A Four-Steps Analysis for Safe Trajectories Assessment of a RVD Mission of Small Satellites

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Abstract

This paper presents a four-step analytical framework designed to ensure the safety of rendezvous and docking missions involving small satellites, which are often constrained by limited thrust and computational resources.

The methodology begins with the definition of a nominal trajectory, establishing a "performance tube" that incorporates navigation and propulsion uncertainties, verified through Monte-Carlo simulations to assess Absolute Performance Error (APE) and Keep-Out Zone (KOZ) compliance. The second step focuses on identifying passive safety by simulating uncontrolled motion during critical phases to detect potential collision risks. For non-passively safe scenarios, the third step defines Collision Avoidance Manoeuvres (CAM) optimized for Δv efficiency, ensuring the chaser maintains a safe distance while remaining positioned for subsequent docking attempts. Finally, single-failure conditions in navigation and propulsion are modelled to evaluate system robustness under off-nominal states.

The framework is applied to two case studies: a 12U CubeSat docking with a larger spacecraft and a 12U-to-12U CubeSat mission. Results demonstrate the method's effectiveness in providing a comprehensive safety assessment and supporting the definition of robust guidance strategies for proximity operations.

1 Introduction

In recent years, the small satellite market has observed a dramatic increase due to the improvement of operational capabilities achieved by these spacecraft while maintaining lower costs and quicker schedules compared to larger platforms. Space exploration [1, 2, 3], in-orbit servicing [4, 5], in-orbit demonstration [6], and advanced remote sensing [7] are prominent examples of small-sat missions. One of the most safety-critical CubeSat mission profiles involves inspecting or observing a mothercraft while manoeuvring in its vicinity [8]. Within the framework of these missions, the most challenging operational capability [9] to be completed is often the retrieval.

Docking is a "planned collision" between two spacecraft, controlled by managing the geometric location of contact points and the relative linear and angular velocities at the moment of contact. To achieve contact conditions within allowed margins, trajectories must be maintained within close tolerances and assessed against off-nominal events that may prevent the correct use of onboard equipment. Any deviation from the nominal trajectory could result in a lost mating opportunity or the danger of a collision at unsuitable points and dynamic conditions, risking serious damage. Consequently, each trajectory should be passively safe, or the chaser must be capable of performing escape manoeuvres to avoid collisions. Furthermore, there is always a "point of no return" beyond which a docking manoeuvre must be executed without the possibility of escape. Moreover, docking imposes a set of stringent constraints that impact the design of critical subsystems involved in navigation [10, 11, 12], guidance, control [13], propulsion, and retrieval mechanisms. The primary drivers for the design and verification of the correct trajectory include 1) accurate relative position and velocity estimation, 2) fine pointing of the mating interface on the target, 3) precise trajectory definition and control, 4) high control agility, and 5) sufficient control authority. The main constraints involve safety protocols, such as approach corridor maintenance and collision avoidance capability, as well as illumination conditions and visibility with the ground segment. The ultimate goal is the identification of suitable trajectories for both nominal and off-nominal conditions.

The rendezvous and docking of CubeSats have been studied in literature, particularly in nominal contexts; however, safety approaches in off-nominal conditions have not been deeply addressed. A rendezvous manoeuvre with proximity operations and docking using a pair of 3U CubeSats with miniaturized components and sensors is described in [14]. Trajectory analyses in nominal and off-nominal conditions with passive safety assessments are proposed in [15, 16, 17]. A consistent study of GNC systems and the use of H-infinity controllers for robust analysis via Monte-Carlo methods is performed in [18] for nominal conditions, demonstrating the capability of CubeSats to remain within safety constraints. Similar performances are demonstrated in [19] and [20] using tracking model predictive control and tube-based model predictive control.

Within this context, the present paper proposes a step-by-step method to design and assess the manoeuvres of a rendezvous and docking mission for small satellites. The methodology outlines strategies for nominal approaches, including uncertainties in system state and equipment performance, as well as off-nominal events such as the loss of navigation or propulsion capabilities. This method is adopted for the design and analysis of the trajectory for the SROC mission, which is currently completing Phase B2 of the program. Section 2 describes the proposed method in detail; Section 3 outlines the mission and the case study context; Section 4 presents the results of the method's application; and Section 5 provides concluding remarks and achievements.

2 Method

The proposed method for the design and verification of spacecraft manoeuvres consists of step-by-step phases (*Figure 1*).

