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Analysis of docking manoeuvres for 12U Cubesat with a collaborative mothercraft

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Abstract. The use of CubeSats as drones for inspecting the collaborative mothercraft is one of the most interesting in-orbit service missions for this kind of small spacecraft. The most challenging operation in this context is the retrieval of the CubeSat by the mothercraft after the inspection phase especially because any violation of safety constraints must be avoided. A well-established docking strategy in nominal and off-nominal conditions is fundamental already during the preliminary design phases. The present paper shows drivers and requirements that identify a set of design parameters on the state boundaries of the CubeSat, its main features, and the uncertainties due to the space environment and the system uncertainties. After the choices of the guidance, navigation, and control strategies and architectures, simulation sessions lead to an assessment of the robust performance in nominal conditions. Then, the off-nominal conditions are deduced and new simulation sessions confirm the capability of the system to react against discrepancies between actual state and desired state and system failures. The proposed solution is applied to a 12U CubeSat mission that will be released and, in case, retrieved by a mothercraft for observation purposes. The paper highlights the solution's effectiveness in nominal conditions, and when an error occurs in the approach velocity and failures affect the propulsion system, as an example of the entire analysis.

Keywords: collision avoidance maneuvers; passively safe trajectory; small satellites docking

1. Introduction

The last years observed a dramatic increment in the small satellites market due to the improvement of the operational capabilities achieved by this type of spacecraft maintaining a lower cost and quicker schedule compared to larger spacecraft. Space exploration (Fabiani *et al.* 2022, Cervone *et al.* 2022, Viscio *et al.* 2013), in-orbit servicing (Nichele *et al.* 2018, Corpino and Stesina 2021), in-orbit demonstration (Lepcha *et al.* 2022), beyond remote sensing (Schwartz *et al.* 2022), and telecommunication missions (Gonzales 2023) are valuable examples of small-sats missions. One of the most interesting missions of CubeSats consists of inspecting/observing a mothercraft moving around it (Bowen 2015). In the framework of these missions, the most challenging operational capability (Lin *et al.* 2020, Richard Noca *et al.* 2016) to be completed is often the retrieval. The satellite should approach the Target vehicle and achieve the retrieval

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position.

Docking is a 'planned collision' of two spacecraft, which is controlled by considering the geometric location of the contact points on the two vehicles and the linear velocities and angular rates at contact. To achieve the contact conditions within the allowed margins, the trajectories have to be maintained within close tolerances before contact. Any deviation from the expected (nominal) trajectory could carry out loss of mating opportunity or, even, the danger of collision of the two spacecraft at unsuitable points and dynamic conditions, with the risk of serious damage. In any case, at each point of the docking, when controls fail and the actual state vector exceeds safety boundaries, the onboard system must execute an operation that prevents collisions, at each point of the docking, when controls fail, and the actual state vector exceeds safety boundaries. In the majority of cases, the execution of a single/combined boost may be sufficient to remove the chaser from the target vicinity, and a collision avoidance maneuver (CAM) is required.

For these reasons, docking imposes a large set of stringent constraints that impact the design of critical subsystems involved in navigation (Opromolla *et al.* 2021, Modenini 2019), guidance, control (Stesina 2021), propulsion system (Mantellato *et al.* 2022) and retrieval mechanisms (Branz *et al.* 2020). The drivers for the design and verification are 1) the accurate relative position and velocity estimation, 2) the fine pointing of the mating point on the Target, 3) the accurate trajectory definition and control, 4) the high control agility, and 5) control authority. the main constraints are safety (e.g., the approach corridor maintenance, the collision avoidance capability), the illumination conditions, and visibility with the ground segment. The final goal is the identification of convenient trajectories both for nominal and off-nominal conditions.

The rendezvous and docking of CubeSats have been partially studied in the literature, especially in nominal contexts. However, the study of safety approach in off-nominal conditions is not deeply faced. A pertinent work can be found in (Roscoe *et al.* 2018) in which a rendezvous maneuver with proximity operations and docking with a pair of 3U CubeSats using miniaturized components and sensors is described. A consistent study of the GNC system and the use of H-infinity controller on robust analysis using the Monte-Carlo method is performed by (Pirat *et al.* 2020) in nominal conditions, showing the capability of the CubeSat to remain within the safety constraints. Similar performances are demonstrated by (Stesina 2021, Mammarella *et al.* 2020) using a tracking model predictive controller and a tube-based model predictive controller.

The present paper aims to show an analysis for the assessment of safe approach trajectories made during the preliminary design phases of a docking mission of a CubeSat. Section 2 describes the case study, the Space Rider Observer Cube (SROC) mission and it shows the choices about the design parameters for a safety analysis and presents the simulation architecture. Section 3 shows the main results obtained during the analysis performed in Phase B1 of the project highlighting the main outputs for nominal and off-nominal conditions. Section 4 concludes the paper with a summary and remarks on the achievements.

2. Mission and system characterization

The Space Rider Observer Cube (SROC) mission (Corpino *et al.* 2022, Corpino *et al.* 2019) aims to demonstrate the disruptive technologies required for successfully executing a rendezvous and docking mission in a safety-sensitive context with small satellites. The SROC mission is constituted by a nanosatellite and a deployment & retrieval system. The system will perform a mission featuring proximity operations in the vicinity of the Space Rider (SR) vehicle before

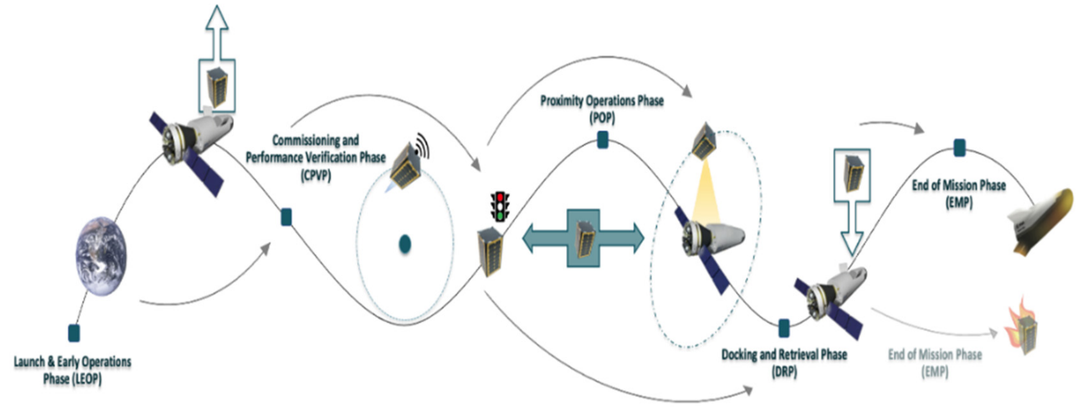


Fig. 1 SROC-Reference mission

docking and re-entering Earth with the mothership.

The SROC project aims at developing and testing in space novel key technologies in the area of proximity operations, such as Propulsion systems (cold gas), Guidance Navigation and Control (hardware and software), Electro-optical systems (visual camera), Mechanisms (docking, deployment, and retrieval), and at improving Autonomous Operations also using Artificial Intelligence algorithms. This in-orbit demonstration has the potential to open a wide spectrum of novel applications for nanosatellites in the area of inspection missions. Furthermore, the development of the advanced technologies needed for the SROC mission will also have a positive impact for pursuing other mission objectives, especially in the domains of in-orbit servicing, space exploration, and debris mitigation.

