MISSION ANALYSIS AND DESIGN FOR AN ACTIVE DEBRIS REMOVAL SERVICE FOR LARGE CONSTELLATIONS

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ABSTRACT

One of the ways to harmonise large constellation deployment trends with the space sustainability is through the responsible behaviour by operators to follow space debris mitigation guidelines. On the other hand, there is no doubt, a removal service will be needed for removing failed satellites. Within the Sunrise project a consortium composed of D-Orbit SpA and Politecnico di Milano is working to propose one of them: a service for Active Debris Removal for failed satellites of large constellations. The paper presents the different mission architectures studied, the rendezvous and close-proximity operation preliminary design and the system design.

INTRODUCTION

In the recent years we are witnessing to a tendency to launch large constellations composed of thousands of satellites for providing enhanced telecommunication services, such as broadband internet from Low Earth Orbit. The rising needs for enhanced services from space leads to the design of more complicated constellation configuration geometries. In addition, commercialisation of the services they offer leads to the deployment of several constellations. The increase of the number of small satellites in orbit, together with the background exponential growth of space debris, will force the implementation of passive and active debris mitigation guidelines. On the other side, the development of space activities in the New Space era will boost new business models for the supply of novel services in and from space. Therefore, is more and more important to harmonise large constellation deployment trends with the space sustainability. This can be achieved through the responsible behaviour by operators to follow space debris mitigation guidelines. On the other hand, there is no doubt, a removal service will be needed for removing failed satellites.

A consortium composed of D-Orbit SpA and Politecnico di Milano is working to propose one of them: a service for Active Debris Removal (ADR) for failed satellites of large constellations. Indeed, as these constellations are being launched in these years, the time is now to interact with operational companies and steer where possible the satellite design, for example to propose the use of standard grabbing interfaces or operational modes.

In this work the phase A design for an ADR service for large constellations is presented. Three mission architectures have been analysed: (1) a mothership, carrying from 2 up to 8 de-orbiting kits, that will approach the failed target s/c and then anchor one kit to it, to provide deorbiting capabilities; (2) a chaser capable of capturing and deorbiting multiple target s/c, one at a time, and (3) a station plus chaser architecture, where the station can perform on-orbit refuelling of the chaser to increase the number of targets serviceable. The output of the mission analysis is the maximum number of serviceable s/c per each mission architecture, together with their displacement in plane and on different orbit planes as a function of the maximum total delta-velocity cost and the allowed time per intervention. Moreover, the most challenging aspects of the missions, that is the design of the guidance, navigation and control for the far-to-close range and close-range phase of the capture will be shown, together with preliminary requirements for the attachment mechanism between the servicer and the failed s/c. The impingement of the engine exhaust gasses onto the failed s/c to control the target tumbling is also considered for reducing the angular rate and making the approach and capture phase viable. The spacecraft design for the selected mission will be shown and the economic viability of such a service will be demonstrated.

MISSION ARCHITECTURE TRADE-OFF

Problem setting

Three different mission architectures were proposed: a mothership + kit architecture, a chaser architecture, and a station + chaser architecture. These will be described in the next Sections. To cover all the possible constellation types for this ADR service, two customer cases where considered: a light target and a heavy target. These cases differ for the characteristics of the spacecraft to be serviced, i.e., the mass, the area, but also the orbit characteristics i.e., altitude, inclination, number of planes

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and the Right Ascension of the Ascending Node (RAAN) spacing among them. For this reason, also the injection orbit for the mission architectures is different for these two service cases. Besides, the launch for the mothership and chaser architectures is rideshared with the constellation operator, and the initial RAAN slot of ADR servicer spacecraft cannot be freely chosen; while the launch for the station + chaser architecture is independent, and the initial RAAN slot of ADR service spacecraft can be freely chosen. Table 1 and Table 2 contains the property of the constellation to be serviced and the injection orbit where the ADR servicer is injected for the three architectures, respectively. For conciseness in this paper only the results of the light case will be presented.