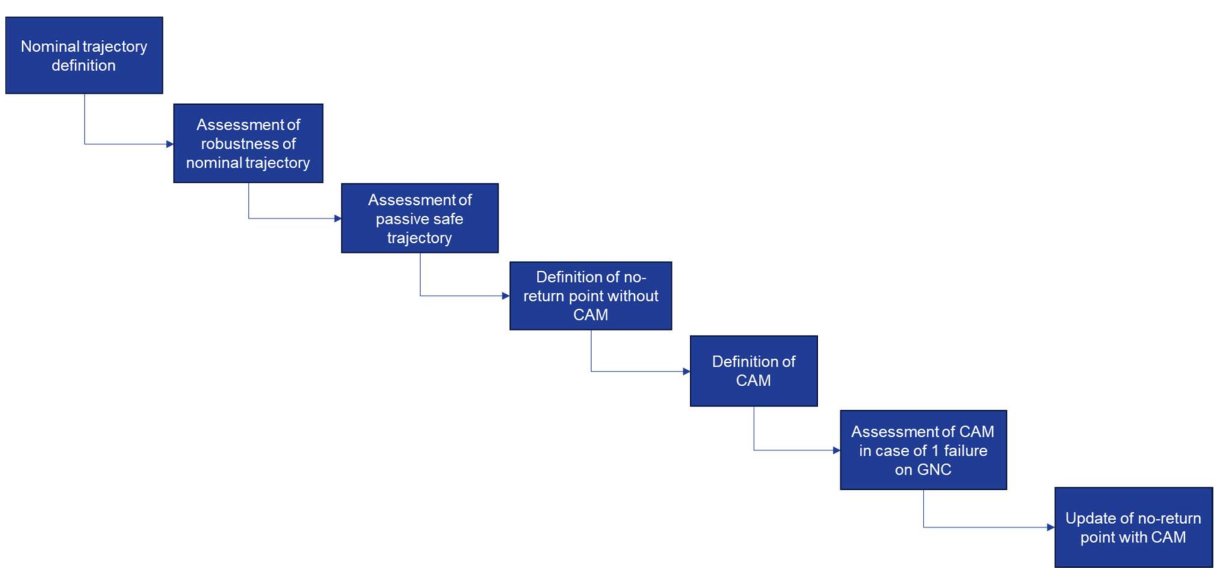

Figure 1: Method description

The first step involves the definition of a nominal trajectory, selected through an extensive literature review, platform-specific constraints - such as limited thrust and computational resources - and safety requirements imposed by the safety authority. The nominal trajectory is then identified by tuning the guidance parameters in terms of maximum velocity, maximum Δv, and maximum time to docking. After a fine tuning of these parameters, a single analysis in the optimal condition is carried out.

The second step focuses on identifying the operational boundaries within which the trajectory can be maintained and considered nominal. In this phase, bounded uncertainties are applied in the analysis performing simulation runs with higher-fidelity models for each crucial/critical element. For example, navigation uncertainties - in terms of initial state - and propulsion dispersions - such as thrust magnitude and direction errors, and uncertainties on the physical properties are introduced. This analysis is verified through a stochastic Monte-Carlo campaign.

The third step is the identification and characterization of the trajectory's safety properties. In close proximity operations, contingencies where the system is unable to perform the entire planned manoeuvre must be considered. This step analyses the residual relative motion resulting from a complete failure for each scheduled burn. The propagation of this motion allows for the assessment of whether the chaser satellite violates any Keep-Out Zones (KOZ) or, more critically, lead to a potential collision risk with respect to the target.

Following the nominal and safety assessments, manoeuvre points characterized by potential collision risks are identified. For non-passively safe manoeuvres, the third step focuses on the analysis of Collision Avoidance Manoeuvres (CAM) designed to mitigate such risks. These CAMs must be capable of maintaining the chaser at a minimum required distance from the target for a predefined minimum duration derived from mission and operational requirements.

In the final analysis step, component-level failure emulation is modelled for both the propulsion and navigation systems to verify the system's behaviour under off-nominal conditions. These two final steps are again verified through a Monte-Carlo campaign to assess the overall robustness of the strategy, with a specific focus on manoeuvres that are critical or characterized by a lack of passive safety.

3 Mission Description and Analysis Framework

The Space Rider Observer Cube (SROC) mission is designed to demonstrate disruptive technologies essential for autonomous rendezvous and docking (RVD) operations using small satellite platforms in safety-critical environments. The mission architecture, in the current baseline, comprises two 12U CubeSats and a dedicated deployment and retrieval system. During its operational phase, the SROC-C (Chaser) CubeSat will execute proximity operations relative to the SROC-T (Target) vehicle before concluding the mission with docking and re-entry. The 12U CubeSats will be launched aboard a Vega-C rocket. Following deployment and initial commissioning, SROC-C will perform formation flying to observe SROC-T from a close distance. The mission sequence culminates in a rendezvous and docking manoeuvre with a compatible docking system located on the target vehicle.