In the current baseline, the 12U CubeSat will be launched with Vega C inside the Space Rider and deployed from the Multi-Purpose Cargo Bay once in orbit. The target launch is the Space Rider Maiden Flight, currently planned Q4 2025. Once deployed and commissioned, SROC will fly in formation with Space Rider observing the vehicle from a close distance. Then, SROC will rendezvous and dock with its Multi-Purpose CubeSat Dispenser (MPCD) hosted in the Space Rider. Fig. 1 illustrates the design reference mission, in which the Observe & Retrieve scenario is assumed as the baseline, and the Observe scenario is considered as an off-nominal mission in case the retrieval is not possible.

The most challenging phase of the mission is retrieval. It means guiding the small satellite to a mating point with very high accuracy and, even, preventing any collision with the target.

2.1 Reference frames

Four reference frames are defined to formulate the problem (Fig. 2):

- ECEF (Earth Centred Earth Fixed) frame R_I, is considered a quasi-inertial frame.
- Radial-InTrack-CrossTrack (RIC) Frame is a system similar to the LVLH frame defined as:
  - Origin O_{RIC}: centre of mass of the target spacecraft;
  - Axis x_{RIC}, or Radial: in the outward radial direction, from Earth's centre to the target CoM;
  - Axis y_{RIC}, or InTrack: the in the direction of the orbital velocity vector, completes the right-handed triad with the other two axes;

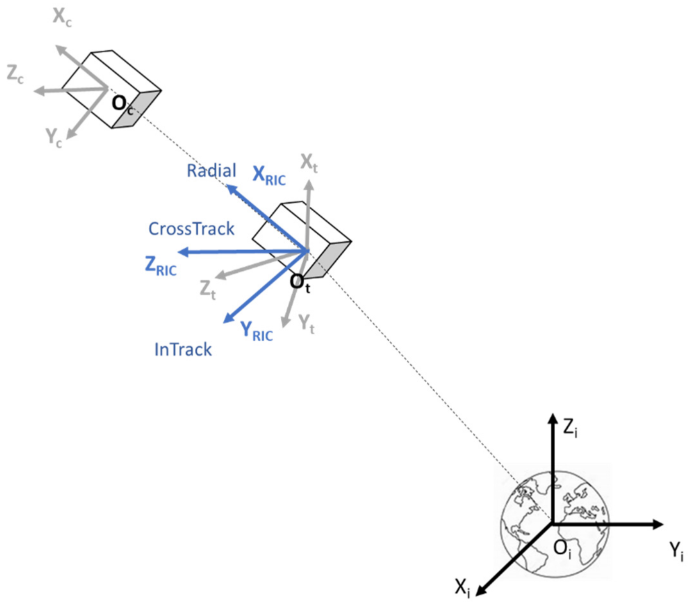


Fig. 2 Reference frames

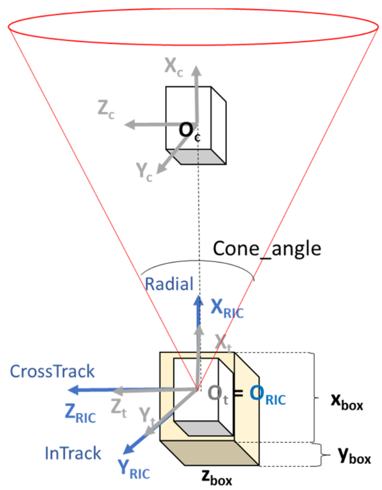


Fig. 3 Approach definition on -Radial axis

◦ Axis z_{RIC}, or CrossTrack: in the direction of the orbit angular momentum vector.

• The Target Body frame R_T.

• The Chaser Body frame R_C.

2.2 Mission and system characterization

The baseline for phase B1 of the SROC mission considers an approach along Radial axis, as shown in Fig. 3.

Table 1 Hold point location

Parameter	Values	Uncertainties
$\omega_{x0}, \omega_{y0}, \omega_{z0}$	$[0;\ 0;\ 0]\ \mathrm{rad/s}$	+/- 1 deg/s
$\varphi_0, \theta_0, \psi_0$	$[0;\ 0;\ 0]$	+/- 0.1
x_0, y_0, z_0	$[-100; 0;\ 0]$ m	+/-2.5 m
$\dot{x}_0, \dot{y}_0, \dot{z}_0$	$[0;\ 0;\ 0]$ m/s	+/- 0.2 m/s

Safety constraints and mission requirements address the definition of crucial parameters and performance required for executing the maneuvers. They are the approach corridor, the state vector of the last Hold Point, the final state at the docking, the time-to-docking, and the collision box.

The *approach corridor* is a cone with the origin in O_{RIC} and an angle (cone_angle) of 15 deg. The CubeSat shall remain inside this zone for the entire duration of a nominal docking. Any deviation imposes a corrective action, such as a CAM. The initial point for the docking maneuver is the last *Hold Point (HP)* characterized by the values in Table 1. It has been defined as a point that lies outside the so-called Keep Out Zone, i.e., a sphere originated from O_{RIC} with a certain radius dimension ($\boldsymbol{r_{KOZ}}$) of 100 m. Any operation (apart from the docking maneuvers) should be performed outside this zone. Table 1 also highlights the uncertainties in any state derived from the requirements and constraints of the Guidance Navigation and Control system on the Absolute Knowledge Error and Mean Knowledge Error. In particular, it is expected) to know the chaser's position with an accuracy lower than 2% of the distance target/chaser. The Hold Point is a point with zero relative velocity (by definition) and a Go/NoGo point where the decision to move is taken when the conditions in terms of safety, illumination, and visibility with the ground station are compliant with the requirements. The desired attitude is the target-pointing strategy to support the navigation cameras. That imposes that the target must point the target with a maximum uncertainty lower than 0.2 deg for axis.

he mating point (i.e., the hold point coincident with O_{RIC}) must be achieved by satisfying the following mating conditions:

◦ the approach velocity ($\dot{x}_f$) along the mating axis shall be less than 5 mm/s

◦ considering the mating mechanism located at (x_f, y_f, z_f)=(0, 0, 0), the lateral misalignment (Δy_f, Δz_f) shall be less than 2 cm, when x_f=0,

◦ the error on relative attitude ($\Delta\varphi_f$, $\Delta\theta_f$, $\Delta\psi_f$) shall be less than 2 deg for any coordinate

◦ the error on relative attitude rate ($\omega_{xf}, \omega_{yf}, \omega_{zf}$) shall be less than 0.1 deg/s with respect any axis

The time-to-docking explains the duration of the maneuver from Hold Point to Mating point the adopted value is 900 sec and depends on the output of the communication windows analysis between the ground and the Cubesat because the entire maneuver shall be completed in the visibility of the ground stations.

Finally, the *collision box* defines the space occupied by the target with a margin of the 10%. It has been defined as x_{box}=2 m, y_{box}=9 m, z_{box}=8 m.

