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Safety Concept of Proximity Operations in Low Earth Orbit: The SpEye Mission

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Abstract

In-space proximity operations are a key enabling technology for future In-Orbit Servicing (IOS) and debris removal missions, which are essential to foster a sustainable and circular space economy. A key feature to design and validate the proximity operations is the safety concept of the close-range flight, which manages the monitoring of the safe operations and is in charge of mitigation of any contingency that can occur and cause a unwanted collision between the two satellites. This paper describes the safety concept philosophy for the SpEye mission, a CubeSat demonstrator of proximity operations funded by the Italian Space Agency through the Alcor programme.
Keywords: CubeSat, Proximity Operations, Safety, LEO

Acronym/Abbreviations

LEO	Low Earth Orbit
DOF	Degrees Of Freedom
SSO	Sun-Synchronous Orbit
FSS	Flight Safety System
SOS	Safety Onboard System
SGS	Safety Ground System
STM	State Transition Matrix
ASI	Italian Space Agency
RTN	Radial Transversal Normal frame
DGNSS	Differential GNSS
EO	Electro-Optical
LRF	Laser Range Finder
TC	Tele-Commands
TM	Telemetry
FF	Formation Flying
POD	Precise Orbit Determination
GNC	Guidance Navigation and Control
CAM	Collision Avoidance Manoeuvre

1. Introduction

In recent years, spacecraft proximity operations have gained significant attention for applications in In-Orbit Servicing (IOS), inspection, and Active Debris Removal (ADR) missions across civil, defence, and commercial sectors. Advancements in Guidance Navigation and Control (GNC) technologies are expected to further expand the range of feasible proximity operation applications. The space community has been highly active in both research and demonstration missions involving proximity operations with space targets. The level of complexity in these operations generally depends on the status of involved satellites; whether cooperative, where state information is actively exchanged during flight, or uncooperative, such as in the case of defunct or malfunctioning objects.

Currently, several programs and missions to demonstrate IOS and ADR technologies are planned and under development. The European Space Agency (ESA), within the ADRIOS project, is funding both an ADR mission (ClearSpace-1) and an IOS mission RISE. The ClearSpace-1 mission, led by ClearSpace, aims to capture and deorbit a debris object from Low Earth Orbit (LEO) [2, 3], while the RISE mission, led by D-Orbit, will dock with a geostationary satellite to provide life-extension services [4]. In parallel, JAXA is advancing its CDR-2 program on ADR technologies and demonstrations, following the successful completion of the ADRAS-J mission, which inspected a derelict rocket body in 2024 [5]. NASA has currently several projects and mission within its In Space Servicing, Assembly and Manufacturing (ISAM) framework regarding robotic refueling, servicing assembly and manufacturing in orbit [6], comprehending the OSAM-1 mission that will perform servicing and refuelling of the Landsat-7 satellite [7].

In recent years, CubeSats have become popular platforms for validating proximity operations due to their low cost and rapid development cycles. Notable examples include CPOD [8], ESA's e.Inspector [9, 10], and CanX-4&5 [11]. Building on this framework, the Space Eye (SpEye) mission aims to demonstrate multiple proximity operations capabilities, including inspection, formation flying, and close approach, using a CubeSat (free-flyer) deployed by a satellite carrier in Low Earth Orbit [1, 12, 13]. The mission is funded through the Alcor program of the Italian Space Agency (ASI) and is carried out by an Italian consortium led by TSD Space, teaming with D-Orbit, T4i, Planetek, Politecnico