A primary objective of the SROC project is the in-orbit validation of key technologies for proximity operations, including cold gas propulsion systems, advanced Guidance, Navigation, and Control (GNC) hardware and software, and electro-optical sensors for visual navigation. Furthermore, the mission seeks to enhance autonomous operations through the implementation of Artificial Intelligence algorithms and specialized docking and retrieval mechanisms. This demonstration is expected to enable new applications for nanosatellites in orbital inspection, in-orbit servicing, space exploration, and debris mitigation.

The simulation is conducted within a MATLAB/Simulink environment, utilizing an architecture composed of multiple high-fidelity and validated dynamic models (Figure 2). At the core of the simulator lies the spacecraft plant, which integrates absolute orbital dynamics and relative rotational dynamics for both satellites. The initial absolute orbital states, expressed in the Earth Centered Inertial (ECI) frame, are propagated by integrating the gravitational accelerations - computed using the EGM2008 geopotential model - combined with perturbation accelerations, including aerodynamic drag and third-body effects. The rotational dynamics is modelled via Euler's equations, accounting for disturbance torques such as aerodynamic drag, gravity-gradient, magnetic torques, and fuel slosh. Rotational kinematics is modelled using quaternions to prevent the mathematical singularities - commonly referred to as gimbal lock - associated with Euler angle representations. For the chaser satellite, the translational and rotational dynamics are coupled by considering the thrust vectoring uncertainty, specifically the alignment offset of the thrusters relative to the spacecraft's center of mass.

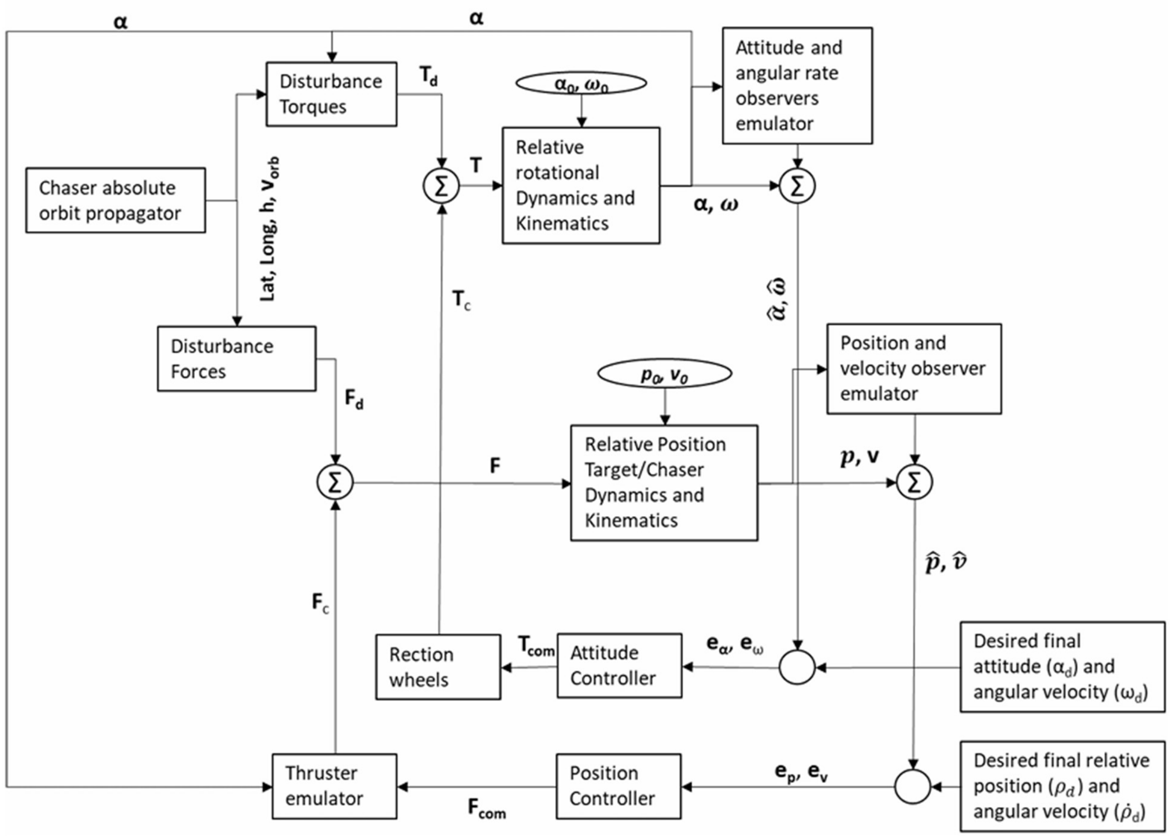

Figure 2: Simulation Architecture

The guidance algorithms are based on the Port-To-Port (P2P) equations. In the case of open-loop strategies, these equations are invoked at the start of the simulation to compute the manoeuvre trajectory and define the shooting plan, generating a pre-calculated thrust profile that can be periodically updated. Conversely, for closed-loop strategies - such as the one presented as a case study in this work - the algorithm operates in real-time to generate a reference velocity profile, which is then processed by the control system and tracked by the actuators. The reference profile is defined and tuned by the user to ensure full compliance with both operational and mission requirements.