At Cubesat system level, the parameters of interest for the analysis and related values (with uncertainties) are the mass $\boldsymbol{m_{ch}}$ of 2 kg +/-10% and the inertia matrix: Diag $[\boldsymbol{I_{xc}}, \boldsymbol{I_{yc}}, \boldsymbol{I_{zc}}] = [0.07;\ 0.18;\ 0.2]\ \mathrm{kg \cdot m^2}$ +/-10%

Navigation sensors are a LIDAR, a Visible Camera with a Narrow Field of View (N-FOV

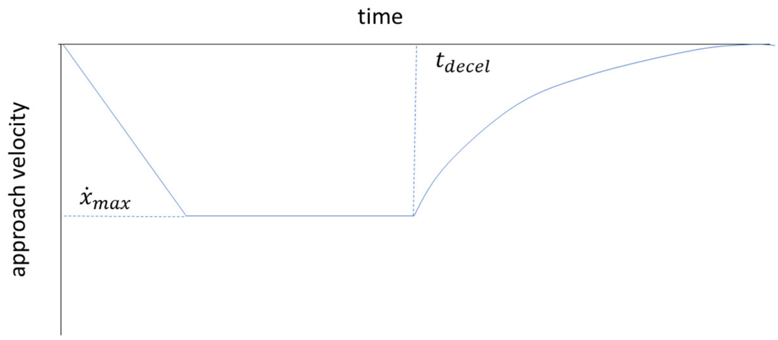


Fig. 4 Approach velocity profile

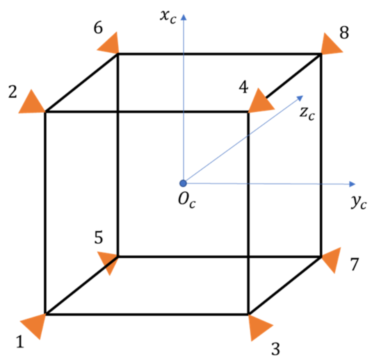


Fig. 5 Thrusters setup for the current analyses

camera), and a Visible Camera with a Wide Field of View (W-FOV camera). Moreover, a GNSS - receiver is included. According to the relative position (**p**), different sensors and navigation filters are active. In general, the adopted state observers are the Extended Kalman Filter, conveniently tuned considering the reliability of the sensors measurements and the models fidelity of the onboard dynamics. The values about mean and the standard deviations derived from analysis and literature review, such as (Opromolla *et al.* 2017, Caon *et al.* 2022, Lovaglio 2024).

The *Attitude determination* is based on 2 Star Trackers and a tri-axial gyroscope, while an extended Kalman filter (EKF) provides the estimation of attitude ($\hat{\boldsymbol{\alpha}}$), and attitude rate ($\hat{\boldsymbol{\omega}}$).

The Guidance strategies are based on the definition of velocity and position profile:

• Velocity profile (Fig. 4): An acceleration profile is implemented at the start of the motion to achieve a desired approach velocity ($\dot{x}_{\max}$=0.2 m/s). At the end, a deceleration profile is implemented to arrive at the desired position with the desired velocity. At the start of motion a constant acceleration will bring the vehicle in the shortest possible time to the desired approach velocity, and thrust in this direction can be stopped when the velocity is achieved. The approach velocity is maintained up to a certain distance (deceleration position) of x_{decel}>30 m or a specific instant t_{decel}<400s for the start. The maneuver is completed through an exponential deceleration profile that allows to fulfil passive safety criteria in case of loss of thrust

• Position profile: the position profile coincides with the straight-line axis and includes the terminal point (i.e., the mating point).

The Control of straight-line maneuver: is guaranteed by a Tracking Model Predictive Controller

(T-MPC) as in (Stesina 2021). The Control of attitude and angular velocity is guaranteed by an H-infinity controller (Pecorilla and Stesina 2023). The advantages of the sliding mode controller applied to the presented rendezvous and docking problem are the capability to efficiently deal with nonlinear dynamics and the robustness against the modeling uncertainties.

The attitude actuators are 3 Rection Wheels and 3 Magnetic Torquers. The maximum control torque is ($|\boldsymbol{T}_{cx\_max}|$, $|\boldsymbol{T}_{cy\_max}|$, $|\boldsymbol{T}_{cz\_max}|$)= [0.5; 0.5; 0.5] Nm (-20%)

The Propulsion system is a cold gas system able to provide a maximum force Max($|\boldsymbol{F}_{cx}|$, $|\boldsymbol{F}_{cy}|$, $|\boldsymbol{F}_{cz}|$)=[0.042; 0.042; 0.035] N. Thrusters position and related number are reported in Fig. 5. (Mantellato *et al.* 2022).

2.3 Simulation architecture

Detailed models and a robust simulation architecture have been built in the MATLAB/Simulink© Environment.

This architecture (Fig. 6) includes:

• *Orbit propagator* models the orbital motion of Chaser and Target to define Latitude, Longitude and Altitude, useful to estimate the disturbance forces and torques.

• *Disturbance Torques* (**T_d**) include disturbance torques from Aerodynamic Drag due to residual atmosphere, Gravitational Gradient, Residual Magnetic Dipole, and Sloshing of Fuel in the tank.

Disturbance Forces ($\mathbf{F_d}$) include aerodynamic drag due to the residual atmosphere and Geopotential Anomaly (J2).

Relative rotational Dynamics and Kinematics and Relative translational Dynamics and Kinematics (Fehse 2011): translational and rotational dynamics are coupled considering an uncertain location of the CoM, an unbalanced thruster activation, an uncertain alignment of the thrust vector, and an uncertain attitude. Clothessy-Wilshire equations are used to compute the relative position ($\mathbf{p}$=[x, y, z]) and the relative velocity ($\mathbf{v}$=[$\dot{x}, \dot{y}, \dot{z}$]) in RIC frame (Eq. (1), where n is the orbit angular rate), while Euler's equations for the rigid body (where $\boldsymbol{\omega}$=[$\omega_x, \omega_y, \omega_z$] is the angular rate) and Euler angles ($\boldsymbol{\alpha}$=[φ, θ, ψ]) are used to compute the rotational part (Eq. (2), where I is the inertia matrix).

$$\begin{cases} \ddot{x} = 3n^2x + 2n\dot{y} + \dfrac{1}{m_c}F_x \\ \ddot{y} = -2n\dot{x} + \dfrac{1}{m_c}F_y \\ \ddot{z} = -n^2z + \dfrac{1}{m_c}F_z \end{cases} \tag{1}$$

$$\boldsymbol{T} = \mathrm{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \mathrm{I}\boldsymbol{\omega} \;\; \Leftrightarrow \;\; \dot{\boldsymbol{\omega}} = \mathrm{I}^{-1}(\boldsymbol{T} - (\boldsymbol{\omega} \times \mathrm{I}\boldsymbol{\omega})) \tag{2}$$

The entire state vector is given by [**p**, **v**, **α**, **ω**]

• *Position and velocity observer emulator*: for sake of simplicity, position and velocity estimation from the observers are emulated as the value of **p** and **v** plus an uncertainty modeled as a percentage of **p** and **v** with a Gaussian distribution.