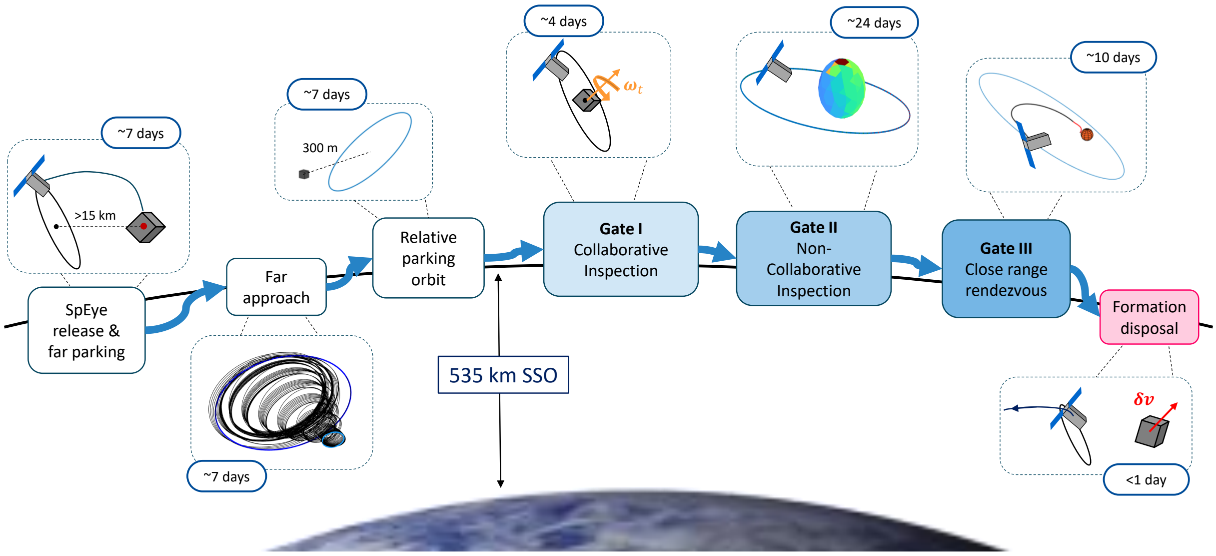

Fig. 1. Synthetic representation of the SpEye mission Concept of Operations [1].

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This paper presents how the SpEye mission addresses one of the key challenges of autonomous proximity operations: ensuring flight safety to guarantee robustness and reliability of the mission. In particular, it describes the flight safety concept adopted in SpEye, together with the collision risk assessment and avoidance methods implemented for proximity operations scenarios.

2. Mission description

SpEye is a proximity operations demonstration mission in LEO featuring a CubeSat free-flyer and a CubeSat satellite carrier, namely the InOrbitNow (ION) platform of D-Orbit . The mission objectives are to demonstrate nanosatellite-based inspection and rendezvous with an in-orbit target in LEO. The free-flyer is an 8U CubeSat equipped with an onboard camera and Laser Range Finder (LRF) for proximity operations. Additionally, the two spacecraft will employ an Inter-Satellite Link (ISL) during the mission. The overall mission concept of operations is illustrated in Figure 1, together with the preliminary timeline of the mission [1].

Following the free-flyer release into a 535 km circular Sun Synchronous Orbit (SSO), the carrier will perform correction and reconfiguration manoeuvres to control the relative motion with the free-flyer, enabling the acquisition of a relative parking orbit at hundreds meters of distance. These manoeuvres are performed by the carrier to minimise propellant consumption by the CubeSat, leaving the full delta-v budget for the subsequent proximity operations phase. From the relative parking orbit, three sequential mission phases - referred to as Gates - will be conducted to demonstrate distinct proximity operations capabilities. The planned demonstrations for each Gate are summarised in Table 1, along with the corresponding scenario conditions of the space segment and relative navigation modes [14, 15, 16, 17].

Note that the RTN frame mentioned refers to the Radial Transversal Normal (RTN) frame used for proximity operations. The Differential GNSS (DGNSS) navigation mode uses GNSS raw measurements from both platforms for relative state estimation. The EO-only mode, which stands for Electro-Optical, employs the camera suite and LRF for vision-based relative navigation [14]. The DGNSS+EO hybrid mode combines DGNSS-based relative navigation with visual observations, as described in [16].

Table 1. SpEye mission proximity demonstrations planned.

Gate I - Collaborative Inspection		
	Conditions	**Rel. Nav.**
Demo 1.1	Inspection with ION collaboration	DGNSS
Gate II - Non Collaborative Inspection		
	Conditions	**Rel. Nav.**
Demo 2.1	ION stable in RTN frame	DGNSS
Demo 2.2	ION rotating with a flat spin	DGNSS+EO
Demo 2.3	ION rotating with perturbed spin	EO-only
Gate III - Close range Rendezvous		
	Conditions	**Rel. Nav.**
Demo 2.1	Rendezvous to stable hold-point in RTN frame at 10 m	EO+DGNSS
Demo 2.2	Rendezvous to stable hold-point in inertial frame at 10 m	EO only
Demo 2.3	Rendezvous to rotating hold-point around ION	EO only

At the end the mission, the free-flyer will perform disposal operations using a drag sail, in order to comply with the ESA guidelines for disposal from the LEO protected region to reenter within 5 years form the end-of-life [18].

3. Safety Concept

The safety concept for the SpEye mission is devised to allow the level of autonomy and efficiency envisioned by the technology demonstrations. Within the safety concept design the terms of passive safety and active safety are defined as follows:

- **Passive safety**: A relative trajectory at a time t_0 is said to be passively safe for ΔT_{safe} if no collision risk between the two objects will occur for the time interval ΔT_{safe} without applying any manoeuvres. This level of trajectory safety is extremely useful in proximity operations to ensure robustness to major failures, which prevent the prompt actions on the formation.
- **Active safety**: A relative trajectory at a time t_0 is said to be actively safe for ΔT_{safe} if no collision risk between the two objects will occur for ΔT_{safe} after the application of a collision avoidance manoeuvre action.