Navigation algorithms are not explicitly integrated into the control loop for this analysis; instead, the observation process is emulated by introducing a percentage-based uncertainty on the position and velocity states, modelled via a Gaussian distribution. The control architecture employs different strategies for translational and rotational dynamics. A Non-linear Model Predictive Control (NMPC) is used for position tracking, while a Sliding Mode Control (SMC) handles attitude and angular velocity. These control laws are translated into actuation commands through dedicated component models. For attitude control, Reaction Wheels (RW) are approximated as second-order dynamic systems. The propulsion system is modelled with higher fidelity, featuring eight control lines with normally-closed valves and tilted nozzles (Figure 3) to ensure 6-degree-of-freedom (6-DOF) controllability, even in the event of a single-line failure. The model explicitly incorporates propulsion uncertainties, including dispersions in thrust magnitude, vector direction, and pulse duration.

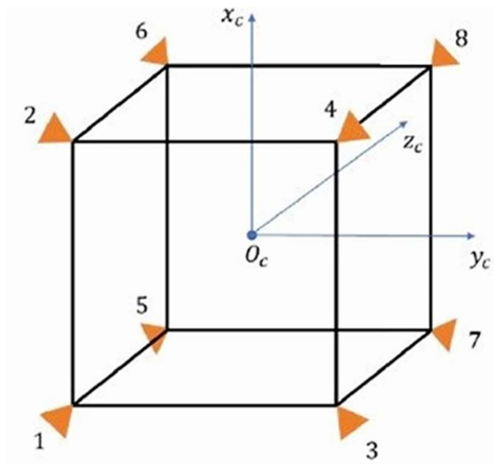

Figure 3: Thrusters Configuration

4 RESULTS

A case study for the Final Approach phase of the SROC mission is here introduced, focusing on the motion of the last few meters between the two spacecraft. For the purpose of this analysis, the approach strategy is based on a closed-loop controlled straight-line trajectory. This selection is preferred over quasi-straight-line "hop" manoeuvres to ensure higher precision during autonomous operations. The adoption of a straight-line profile addresses specific operational constraints: primarily the need to maintain the target within the limited Field of View (FOV) of the navigation cameras, and the requirement to align the docking interfaces along the vehicles' respective symmetry axes. To ensure operational safety and facilitate monitoring, a conical approach corridor is defined. This corridor originates at the target’s docking interface with a half-opening angle typically of 10 degrees. Maintaining the chaser within this volume is a necessary condition for nominal manoeuvre validation. Any violation of these boundaries is assumed to trigger immediate contingency protocols, such as a station-keeping "hold," a "back-away" manoeuvre, or the execution of an active CAM.

4.1 First and Second Step: Baseline Trajectory and Nominal Boundaries Definition

In the context of the case study, the analysis focuses on a straight-line approach initiated from a relative distance of 25 m. The initial state assumes zero relative velocity with the chaser positioned entirely along the V-bar. A trapezoidal velocity profile in the time domain was selected for this phase because it is easily implementable and allows for controlled acceleration, which gradually reduces the approach speed to minimize collision risks [23]. The velocity command is divided into distinct regions based on the relative distance to the target (Figure 4). During the initial phase, the spacecraft accelerates to a constant approach velocity of 5 cm/s, which is maintained until a distance of approximately 12 m from the target. At this point, the velocity is reduced to 2 cm/s by the time the chaser reaches 7 m, a speed that is then held constant until a relative distance of 3 m. In the final stage, a further deceleration is performed to reach a final contact velocity of 5 mm/s, satisfying the specific mission requirements for docking. The velocity profile is correctly followed by the controller and the final desired position is achieved (Figure 5).