• *Desired attitude and angular velocity:* the desired attitude is Target pointing, meaning that the Chaser attitude and the Target attitude coincide. For the nominal approach along the Radial

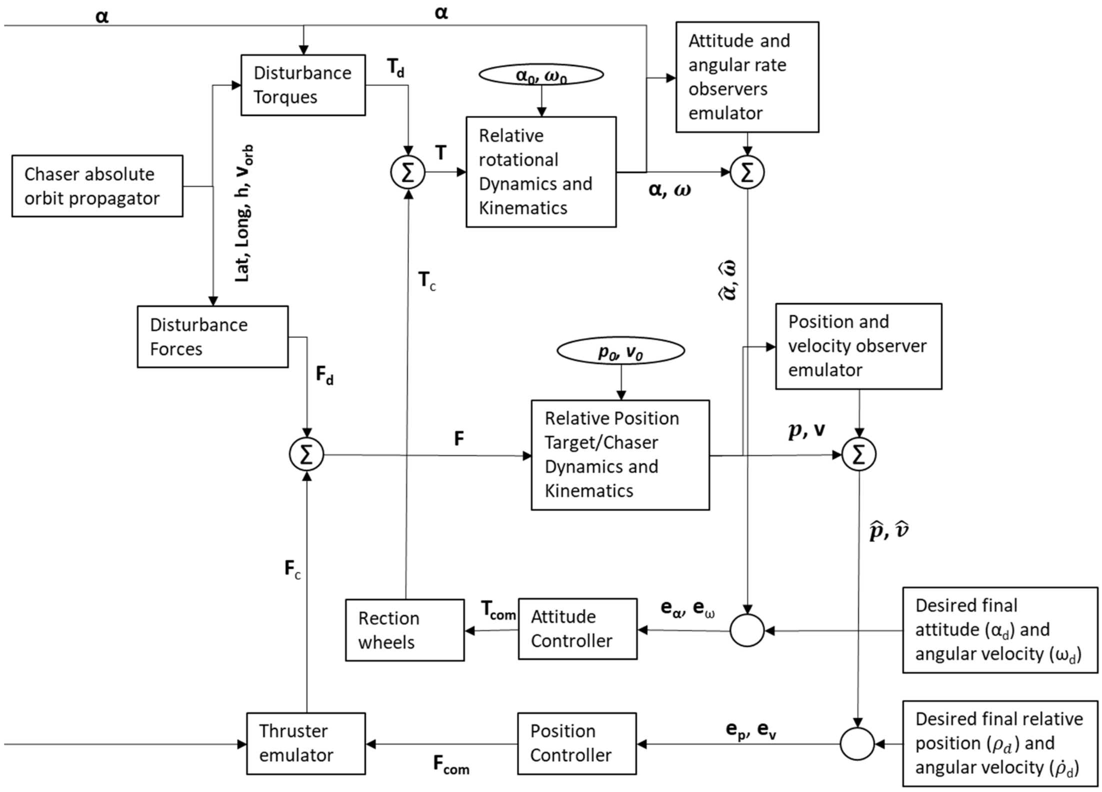


Fig. 6 Simulation architecture

axis, the Target is aligned with RIC and its attitude is the reference for the target. The desired angular velocity is null around all body axes.

• *Desired relative position and velocity*: solutions for guidance are described in the previous paragraph.

• *Attitude Controller and Position Controller*: a Non-linear Model Predictive Control (NMPC) was implemented for position control, while a Sliding Mode Control was adopted for attitude. Attitude Control is based on H infinity strategy (as in Pecorilla and Stesina (2023)).

• *Reaction wheels (RW)*: three reaction wheels installed along the main body axes of the Chaser transform the commanded torques into the actuated torques. The effective torque generated by RWs is simulated with a second-order dynamical system.

• *Thruster*: the propulsion system has eight lines equipped with Normally-Closed -valves (independently controlled) and a nozzle. Every nozzle is tilted with respect to R_c angles:

- $\varepsilon=\pi/4$ with respect to x_c axis;
- $\tau=\pi/6$ with respect to z_c axis.

That allows to maintain a 6DoF control also in case of one failure. Moreover, the adopted mathematical model includes thrust vector errors in terms of thrust force (reduced up to 20% of the nominal value), thrust duration (+/-5% of the desired time to open and close the valves), and thrust misalignment (up 0.2 deg of deviation from the desired direction, i.e., thruster angles ε and τ w.r.t. the *Rc*).