Within the SpEye mission operations, strong priority is given to allow passively safe conditions for the trajectory, which allow flexibility in the contingency management and enhance the autonomy of the formation, towards a reduced need of ground support. In order to confirm the passive safety, failure trajectories are propagated and analysed in terms of their collision risks. The SpEye safety concept is embedded in the design of the SpEye Flight Safety System (S-FSS), which governs the monitoring of the proximity operations and the mitigation of possible risks and contingency. The S-FSS is composed by two main segments: (1) the SpEye Safety Onboard System (S-SOS) which runs autonomously onboard the SpEye CubeSat, and (2) the SpEye Safety Ground System (S-SGS) which is implemented in the ground control centre and interacts with the formation during the ground contacts. On the other hand, the S-SGS is the ground based pipeline to monitor *post-facto* the state (from the proximity operations perspective) of the formation, to monitor the behaviour of the S-SOS itself, and to provide dedicated Tele Commands (TCs) (*e.g.*, S-SOS tunable settings, recovery manoeuvres computed on-ground). In the S-SGS pipeline, the functions of collision assessment and avoidance will feature more advanced and computationally heavy methods, that are unsuitable for the onboard implementation but allow a refinement of the knowledge of the formation's health. It is important to note that the system-level contingency and anomalies are managed by the two satellites FDIR systems, which will communicate tailored health status to the S-FSS in order to manage the formation safety accordingly. The S-FSS will be in charge of managing the trajectory safety of the proximity and oversee the relative GNC system. The timeline of operations of the FSS is shown in Figure 2, where is displayed how the S-SOS and S-SGS calls are performed. A key factor in the design is the location of the ground contacts t_{gi} which determine the onboard collision risk assessment prediction time ΔT_{pred}. For the majority of the mission operations, except some delicate phases such as the forced motion approach of Gate 3, the ΔT_{pred} shall encompass at least two ground contacts to allow the downlinking of the S-SOS status and the uplinking of the eventual mitigation actions refined by the S-SGS. In any phase, according to the contingency encountered which requires a prompter action, the S-SOS features also a spaceborne autonomous intervention capability. The definition of the prediction time in the risk evaluations of the safety subsystems allows to grant passive safety (or active safety) for $\Delta T_{safe} = \Delta T_{pred}$, which grants a high level of robustness to the GNC operations and relative trajectories.

The key inputs to the S-FSS is the relative state information that has available to perform the monitoring and protection function, as summarise in Table 2.

Table 2. SpEye mission proximity demonstrations planned.

	Description	Availability to S-SOS	Availability to S-SGS
$\delta\alpha_N$	Onboard rel. navigation solution	real time ($t_N = t$)	Post facto, at t_{gi}
$\delta\alpha_H$	Health rel. navigation solution	Delayed δt_H	Post facto, at t_{gi}
$\delta\alpha_{pod}$	POD rel. nav solution	Delayed, δt_G	Current t_{gi}

The S-SOS is in charge of monitoring the formation health, evaluate collision risk of the trajectories and implement eventual mitigation actions directly onboard the SpEye 8U Cubesat in a centralised manner. The functional architecture of the S-SOS is displayed in Figure 3, where the interfaces with the SpEye relative GNC system, the SpEye system FDIR and the TC are depicted. Note that the information about the health of the carrier target, exchanged through ISL, are communicated through the SpEye system FDIR. The two main modules of the functional architecture of the S-SOS are the formation monitoring, which performs the required collisions check for the nominal and failure trajectories, and the formation protection, which implements commands for the mitigation of the collision risks during operations. Details on the former will be presented in Section 4, while the latter is explained in Section 5.

4. Formation monitoring

In this section, the functions that perform the formation monitoring tasks are described, with particular focus on the onboard module S-SOS. Within the mis-