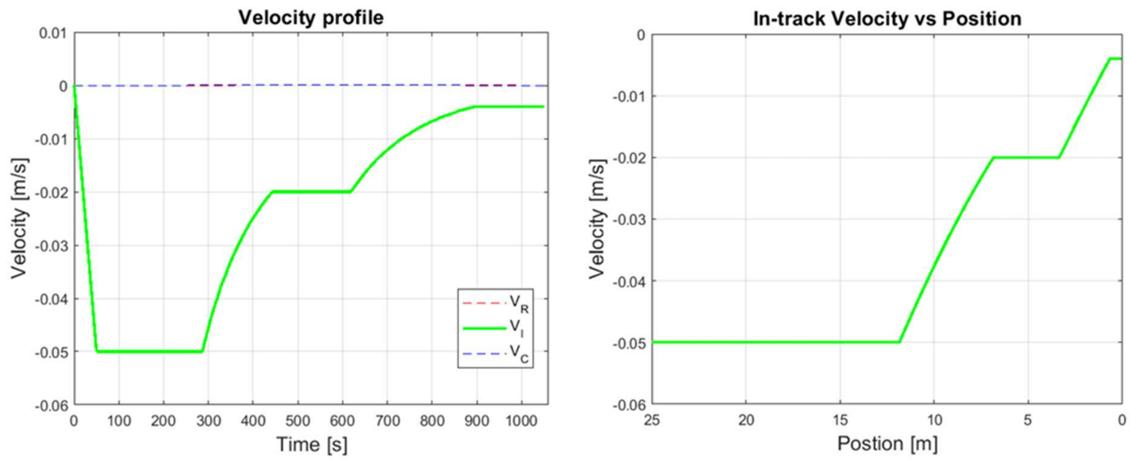

Figure 4: Assumed Velocity Profile

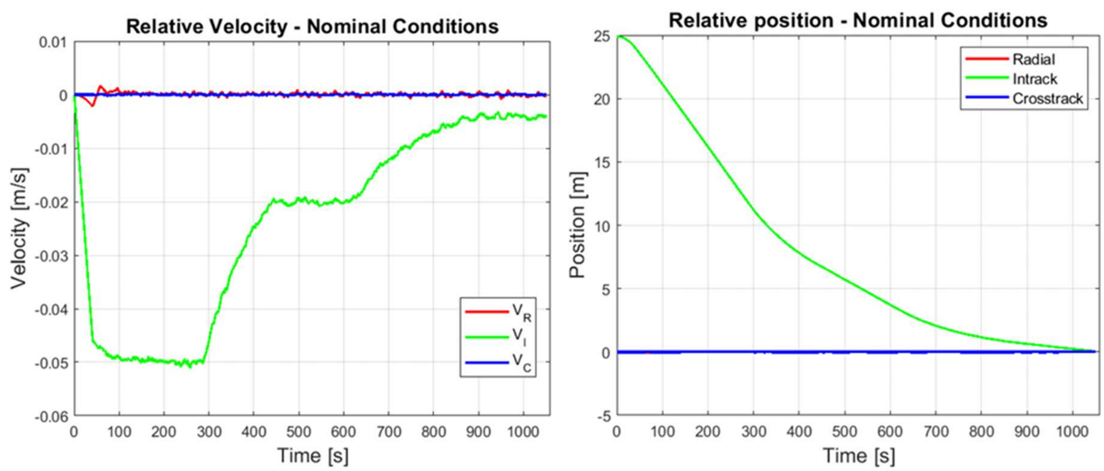

Figure 5: Controlled Velocity and Position

The Monte Carlo simulation campaign (Figure 6) was conducted by incorporating a 2% relative distance error into the initial state. Similarly, an initial velocity error of 2 cm/s was introduced for each axis. The mass of the 12U satellite was varied between 20 kg and 22 kg, while the thrust magnitude was subjected to a random reduction ranging from 0% to 10% of its nominal value.