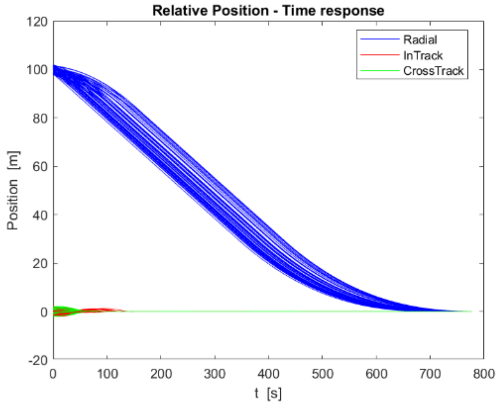


Fig. 7 Trend of the trajectory vs time

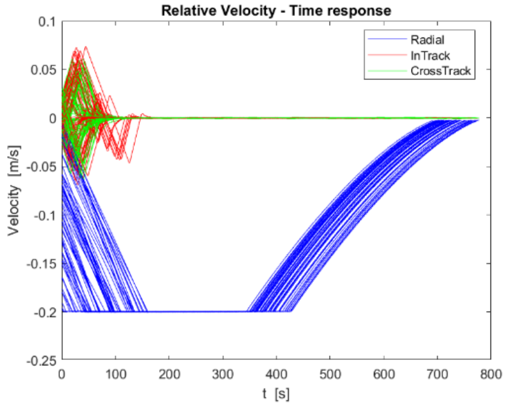


Fig. 8 Trend of the velocity vs time

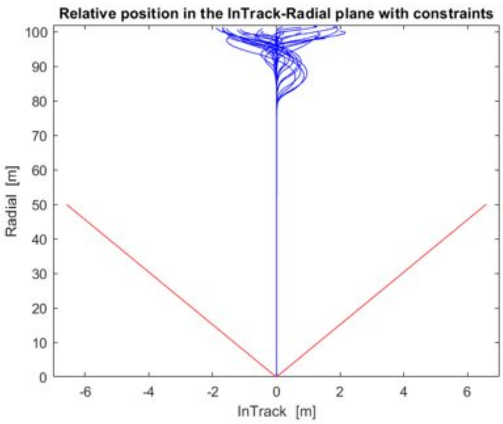


Fig. 9 Trajectory in InTrack/Radial plane

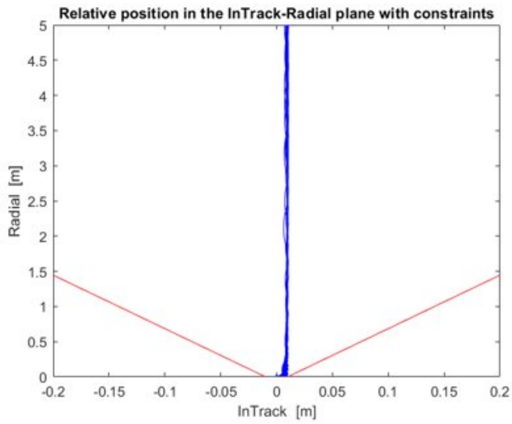


Fig. 10 Details of the last 5-meters trajectory in InTrack/Radial plane

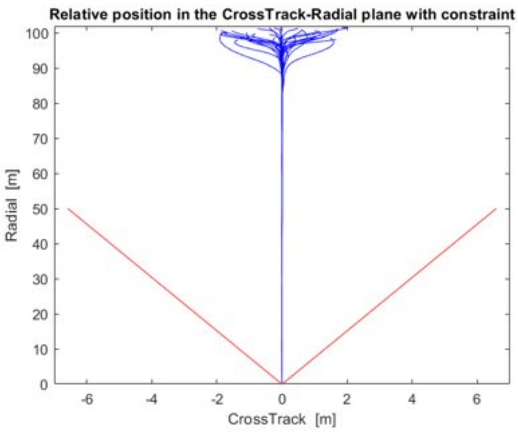


Fig. 11 Trajectory in CrossTrack/Radial plane

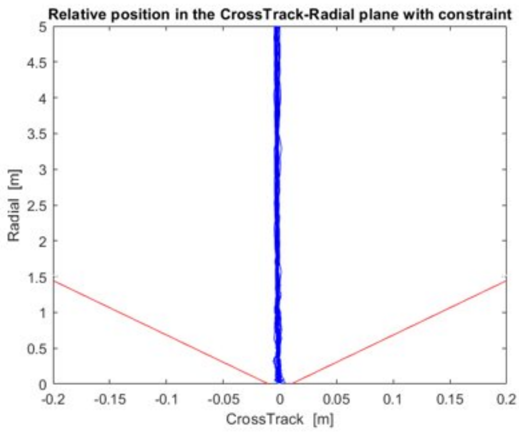


Fig. 12 Details of the last 5-meters trajectory in CrossTrack/ Radial plane

3. Analysis of the safe trajectories in nominal conditions

"Nominal case" means that the maneuvers are completed under the desired conditions without relevant discrepancies. The term relevant indicates that the actual condition of the spacecraft violates one or more constraints and prevents any possibility of recovering the nominal conditions in the future. In general, a range of margin should be defined on any desired parameter and inside that range, the satellite correctly and safely operates. The analysis of the nominal conditions supported the tuning of controllers and state observers, the definition of the worst case, and the assessment of the robustness of the design through Monte Carlo simulations.

The main results of the robust analysis are focused on in this paper because they lead to identifying the boundaries of the nominal conditions. In particular, 60 Monte Carlo simulations have been run by randomly changing 1) HP initial conditions (see Table 1), 2) CubeSat mass (m_{ch}), 3) CubeSat inertia (I_{ch}) according to the above-specified values, and it has been observed if the mating conditions are satisfied without violation of the safety constraints.

Trajectory follows the guidance rules (Fig. 7 and Fig. 8) and the mating conditions are satisfied: the final misalignment is within a circle with 15 mm diameter (from Fig. 9 to Fig. 12). The maneuver is always completed in less than 760 seconds and the reference profile on the velocity is tracked: the $V_{\max}$ is reached in less than 180 s and the expected deceleration starts no later from d_{decel}=40 m. The final approach velocity is no more than 2 mm/s, the lateral misalignment is less than 2 cm. The final misalignment from expected pointing is less than 0.2 deg and the final angular rate is less than 0.005 deg/s.

4 Analysis in off-nominal conditions

For this analysis at a preliminary stage, the identification of the misbehaviors is carried out at the functional level, without the necessity for a complete FMEA of the system and subsystem elements, because only preliminary information on the system is known.

In this way, misbehavior effects are the generation of errors on the state vector and/or the loss of one of the GNC/ADCS functions. Since the system needs to be tolerant to no more than one failure and guarantee that corrective actions can be completed.

Corrective actions are all the strategies that, applied to the chaser, lead the CubeSat to avoid collisions with the target and move away from it and/or to avoid collision with the target and achieve a stable point that can enable a new attempt of docking, and/or to recover the nominal conditions and continues the docking.

Most of these strategies are normally based on the definition of passive-safe trajectories or CAM when possible: when an off-nominal condition occurs, the selection of a passive-safe trajectory or a CAM depends on the distance from the target and the type of failure.

In every case in which active trajectory control has failed and the present trajectory, if not controlled, results as dangerous as it may or will lead to a collision, the execution of a CAM is necessary. A CAM is executed in any case of violation of the position and velocity safety margins. Such a maneuver must be as simple as possible, to be performed by the system with minimal resources: the simplest case is a single lateral boost from straight line motion, where the CAM thrust is fixed in a single direction with respect to the body frame. No functioning of the GNC is required during the execution of a CAM. In practical terms, predetermined thrust directions and burn times are processed following an open loop type of control for the application of the desired ΔV.

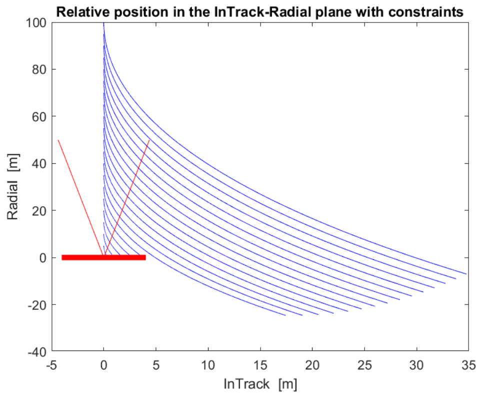


Fig. 13 Passive safe trajectory analysis from 100 to 10 meters

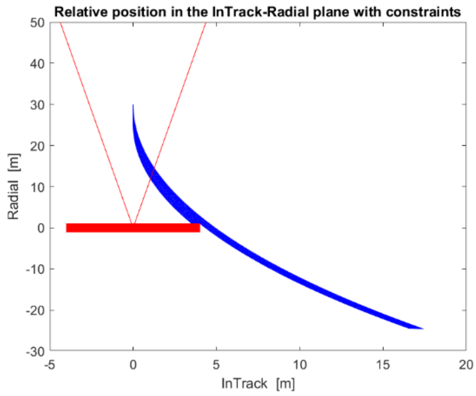


Fig. 14 Passive safe trajectory-detail on 25 m to 30 m range

Moreover, the collision avoidance maneuvers do not include any maneuvers for a new attempt in case of hard and permanent failure. On the contrary, a new docking attempt can be enabled in case of a transient failure. The entire analysis allows to determine the minimum distance from which trajectory remains passive-safe and the minimum distance for effective CAM in case of off-nominal conditions on relative velocity, relative position, relative angular rate, and relative attitude, and assess the CAM successful in case of one failure on navigation, propulsion system, and attitude determination and control.

A selection of the most representative results of the off-nominal analysis is presented in this paper. They are: the assessment of the minimum distance from which passive-safe trajectories are effective, the assessment of the minimum distance from which CAM are effective with off-nominal conditions on relative velocity, and the when one failure occurs on propulsion

4.1 Passive safe trajectory assessment

This analysis aims to identify the last point from which the trajectory remains passive-safe.

The analysis is performed by disconnecting the controller on the position and the propulsion system from the simulation architecture to prevent the use of any control force

Any simulation run starts at a distance that changes from 100 to 10 meters along the docking axis, with the nominal velocity (i.e., compliant with the velocity profile) nominal attitude, and attitude rate.

Fig. 13 shows that the collision is avoided from a distance between 25 and 30 meters. Fig. 14 shows the details on the range 25 to 30 highlighting that the chaser trajectory remains passively safe for a distance higher than 27.5 meters.

4.2 Collision avoidance maneuvers assessment

The assessment of the collision avoidance maneuvers aims at identifying the maneuver's effort and the effectiveness.