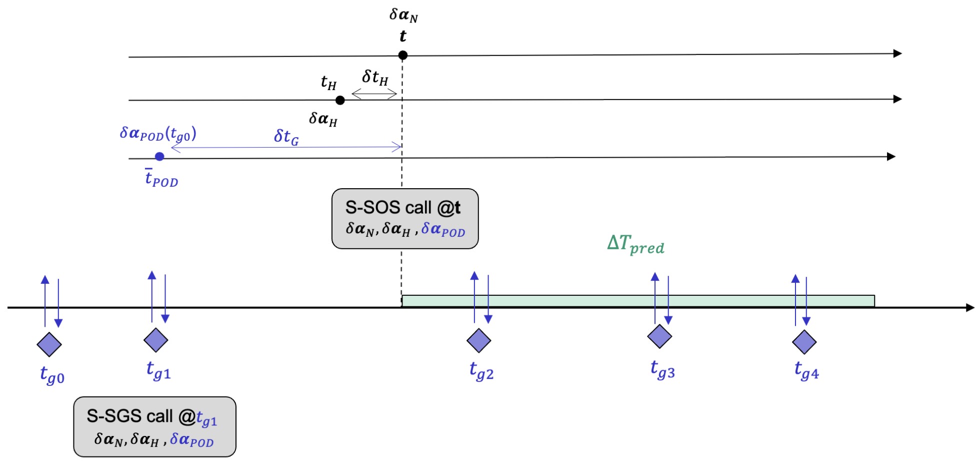

Fig. 2. Timeline of the calls and operations of the S-FSS, showing the concept of prediction of safety checks with respect to planned ground contacts within the mission ConOps.

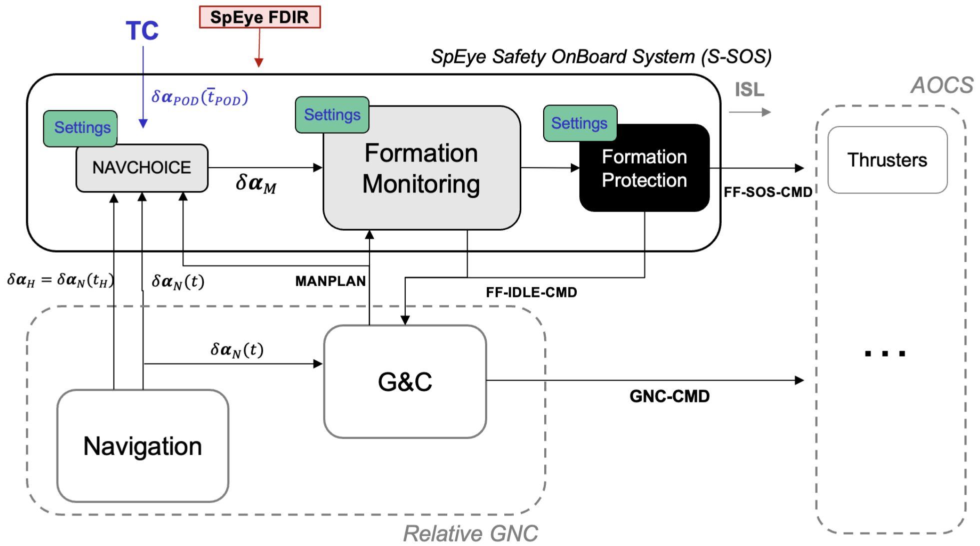

Fig. 3. Functional architecture of the S-SOS centralised on SpEye free-flyer platform.

sion, formation monitoring is responsible for checking, at each call, the collision risk of both the nominal and failure trajectories in order to determine whether mitigation actions are required. Different formation monitoring functions apply to different phases of the SpEye mission, since the trajectories are inherently different. For example, the elliptic relative trajectories used in Gates 1 and 2 implement the concept of E/I vector separation to guarantee passive safety [19, 1]. In contrast, during the close approaches planned in Gate 3 to demonstrate autonomous rendezvous, the trajectories violate the E/I separation conditions, and trajectory safety must be ensured in a different way. To fulfil these objectives, two main functionalities are implemented in the formation monitoring module:

- **Safety Monitoring Radial Normal (SMRN)** : checks the one-orbit minimum distance in the RN plane, similar to the E/I separation concept.
- **Safety Monitoring Radial Transversal Normal (SMRTN)** : evaluates the full 3D collision risk of the trajectories.

Both functions can assess the nominal planned trajectory, which includes manoeuvres plans, as well as uncontrolled failure trajectories for passive safety. Therefore, according to the current state solution provided to the S-SOS, $\delta\alpha_N$, the modules must propagate the trajectory and its uncertainties forward in time of the set ΔT_{pred}. The relative trajectories and the uncertainties (state covariance) are here propagated considering the linear State Transition Matrix (STM) of reference [20] as follows:

$$\delta\alpha_N(t) = \Phi(t_0, t)\delta\alpha_N(t_0) + \mathrm{B}(t)\delta\mathbf{v} \quad (1)$$

$$\mathrm{P}(t) = \Phi(t_0, t)\mathrm{P}(t_0)\Phi(t_0, t)^{\mathbf{T}} + \mathrm{Q} + \mathrm{P}_m \quad (2)$$

where $\Phi(t_0, t)$ is the STM from t_0 to t, the B is the control matrix, the Q the process noise matrix to model the uncertainties in the dynamics modelling, and P_m the matrix that includes the manoeuvre uncertainties (magnitude and direction) with the Gates model [21]. Note that the parametrisation used for the relative trajectories exploits quasi non-singular Relative Orbital Elements (ROEs), denoted as $\delta\alpha$.