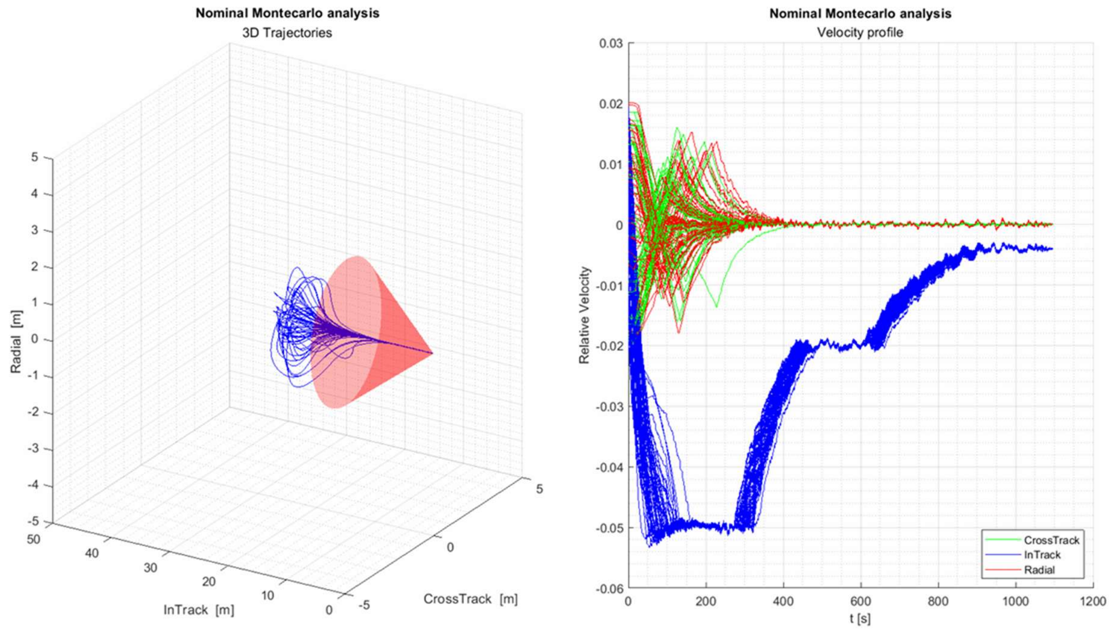

Figure 6: Nominal Trajectory Monte-Carlo Campaign

4.2 Third Step: Passive-Safety Assessment and CAM Definition

The passive safety of the trajectory was assessed by evaluating the system's response to a complete propulsion system shutdown at three critical points along the approach profile. In the first scenario, a shutdown is triggered during the continuous acceleration phase at approximately 20 m from the target, precisely when the chaser's velocity exceeds the maximum threshold of 5 cm/s. It can be observed (Figure 7) that the chaser naturally follows a trajectory that leads it to a lower orbit, thus resulting in a drift away motion.

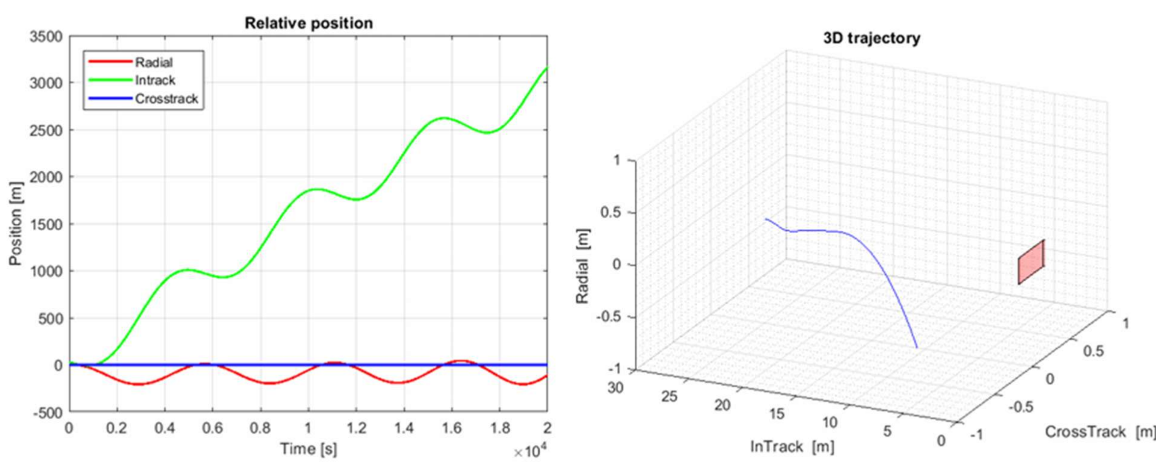

Figure 7: First Shutdown

The second case examines a failure during the phase where the first deceleration fails to occur; here, the thrusters are deactivated while the velocity remains at 5 cm/s, even after the spacecraft has passed the designated deceleration point of the trapezoidal profile. Also in this case, no collision occurs (Figure 8).