The CAMs are modeled as open-loop impulsive maneuvers: a maximum thrust in a predetermined direction for a given time interval is applied. Two strategies are assessed:

Table 2 Summary of the results for the assessment of CAM effectiveness

	Radial Approach Baseline	
CAM thrust direction	+Radial +InTrack	+InTrack
Thrusts duration	200 s Radial 100 s InTrack	100 s InTrack
Total ΔV	0.528 m/s	0.22 m/s
CAM effectiveness	Collision always prevented for **Radial distance≥7 m**	Collision always prevented for **Radial distance≥14 m**

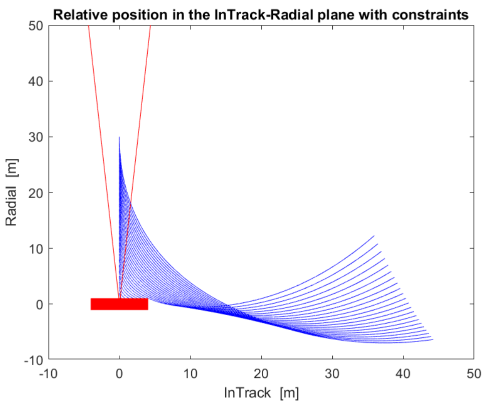


Fig. 15 Best approach for CAM with deceleration along -Radial in Radial approach. (a) Radial/InTrack view

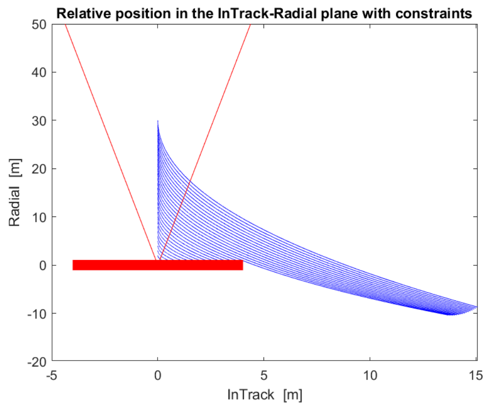


Fig. 16 Best approach for CAM without deceleration along -Radial in Radial approach.: Radial/InTrack view

maneuvers that include the thrust toward the Target (i.e., deceleration along the docking axis) and maneuvers that avoid thrusts toward the Target.

To study CAM effectiveness, CAMs are performed moving from the docking axis, starting from a relative distance of 1 m with steps of 1 m up to a distance of 30 m, where maximum velocity is reached. Initial velocities are calculated from the reference velocity function, increased by a margin of 100%. If CAMs are completed at 30 m, any CAM performed from a greater distance is assumed completed too, as nominal velocity is constant for distances>30 m.

Results for best CAMs are briefly reported in Table 2.

The collision is prevented for distances higher than 7 m for a combined maneuver InTrack+Radial (Fig. 15) and higher than 14 m for only In-Track maneuver (Fig. 16).

4.2.1 Passive safe trajectory assessment after a CAM

This analysis aims to verify that SROC continues to move away from SR after the completion of the CAM, maintaining a passive-safe trajectory.

In this case, the CAM starts at a random point inside the approach cone between 15 m and 50 m of relative distance CAMs are modeled as open-loop maneuvers, i.e., the maximum thrust is requested to the actuators in a specific direction for a certain time. Two direction options are evaluated, i.e., -InTrack and+InTrack.

The maneuver effectiveness is evaluated over 3 orbits, i.e., about 18000 seconds.

The simulations show (Fig. 17 and Fig. 18) that, after mid-orbit, the relative distance is about

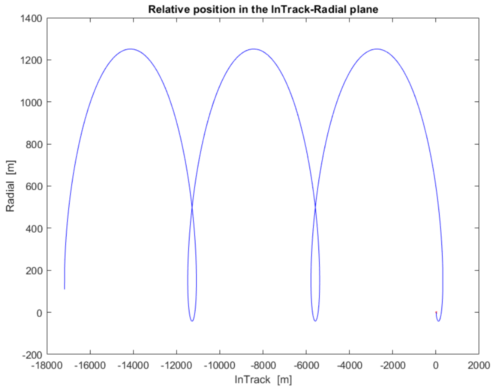


Fig. 17 Trajectory after CAM: InTrack/Radial view

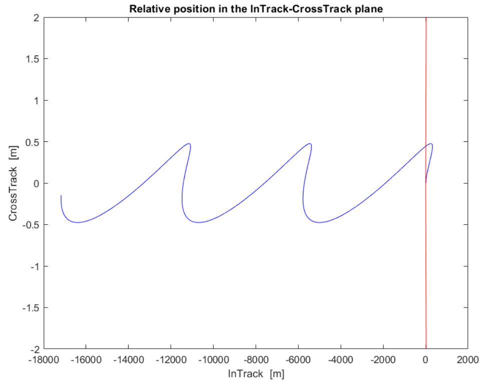


Fig. 18 Trajectory after CAM: InTrack/CrossTrack view

Table 3 Docking and CAM maneuver in the presence of one failure on one thruster

	Th 1	Th 2	Th 3	Th 4	Th 5	Th 6	Th 7	Th 8
Percentage of success	55	100	1.7	100	56.6	100	3	100

[1200 m, 3000 m, 0 m], expressed in RIC reference frame, and, after one orbit, the relative distance target/chaser is about [0, 6000 m, 0]. It means that the CAMs effectively move away the Cubesat without further risk of collision.

4.3 Docking and collision avoidance maneuvers assessment for propulsion system failure

Thruster failure represents a major loss for the system propulsion capabilities, especially if the failure affects one of the thrusters mostly involved in the maneuvers.

This analysis aims to assess the capability of the chaser to perform docking and collision avoidance maneuvers in case of one-thruster failure.

This simulation session is divided into two parts. The first one allows verifying if the docking is possible with a failure. If the mating is impossible under the safety constraints, a second run is executed to confirm the possibility of completing a CAM.

For the first session, the initial conditions are set and a failure on one of the thrusters is randomly generated; in particular, one of the valves remains permanently in normally-closed condition. 60 Monte-Carlo simulations are applied for each of the eight thrusters in failure in order to assess the percentage of successful mating.

A second simulation session runs to assess the planned CAM by excluding the thruster in failure contribution. CAM assessment is repeated for any single failure of the eight thrusters of the propulsion system.

The results of the first part of this analysis are reported in Table 3.