By definition, SMRN provides a more conservative assessment of the trajectory's collision risk, whereas SM-RTN offers a more refined estimation of the risk evaluating it point-wise in the three direction of the Cartesian relative frame. The methods described hereafter focus on onboard autonomous collision monitoring, prioritizing analytical techniques to comply with the limited computational resources of a CubeSat.

4.1 Safety Monitoring Radial Normal (SMRN)

The SMRN functionalities implements a metric to evaluate the collision risk in the RN plane that evaluates at each instant, the RN one-orbit minimum distance as described in reference [22]. This metric exploits the unscented transform method to compute the mean and variance of the RN one-orbit minimum distance and it is fully analytic. The method has been demonstrated in flight during the passively safe operations with E/I separation performed during the AVANTI experiment [22].

An application of the proposed metric to an elliptic relative orbit is illustrated in Figure 4. The example considers a two-day formation-keeping trajectory that maintains the ROE state within a bounded control region around the nominal ROE state of $\delta\alpha_{nom}$ = [2, 150, 0, 45, 0, 45] meters. In this case, the SMRN is executed with a prediction horizon ΔT_{pred} equal to 12 hours, used to propagate failure trajectories. In the upper plot of Figure 4, the RN safety metric values of the initial states $\delta\alpha_N(t_{0i})$ are shown as markers, while the corresponding propagated failure trajectories are represented by the gray lines. The results indicate that the RN safety metric—defined as the one-orbit minimum distance distribution relative to a predefined collision margin—gradually decreases along the failure trajectory propagation. This behaviour is attributed both to the natural trajectory evolution influenced by differential drag and to the increasing uncertainty growth over time. The lower plot reports the associated isSafe flag for each initial SMRN evaluation, highlighting several states that violate the 12-hour passive safety requirement when adopting a collision margin of 4 meters (red dashed line). It should be noted that the trajectories presented here are not those planned for flight demonstrations in the SpEye mission phases; rather, they are provided solely to illustrate the functionality of the SMRN.

This functionality is used by the S-SOS from the far approach phases up to the Gate 2 demonstrations, see Figure 1.

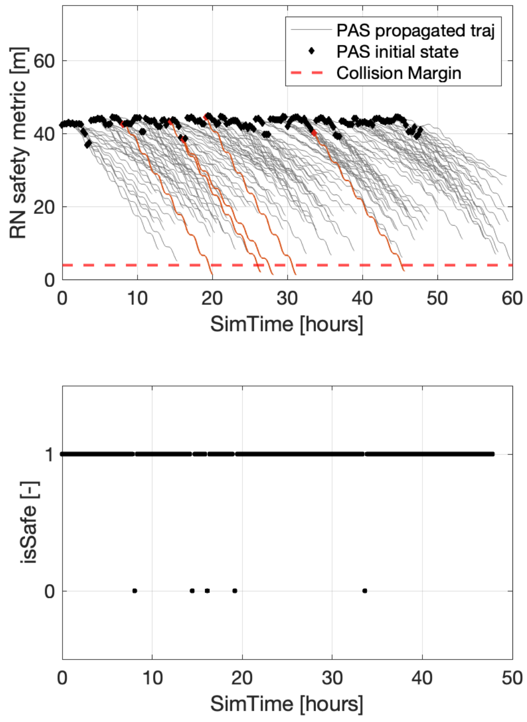

Fig. 4. One-orbit minimum RN distance metric [22] of the failure trajectories over the formation keeping scenario (top), isSafe flag of the SMRN to discern failure trajectories that violate the RN plane metric (bottom).

4.2 Safety Monitoring Radial Transversal Normal (SM-RTN)

The SMRTN functionality is employed to compute the three-dimensional collision risk of the mission trajectories. Again, efficiency from a computational point of view is of paramount importance to allow the autonomous execution of the method onboard the CubeSat. The risk assessment is carried out by linearly propagating both the state and its associated uncertainty, and by evaluating the collision risk at predefined sampling times. The metric is based on the Mahalanobis distance between the target Keep-Out Zone (KOZ) and the position uncertainty of the trajectory, under the assumption that the uncertainty retains a Gaussian distribution during propagation. Given the quasi-linear relative motion in close-proximity, the assumption of the Gaussianity of the distribution holds reasonable. A threshold corresponding to the 3σ probability level is applied to flag unsafe trajectories. This approach enables fast and efficient risk computation, requiring only a single eigendecomposition at each evaluation step.