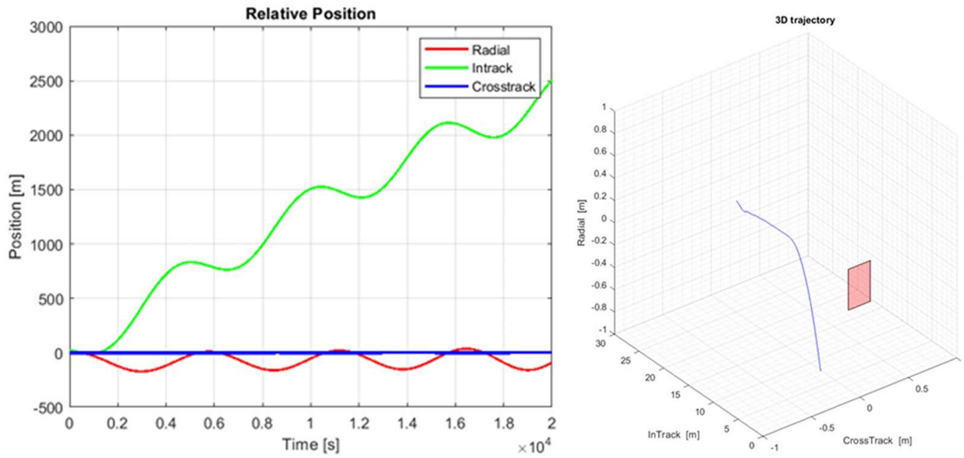

Figure 8: Second Shutdown

In the third scenario, a failure is modeled near the target by inhibiting the final deceleration, resulting in a thruster shutdown while the satellite is still maintaining a velocity of 2 cm/s beyond the final braking position. For each of these cases, the failure was implemented by disabling the controller and nullifying the control force for all thrusters, effectively simulating a free-drift condition to determine the resulting relative motion and potential collision risk. Again, choosing this velocity profile does not lead to a collision, resulting in a drift away motion (Figure 9).

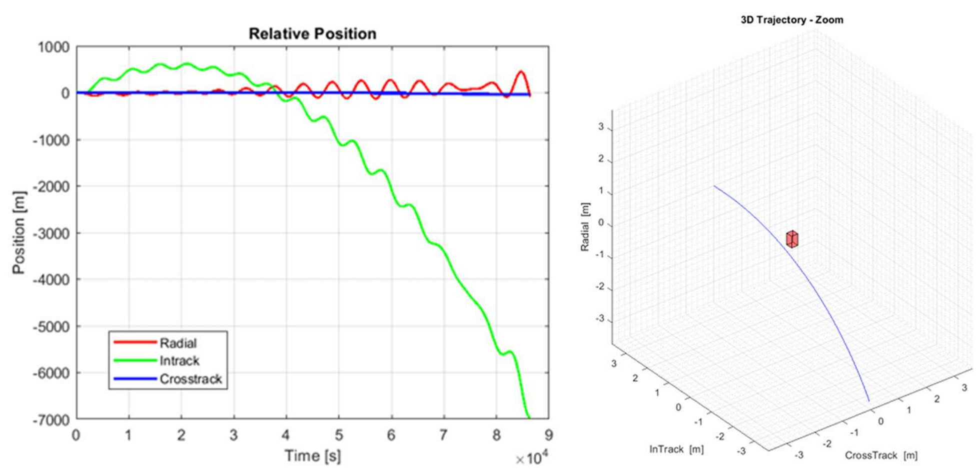

Figure 9: Third Shutdown

Following the assessment of manoeuvre safety, the framework incorporates the execution of radial or in-track CAMs. This analysis specifically defines the critical thresholds and boundary conditions beyond which an escape manoeuvre must be initiated. These scenarios (Figure 10) are then utilized to verify the effective performance of the three CAM strategies, ensuring they achieve the required separation and meet the predefined safety behaviour.