Failures on thrusters 3 and 7 are critical because they guarantee a fundamental direction of firing for maintaining the straight line trajectory along the docking axis and to prevent lateral drift. So, their failure leads to very low success rates with major deviations from final mating conditions. For example, a failure of thruster 3 generates significant violations (over the

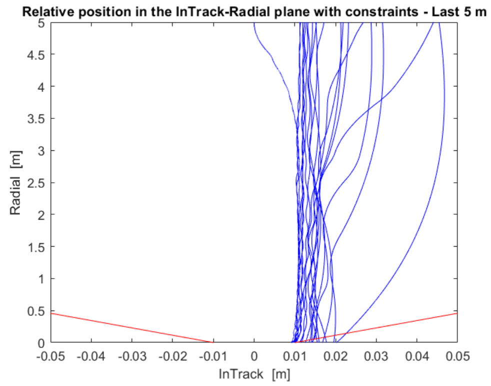


Fig. 19 Trajectory for thruster 3 failure-InTrack/Radial view

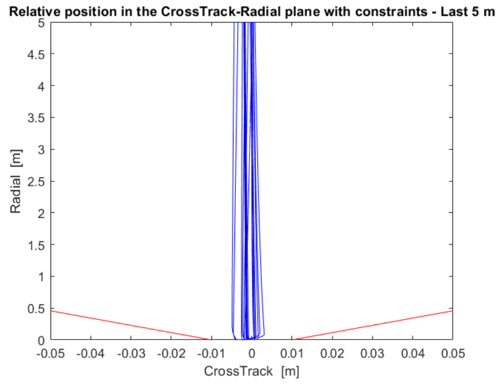


Fig. 20 Trajectory for thruster 3 failure-Radial/CrossTrack view

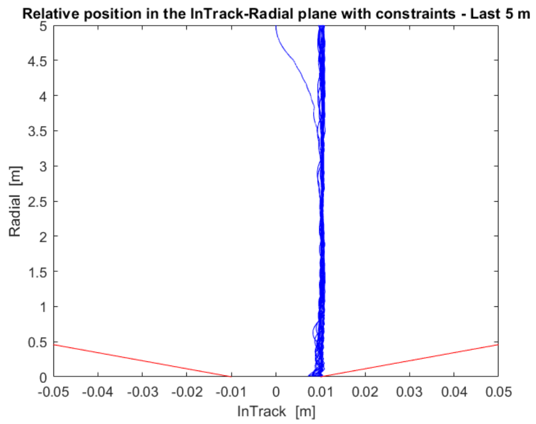


Fig. 21 Trajectory for thruster 8 failure-InTrack/Radial view

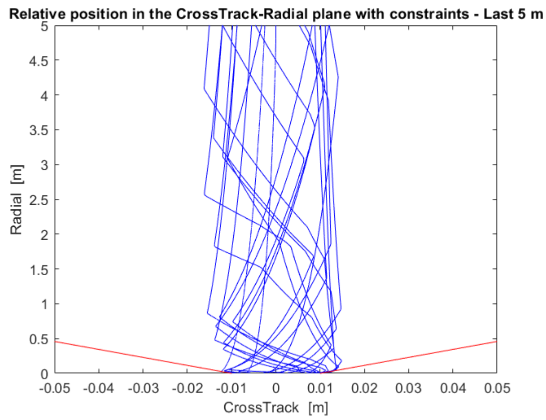
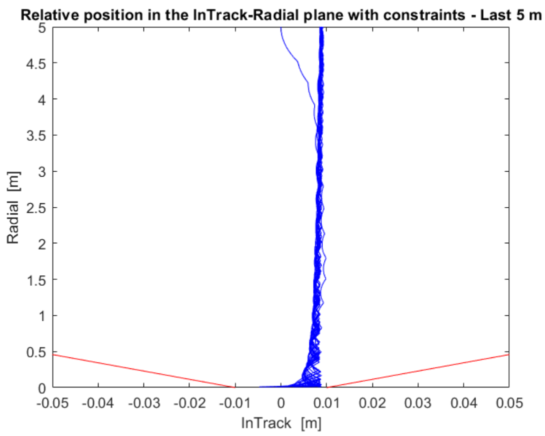
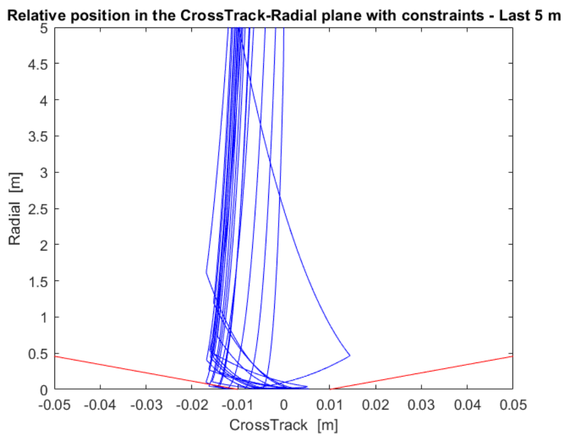


Fig. 22 Trajectory for thruster 8 failure-Radial/CrossTrack view



(a)

Fig. 23 Trajectory for thruster 1 failure-InTrack/Radial view



(b)

Fig. 24 Trajectory for thruster 1 failure-Radial/CrossTrack view

Table 4 Mean and maximum deltaV for any maneuver

	Mean deltaV	Max deltaV
Final approach from 100m	1,1663 m/s	1,3483 m/s
CAM	0,5961 m/s	0,7332 m/s

requirement of 2 cm) as shown in Fig. 19 and Fig. 20.

Failure of thrusters 2, 4, 6, and 8 leads to success rates of 100%, with no final conditions violations.

The remaining cases (on thrusters 1 and 5) present a success rate of around 55% from the final point requirements. For example, the docking success rate is 55% when thruster 1 fails (see Fig. 23 and Fig. 24) and the maximum violation is 2 mm only along CrossTrack.

The second simulation session highlights that CAM is always successfully performed, for any thruster in failure and any initial condition.

Table 4 reports the deltaV required for the execution of each maneuver. The values are compatible with the selected propulsion system. (Corpino *et al.* 2020).

5. Conclusions

The paper proposes the analysis of the nominal and off-nominal approach of the SROC CubeSat during the docking with a larger and collaborative target (i.e., Space Rider) that retrieves the SROC. The analysis refers to the preliminary design phases (phase A and phase B1) when the main constraints at the mission level are identified, and the small satellite features are preliminarily defined.

The results prove that a 12U CubeSat can perform docking maneuvers in nominal conditions up to achieving the mating with a lateral misalignment of less than 2 cm with a low velocity (less than 1 mm/s @ the mating point). Moreover, it is shown that the satellite can safely complete collision avoidance maneuvers in case of off-nominal occurrences. Finally, the paper traces a method to conduct a safety analysis for a small satellite involved in docking, highlighting the parameters that should be defined, the complete simulation sessions list and related conditions and setup, and the best practices to obtain the expected outputs for a preliminary requirement review (PPR).

References

Bollattino, S. and Stesina, F. (2024), “Fast development and validation of a Sensing Suite system for CubeSats”, *Acta Astronautica*, **223**, 342-354. https://doi.org/10.1016/j.actaastro.2024.07.005.

Bowen, J., Villa, M. and Williams, A. (2015), “Cubesat based rendezvous, proximity operations, and docking in the CPOD mission”, *Proceedings of Small Satellite Conference*, Logan, Utah, August.

Branz, F., Olivieri, L., Sansone, F. and Francesconi, A. (2020), “Miniature docking mechanism for CubeSats”, *Acta Astronautica*, **176**, 510-519. https://doi.org/10.1016/j.actaastro.2020.06.042.

Caon, A., Peruffo, M., Branz, F. and Francesconi, A. (2022), “Consensus sensor fusion to estimate the relative attitude during space capture operations”, *2022 IEEE 9th International Workshop on Metrology for AeroSpace (MetroAeroSpace)*, June.

Cervone, A., Topputo, F., Speretta, S., Menicucci, A., Turan, E., Di Lizia, P., ... & Walker, R. (2022), "LUMIO: A CubeSat for observing and characterizing micro-meteoroid impacts on the Lunar far side", *Acta Astronautica*, **195**, 309-317. https://doi.org/10.1016/j.actaastro.2022.03.032.