An example of the SMRTN call is provided in Figures 5 and 6. The test case simulated is an approach trajectory of the close range rendezvous in Gate 3, where a contingency occurred. Figure 5 shows in black the nominal operative close approach trajectory, and the failure trajectory propagated from the failure time together with the 3σ uncertainty ellipsoids. The correspondent RTN safety metric evaluation is shown in Figure 6, demonstrating that the failure trajectory remains within the collision margin defined by the Mahalanobis distance threshold of the safety system.

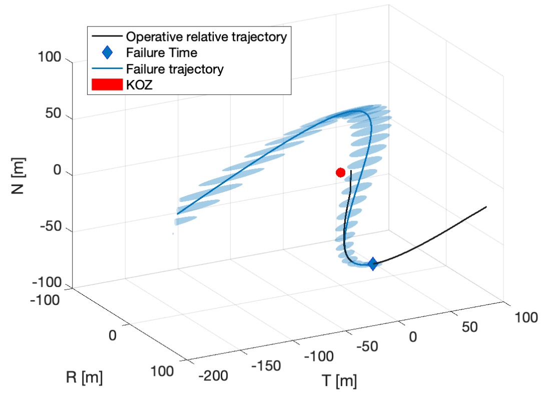

Fig. 5. Failure trajectory (blue) from a close approach experiment of Gate 3, together with the 3σ uncertainty ellipsoids.

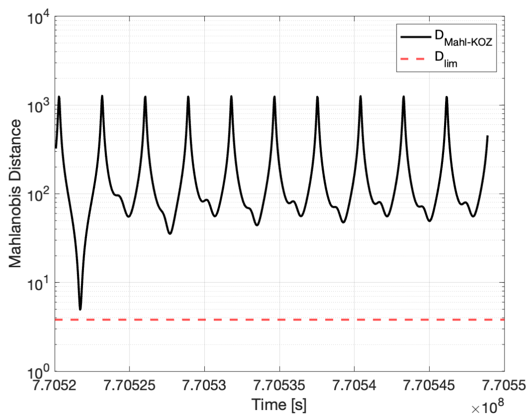

Fig. 6. Mahlanobis distance RTN collision metric over the test case failure trajectory.

5. Formation protection

The formation protection module is responsible for mitigating collision risks during contingent scenarios. Depending on the specific contingency, different levels of protection may be employed. This section focuses on the highest level of protection, corresponding to the worst-case scenario in which an active collision avoidance manoeuvre is required. Such a case may arise either from a predicted collision with the carrier target to occur before possible ground intervention or from a major anomaly or subsystem failure communicated to the S-SOS module by the FDIR system. In addition to this major protection scenario, less severe cases are also possible. For instance, if sufficient time remains before a predicted collision, ground support can be engaged to design the avoidance manoeuvre. Alternatively, if the uncontrolled trajectory assessed by the formation monitoring module does not indicate a collision risk, but a contingency has nonetheless occurred, the formation protection module may simply issue an idle command, allowing the formation to evolve naturally without leading to a collision.

The autonomous collision avoidance manoeuvres design relies on the nominal relative trajectories planned for the proximity operations. Mainly are divided in:

- **PLAN-CAM**: executed when the formation is flying on a elliptical relative trajectory with the concept of passive safety of Section 4 of separation in the RN plane. This manoeuvre is executed within one period of revolution of the satellites, and is usable when the collision prediction does not occur before this time.
- **FAST-CAM**: executed when an immediate action is required and the chaser is flying on relative transfer trajectories or forced motion trajectories of Gate 3.

The PLAN-CAM relies on a single planar manoeuvre to increase the relative trajectory size and restore a safe one-orbit minimum RN distance. The FAST-CAM is a 3D manoeuvre calculated on an algorithm that relies on precomputed candidates and selects the best one according to the relative trajectory state at the time of failure. To select from the precomputed candidates the analytic collision checks presented in Section 4 are exploited. The autonomy of these CAM operations is granted by the analytic nature of the CAM algorithms which can be readily implemented during flight.

An example of a PLAN-CAM during the test case simulated for the SMRN formation monitoring described in Section 4 is shown in Figure 7. In this case, the avoidance manoeuvrer planned within one period of the failure communication successfully induce RN separation for passive safety, while inducing a positive along-track drift.