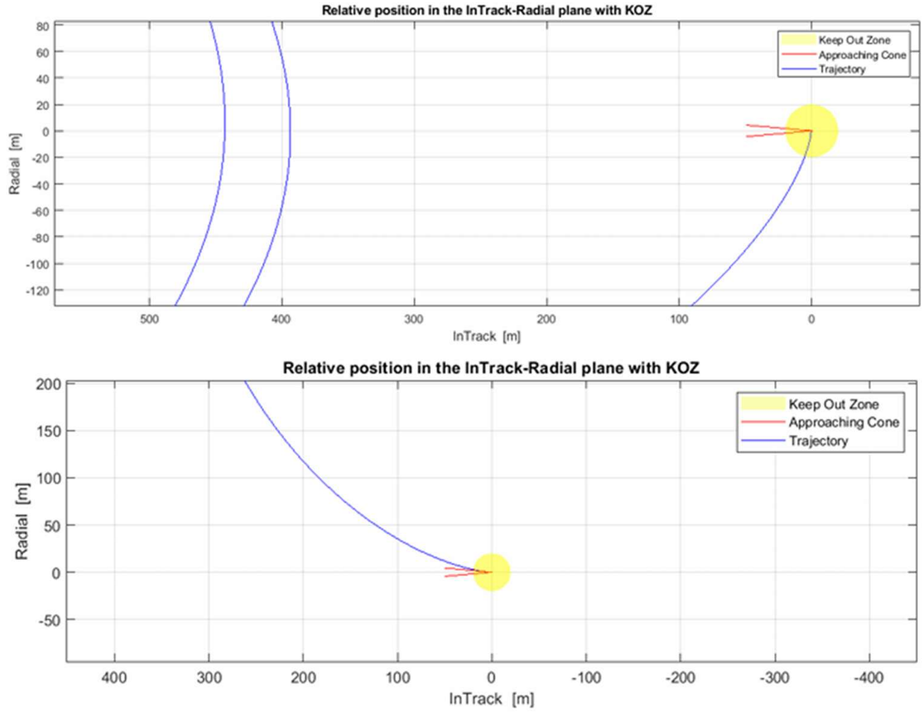

Figure 10: Radial and In-Track CAMs

4.3 Fourth Step: Off-Nominal Conditions

Off-nominal conditions, specifically thruster failures, are addressed as the final stage of the analysis. This study considers two primary failure modes: a propulsion line malfunctioning in either a closed or open valve state. In the first scenario, a single nozzle loses its thrust-generation capability, which reduces manoeuvrability in a specific direction and induces an attitude disturbance whenever a manoeuvre is executed along the affected axis. If left uncorrected, this imbalance leads to a cascading series of errors in subsequent boost directions. These simulations are initialized by deactivating a nozzle at the last available point for a CAM, as determined in the previous analytical step.

The second scenario, characterized by an open nozzle generating continuous thrust, represents a significantly more critical condition. This failure mode results in persistent attitude and position disturbances that require constant correction, lead to continuous propellant depletion, and increase the risk of collision. To ensure a comprehensive assessment, simulations were performed for every thruster and for each CAM strategy considered. For the sake of conciseness, only one representative case is reported (Figure 11), specifically involving an open-valve failure coupled with a radial CAM execution. The overall results show that the strategy is robust and one-failure tolerant.

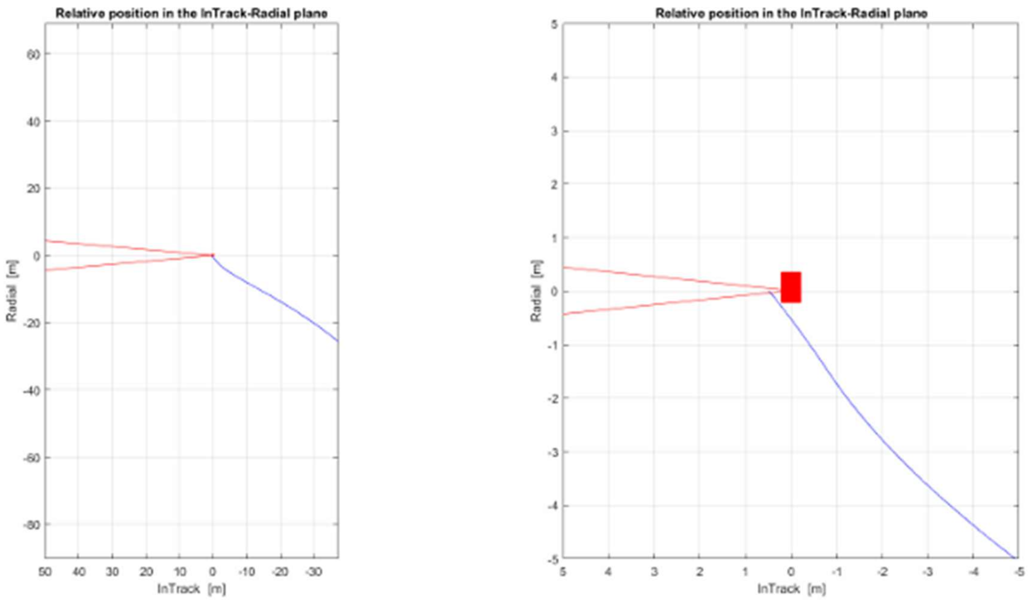

Figure 11: Example of Single Open-Valve Failure and Radial CAM Execution

5 CONCLUSIONS

This case study effectively demonstrates the four-step strategy in action. It is possible to conclude that this approach allows for a smart, incremental increase in analysis complexity, starting with basic simulations and moving toward detailed Monte-Carlo campaigns with integrated fault injection.

The results show that the method is both robust and practical. It proves that mission requirements can be met while staying within system constraints, even when accounting for real-world uncertainties. Finally, this moves the project beyond "best-case" paper calculations and into the kind of high-fidelity simulation environment needed for actual space operations. By systematically layering these steps from nominal paths to off-nominal scenarios, it is possible to bridge the gap between a theoretical model and a mission that actually survives its first contact.

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