Corpino, S. and Stesina, F. (2020), "Inspection of the cis-lunar station using multi-purpose autonomous Cubesats", *Acta Astronautica*, **175**, 591-605. https://doi.org/10.1016/j.actaastro.2020.05.053.

Corpino, S., Ammirante, G., Daddi, G., Stesina, F., Corradino, F., Basler, A., ... & Van den Eynde, J. (2022), "Space rider observer Cube-SROC: A CubeSat mission for proximity operations demonstration", *Proceedings of the International Astronautical Congress*, IAC, Paris, October.

Corpino, S., Franchi, L., Calvi, D., Guerra, L., Sette, S. and Stesina, F. (2019), "Small satellite mission design supported by tradespace exploration with concurrent engineering: Space rider observer cube case study", *Proceedings of 70th International Astronautical Congress, IAC 2019*, Washington (US).

Corpino, S., Stesina, F., Calvi, D. and Guerra, L. (2020), "Trajectory analysis of a CubeSat mission for the inspection of an orbiting vehicle", *Adv. Aircraft Spacecraft Sci.*, **7**(3), 271-290. https://doi.org/10.12989/aas.2020.7.3.271.

Fabiani, S., Baffo, I., Bonomo, S., Contini, G., Costa, E., Cucinella, G., ... & Zambardi, A. (2022), "CUSP: a two CubeSats constellation for space weather and solar flares x-ray polarimetry", *Proceedings of SPIE-The International Society for Optical Engineering*, Montreal, July. https://doi.org/10.1117/12.2629233.

Fehse, W. (2011), *Automated Rendezvous and Docking of Spacecraft*, Cambridge University Press.

Lepcha, P., Malmadayalage, T.D., Örger, N.C., Purio, M.A., Duran, F., Kishimoto, M., ... & Cho, M. (2022), "Assessing the capacity and coverage of satellite iot for developing countries using a CubeSat", *Appl. Sci.*, **12**, 8623. https://doi.org/10.3390/app12178623.

Limón-González, M., García-Sánchez, E.R., Vargas-Martínez, H.S., Quiroz-Hernández, N. and Maya-Rueda, S.E. (2023), "Performance analysis of inter-satellite and satellite-ground communication: A report on flight data for a low earth orbit Cubesat", *Aerosp.*, **10**, 973. https://doi.org/10.3390/aerospace10110973.

Lin, X., Shi, X. and Li, S. (2020), "Optimal cooperative control for formation flying spacecraft with collision avoidance", *Sci. Progr.*, **103**(1), 0036850419884432. https://doi.org/10.1177/0036850419884432.

Lovaglio, L. (2024), "AI-based optical navigation for Rendezvous and Proximity Operations (RPOs) missions of small satellites", Doctoral dissertation, Politecnico di Torino.

Mammarella, M., Lee, D.Y., Park, H., Capello, E., Dentis, M. and Guglieri, G. (2019), "Attitude control of a small spacecraft via tube-based model predictive control", *J. Spacecraft Rocket.*, **56**(6), 1662-1679. https://doi.org/10.2514/1.A34394.

Mantellato, R., Bellomo, N., Barato, F., Milza, F., Pavarin, D., Cardi, M., ... & Corradino, F. (2022), "Characterization of the perseus cold gas propulsion system", *Proceedings of Small Satellite Conference*, Logan, Utah, August.

Modenini, D. (2019), "Five-degree-of-freedom pose estimation from an imaged ellipsoid of revolution", *J. Spacecraft Rocket*, **56**(3), 952-958. https://doi.org/10.2514/1.A34340.

NASA Ames Research Center (2023), NASA/TP—2022-0018058-State-of-the-Art Small Spacecraft Technology, January.

Nichele, F., Villa, M. and Vanotti, M. (2018), "Proximity operations-autonomous space drones", *Proceedings of the 4S Symposium*, Sorrento, May.

Opromolla, R., Fasano, G., Rufino, G. and Grassi, M. (2017), "A review of cooperative and uncooperative spacecraft pose determination techniques for close-proximity operations", *Progr. Aerosp. Sci.*, **93**, 53-72. https://doi.org/10.1016/j.paerosci.2017.07.001.

Pirat, C., Ankersen, F., Walker, R. and Gass, V. (2020), "H∞ and μ-Synthesis for nanosatellites rendezvous and docking", *IEEE Trans. Control Syst. Technol.*, **28**(3), 1050-1057. https://doi.org/10.1109/TCST.2019.2892923.

Richard, M., Gorret, B., Métrailler, L., Pirat, C.S., Voillat, R., Frei, T., ... & Lauria, M. (2016), "Developing a reliable capture system for Cleanspace one", *Proceedings of the International Astronautical Congress*, Guadalajara, October.

Roscoe, C.W., Westphal, J.J. and Mosleh, E. (2018), "Overview and GNC design of the CubeSat Proximity

Operations Demonstration (CPOD) mission", *Acta Astronautica*, **153**, 410-421. https://doi.org/10.1016/j.actaastro.2018.03.033.

Schwartz, N., Brzozowski, W., Ali, Z., Milanova, M., Morris, K., Bond, C., ... & Bruce, H. (2022), "6U CubeSat deployable telescope for optical Earth observation and astronomical optical imaging*", Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave*, **12180**, 1097-1108.

Stesina, F. (2021), "Tracking model predictive control for docking maneuvers of a cubesat with a big spacecraft", *Aerosp.*, **8**, 197. https://doi.org/10.3390/aerospace8080197.

Stesina, F., Corpino, S. and Feruglio, L. (2017), "An in-the-loop simulator for the verification of small space platforms", *Int. Rev. Aerosp. Eng.*, **10**(2), 50-60. https://doi.org/10.15866/irease.v10i2.10593.

Stesina, F., Corpino, S., Novara, C. and Russo, S. (2022), "Docking manoeuvre control for cubesats", *J. Astronaut. Sci.*, **69**(2), 312-334. https://doi.org/10.1007/s40295-022-00307-1.

Viscio, M.A., Viola, N., Corpino, S., Stesina, S., Circi, C., Fineschi, S. and Fumenti, F. (2013), "Interplanetary cubesats mission to earth-sun libration point for space weather evaluations*", Proceedings of 64th International Astronautical Congress 2013*, Cape Town, September.

Votta, R., Gardi, R., Zaccagnino, E., Cardi, M., Basler, A., Corradino, F., ... & Fedele, A. (2022), "DAVID the first 6U Cubesat mission of the Italian space agency programme iperdrone as demonstration of new on orbit services performed by space drones", *Proceeding of Small Satellite Conference*, Utah, August.

Yu, K., Han, S., Bu, J., An, Y., Zhou, Z., Wang, C., ... & Cheong, J.W. (2022), "Spaceborne GNSS reflectometry", *Remote Sensor.*, **14**, 1605. https://doi.org/10.3390/rs14071605.

Zannoni, M., Tommei, G., Modenini, D., Tortora, P., Mackenzie, R., Scoubeau, M., ... & Carnelli, I. (2018), "Radio science investigations with the Asteroid impact mission", *Adv. Space Res.*, **62**(8), 2273-2289. https://doi.org/10.1016/j.asr.2017.12.003.

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