Furthermore, Figures 8 and 9 illustrate a scenario in which the FAST-CAM is applied during a forced-motion close-approach trajectory relevant for Gate 3. It can be observed that the FAST-CAM successfully induces a drift away (Figure 8) from the target object while maintaining RN separation (Figure 9). Note that this feature may not always be achievable in forced-motion trajectories. In such cases, avoidance is ensured by selecting precomputed manoeuvrers that guarantee only the relative trajectory drifts away from the target. Nonetheless, the guidance profiles generated in the Gate 3 to perform the close approaches will implement the intrinsic safety constraints of reference [23], which will allow the RN passive safety conditions to be reachable

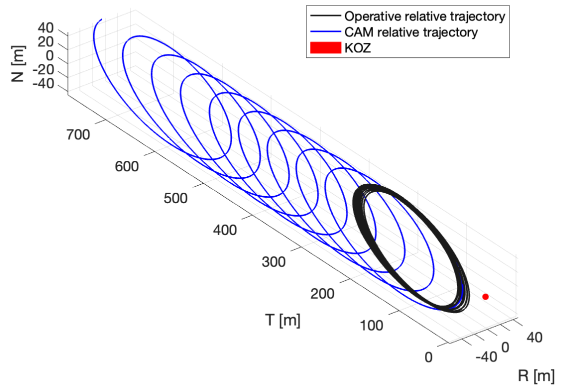

Fig. 7. Relative trajectory after the PLAN-CAM scenario simulating a failure in the formation keeping on the nominal $\delta\alpha_{nom} = [2, 150, 0, 45, 0, 45]$ meters.

by the CAM manoeuvre in a large portion of the approach trajectory.

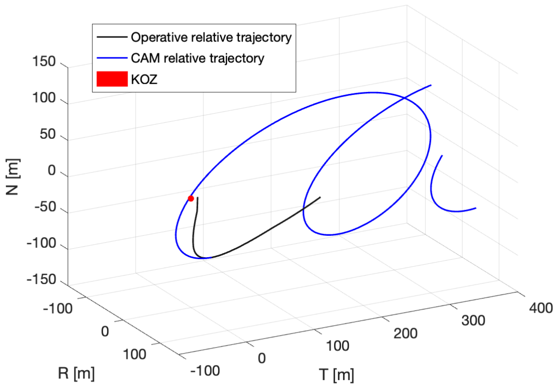

Fig. 8. Relative trajectory after the FAST-CAM scenario simulating a failure during a close approach forced motion trajectory.

6. Conclusions

Flight safety is critical for the robust and successful execution of autonomous proximity operations, particularly when dealing with uncooperative and/or non-collaborative targets. This paper has presented the flight safety system concepts and tools developed for the SpEye mission. Special emphasis was placed on the onboard autonomous safety module, which serves as an enabling technology for future robust operations across a wide range of in-orbit servicing and debris removal applications. The paper has demonstrated the analytical methods used to assess collision risk of relative trajectories and to plan avoidance and mitigation manoeuvres effectively.

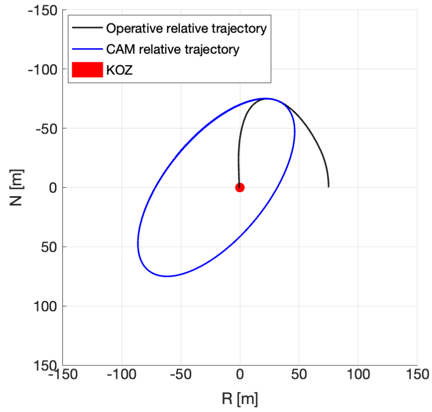

Fig. 9. RN view of the relative trajectory after the FAST-CAM scenario simulating a failure during a close approach forced motion trajectory.

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References

[1] Borelli, G., Gaias, G., Nakajima, Y., Colombo, C., Capuano, V., Saggiomo, F., Leccese, G., and Natalucci, S., “Mission analysis and guidance and control for the SpEye inspection CubeSat,” *Acta Astronautica*, Vol. 220, 2024, pp. 75–87.

[2] Biesbroek, R., Aziz, S., Wolahan, A., Cipolla, S.-f., Richard-Noca, M., and Piguet, L., “The clearspace-1 mission: ESA and clearspace team up to remove debris,” *Proc. 8th European Conference on Space Debris*, 2021.

[3] Vasconcelos, J., Gaggi, S., Amaral, T., Bakouche, C., Cotuna, A., and Friaças, A., “Close-Proximity Operations Design, Analysis, and Validation for Non-Cooperative Targets with an Application to the ClearSpace-1 Mission,” *Aerospace*, Vol. 12, No. 1, 2025.

[4] European Space Agency (ESA), “ESA to build first in-orbit servicing mission with D-Orbit (RISE),” `https://www.esa.int/Space_Safety/ESA_to_build_first_in-orbit_servicing_mission_with_D-Orbit`, Oct. 2024, Accessed: 2025-08-21.

[5] Yamamoto, T., Matsumoto, J., Okamoto, H., Yoshida, R., Hoshino, C., and Yamanaka, K., “Pave the way for active debris removal realization: Jaxa commercial removal of debris demonstration (crd2),” *8th European Conference on Space Debris*, 2021, p. 200.

