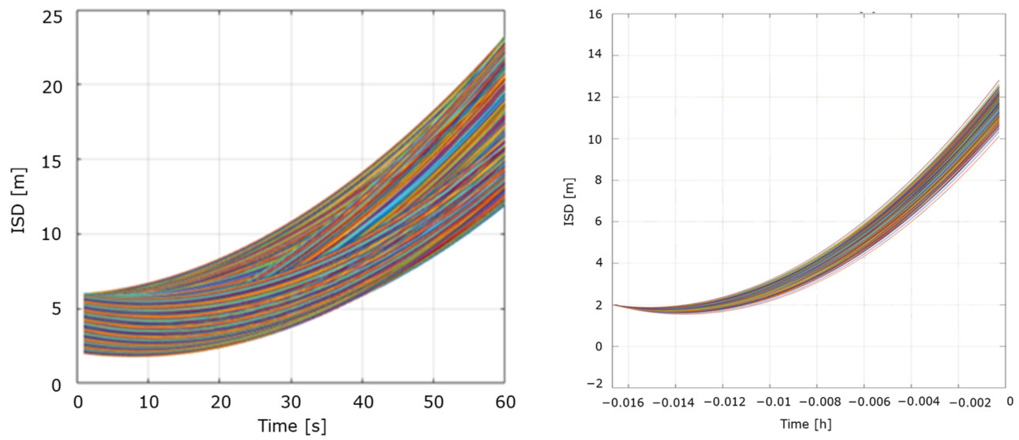
5.4. Abort

The Abort solution is demonstrated for the case of single thruster failure when flying in the KOZ. The Abort applies a sequence of boosts to drift away from the client both in close proximity and in the long term (Figure 21). For the assessment of the Abort, two different tools are used as follows: a fast simulator for intensive testing, to identify the worst-case conditions, and a high-fidelity simulator (Functional Engineering Simulator—FES) to perform MC campaigns around the identified worst-case conditions. The results are presented in Figures 21 and 22. This also validates the autonomous strategy for safety in the sense that the autonomous or ground commanding at any time of the Abort leads to the desired active and passive safety.



(**a**) (**b**)

Figure 21. Abort drifting trajectories characterization: Inter-Satellite Distance (**a**) and orbital plane trajectory (**b**).



(**a**) (**b**)

Figure 22. Abort Inter-Satellite Distance simulation with fast (**a**) and high-fidelity (**b**) simulators.

5.5. Cancel

Similarly to the Abort procedure, the Cancel is extensively tested in simulation. The results, shown in Figure 23, prove that the Cancel is able to place the servicer in a passively safe trajectory, such that if the stop-hop fails, the servicer will continue to drift away from the target. This validates the autonomous strategy for safety. Similar to the Abort, the requirement is validated in the sense that the autonomous or ground commanding at any time of the Cancel leads to the desired active and passive safety.

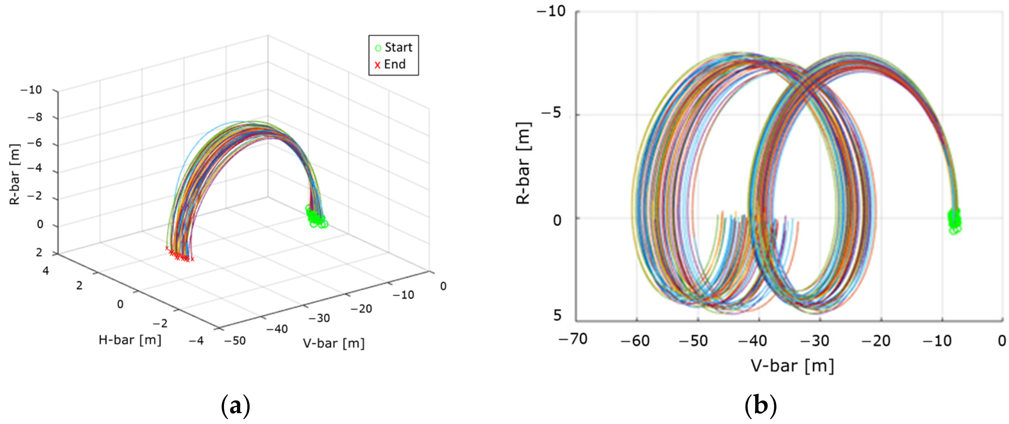


Figure 23. Cancel simulation with a stop at FKP (**a**) and with a failed stop-hop (**b**).

6. Conclusions

The aim of this work was to elaborate and demonstrate how Close-Proximity Operations can be successfully achieved, in particular for the case study of the ClearSpace-1 mission.

It was demonstrated that, as follows:

- The guidelines of [11] are well posed and can be adopted in general, providing methods for design, development, and validation in other missions from the perspective of GNC, Mission Analysis, and the Concept of Operations;
- The approach zones are well defined, being mutually exclusive, and with clear entry criteria;
- The corridors were defined, and the corresponding contingency actions (Abort and Cancel) were shown to be effective in achieving active and passive safety;
- The GNC subsystems were defined to achieve the goal of safely operating around a non-cooperative target:
    - The Navigation operated in the presence of external interferences (Earth behind the target and illumination conditions), providing for a continuous estimate of the relative state. Furthermore, the nature of the estimate was enhanced as the proximity was reduced, going from angle-only in Client Phasing, to 6DOF at Close Rendezvous;
    - The control was robust to perturbations and other effects found in the CPO phases, attaining the desired performance levels;
    - Guidance strategies based on ROEs were designed to allow for inspection. Also, the close-proximity profiles were compliant with aspects such as the control authority and the capability to assess the decision points criteria for the go/no go.
- The combination of a dedicated fast simulator with a high-fidelity simulator proved effective for the validation of active safety (CAM). The fast simulator enabled extensive testing of the initial states to identify worst-case configurations that were reproduced and investigated in detail in the high-fidelity simulator.

There is a known balance between applicable requirements and the cost of compliant solutions. Conservative requirements can impose unnecessary costs or even the unfeasibility of a commercial service, whereas a relaxation of the requirements can yield undesired consequences. The guidelines verified and validated were formulated for general ADR and IOS application and were shown to be correctly defined and achievable for the CS-1 mission, setting the ground for other commercial solutions to follow.

The guidelines derived are agnostic to target dimensions, being scalable to bodies of different sizes. The dimensions of the ROE ellipses and of the Approach and Abort corridors should be scaled to consider the larger/smaller regions for the involved targets. In particular, smaller targets may allow for an abort corridor with a closer proximity to the PNR, and a PNR closer to the target.

Regarding ground intervention, the solutions were designed to be independent of ground services, with on-board guidance, navigation, control and FDIR algorithms that are autonomous, and an interface with the ground only in monitoring and at go/no go at the decision points. Autonomy is a key characteristic for ADR and IOS missions, in particular for constellations or large-scale debris removal. The approach adopted in CS-1 is driven towards full autonomy, and it is expected that ground control will be relieved as in-flight experience demonstrates the reliability of the derived solutions.

Future work may address generalization to rendezvous in other scenarios, such as small asteroids and small bodies, which have similarities (forced approach for capture and a combination of simulators for validation) as well as challenges (very limited ground communication and hence a high GNC autonomy).

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Conflicts of Interest: Authors José Vasconcelos, Serena Gaggi, Tiago Amaral and Ana Friaças were employed by the company Deimos Engenharia. Author Charles Bakouche was employed by the company Clearspace. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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