[6] National Aeronautics and Space Administration (NASA), "In-Space Servicing, Assembly, and Manufacturing (ISAM)," `https://www.nasa.gov/nexis/isam/`, 2025, Accessed: 2025-08-21.

[7] Vavrina, M. A., Skelton, C. E., Deweese, K. D., Naasz, B. J., Gaylor, D. E., and D'Souza, C., "Safe Rendezvous Trajectory Design for the Restore-L Mission," *Advances in the Astronautical Sciences*, 2019, pp. 3649–3668.

[8] Bowen, J., Tsuda, A., Abel, J., and Villa, M., "CubeSat proximity operations demonstration (CPOD) mission update," *2015 IEEE Aerospace Conference*, IEEE, 2015, pp. 1–8.

[9] ESA, "e.Inspector CDF Study Report - Assessment of an ENVISAT Imaging Mission as a Precursor to a Potential ENVISAT Deorbit," Tech. rep., European Space Agency (ESA), 2017.

[10] Silvestrini, S., Prinetto, J., Zanotti, G., and Lavagna, M., "Design of Robust Passively Safe Relative Trajectories for Uncooperative Debris Imaging in Preparation to Removal," *Advances in the Astronautical Sciences*, Vol. 175, 2021, pp. 4205–4222.

[11] Kahr, E., Roth, N., Montenbruck, O., Risi, B., and Zee, R. E., "GPS Relative Navigation for the CanX-4 and CanX-5 Formation-Flying Nanosatellites," *Journal of Spacecraft and Rockets*, Vol. 55, No. 6, 2018, pp. 1545–1558.

[12] Capuano, V. and et. al., "SpEye: a CubeSat Technology Demonstration Mission for On-Orbit Inspection and Formation-Flying," *Proceedings of 75th International Astronautical Congress*, Milan, Italy, 2024.

[13] Capuano, V. and et. al., "Space Eye (SpEye): Preliminary Design of an On-Orbit Inspection and Formation-Flying Demonstration," *Proceedings of 76th International Astronautical Congress*, Sydney, Australia, 2025.

[14] Opromolla, R., Nocerino, A., Napolano, G., Fasano, G., Grassi, M., Capuano, V., Leccese, G., and Natalucci, S., "Electro-Optical Relative Navigation for Inspection and Rendezvous in the SpEye Mission," *Journal of Spacecraft and Rockets*, Vol. 62, No. 3, 2025, pp. 880–897.

[15] Opromolla, R., Nocerino, A., Napolano, G., Fasano, G., Grassi, M., Capuano, V., Illiano, S., Votta, R., Rinaldi, M., Leccese, G., and Natalucci, S., "Electro-Optical based relative navigation for close-range inspection and rendezvous in the SpEye CubeSat-based mission," *AIAA SCITECH 2024 Forum*.

[16] Capuano, V., Harvard, A., Lin, Y., and Chung, S.-J., "DGNSS-vision integration for robust and accurate relative spacecraft navigation," *Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019)*, 2019, pp. 2923–2939.

[17] Opromolla, R. and et. al., "Preliminary Design and Testing of Multi-sensor Relative Navigation Architectures for the SpEye CubeSat Missionn," *Proceedings of 76th International Astronautical Congress*, Sydney, Australia, 2025.

[18] ESA Space Debris Mitigation Working Group, "ESA Space Debris Mitigation Requirements," Tech. Rep. ESSB-ST-U-007 Issue 1, European Space Agency, 2023.

[19] D'Amico, S. and Montenbruck, O., "Proximity Operations of Formation-Flying Spacecraft Using an Eccentricity/Inclination Vector Separation," *Journal of Guidance, Control, and Dynamics*, Vol. 29, No. 3, 2006, pp. 554–563.

[20] Gaias, G., Ardaens, J.-S., and Montenbruck, O., "Model of J_2 perturbed satellite relative motion with time-varying differential drag," *Celestial Mechanics and Dynamical Astronomy*, Vol. 123, No. 4, Dec 2015, pp. 411–433.

[21] Gates, C. R., "A Simplified Model of Midcourse Maneuver Execution Errors," Technical Report Technical Report No. 32-504, Jet Propulsion Laboratory, 1963.

[22] Gaias, G. and Ardaens, J.-S., "Design challenges and safety concept for the AVANTI experiment," *Acta Astronautica*, Vol. 123, 2016, pp. 409–419, Special Section: Selected Papers from the International Workshop on Satellite Constellations and Formation Flying 2015.

[23] Borelli, G., Gaias, G., and Colombo, C., "Safe Guidance Scheme for Proximity Operations Forced Motion," *Journal of Guidance, Control, and Dynamics*, Vol. 48, No. 2, 2025, pp. 340–357.