Some requirements were set. After the separation from the ADR servicer spacecraft (i.e., mothership, kit, and chaser), the target shall re-enter within 5 years. At the end of mission, the ADR servicer spacecraft (i.e., mothership, kit, chaser, and station) must re-enter within 25 years. For the ADR servicer spacecraft (i.e., mothership, kit, and chaser) that will de-orbit together with target, they must re-enter within 5 years, with target being the most dimensioning. For mothership + kit architecture, the chaser shall be compatible with maximum lifetime of 5 years, starting from the separation from the launch vehicle and ending with disposal.

Table 1 Properties of constellations.

Constellation	Reference	Mass per target, kg	Area per target, m^2	Altitude, km	Inclination, deg	RAAN spacing, deg	Number of planes
Light-target	OneWeb	150	1.7	1200	87.9	15.2	12
Heavy-target	Globalstar	750	7.8	1400	52.0	22.5	8

Table 2 Properties of injection orbits.

	Mothership + kit		Chaser		Station + chaser	
Constellation	Altitude, km	Inclination, deg	Altitude, km	Inclination, deg	Altitude, km	Inclination, deg
Light target	500	86.0	500	86.0	1100	87.9
Heavy target	Not applicable		920	52.0	1300	52.0

Mothership plus kit architecture

This architecture is composed of two types of distinct but dependent ADR servicer spacecraft, named as mothership and kit; one mothership hosts up to 8 kits. For the mothership, it can capture one target at a time and attach one kit to the target. For the kit, it can de-orbit the target and then re-enter together. After all the eight kits are released, the mothership will capture one last target, de-orbit it, and re-enter together. All motherships are launched together by a single launch vehicle.

The major mission phases are launch, early operation, and commissioning, orbit transfer for coarse orbit phasing for rendezvous, close-proximity operations, capture, de-orbiting. In this Section, we focus on the orbit transfer phases of the mothership, that are, coarse orbit phasing for rendezvous and de-orbiting of the last target. The detailed orbit transfer steps are as follows.

a. Waiting in injection orbit till reaching target's plane
b. Orbit raising towards target's orbit and coarse orbit phasing for rendezvous with the target
c. In-plane coarse orbit phasing for rendezvous with next target

… iteration of Step c till removing all targets in one plane

d. Waiting in drift orbit till reaching next plane
e. Orbit change and coarse orbit phasing for rendezvous with target

… iteration up to all kits are released

f. De-orbiting the last target to disposal orbit

Each mothership shall be compatible with a maximum Δv budget of 1 km/s and with a maximum mission time of 2 years [1].

Two different mission scenarios are considered. In the first scenario, each plane contains 9 targets, and each mothership is responsible for one plane such that in total 12 motherships are required for the full constellation. In the second scenario, each plane contains 4 or 5 targets, and each mothership is responsible for two planes such that in total 6 motherships are required for the full constellation.

In the second scenario the mothership will have to move to the next plane after it finishes cleaning the first one. To save propellant, the mothership will wait in a drift orbit to passively change the RAAN by exploiting the J_2 effect. As it was shown in [2] the best strategy in terms of required Δv budget of orbit transfer and drifting time Δt is to choose an orbit with the same semi-major axis but a different inclination.

Table 3 reports the simulation results of the first scenario. The Δv budget of each mothership (for orbit transfer only) is 0.9176 km/s, less than 1 km/s and hence satisfying the Δv constraint of 1 km/s. All motherships can fulfil their respective missions within 2 years, satisfying the mission time constraint.

Table 3. Mission time for Scenario I.

Mothership	Mission time (months)
1	1.6
2	3.1
3	4.7
4	6.2
5	7.7
6	9.2
7	10.7
8	12.3
9	13.8
10	15.3
11	16.9
12	18.4

For what concerns the second scenario, through the analysis of Δv budget, the inclination of the drift orbit is designed as 87.67 deg, so that there can be enough propellant left to other mission phases such as close-proximity operations. Table 4 reports the simulation results of the second scenario. The Δv budget of each mothership (for orbit transfer only) is 0.9582 km/s, less than 1 km/s and hence satisfying the Δv constraint of 1 km/s. The mission time of each mothership is listed in Table 4. As indicated in the table, none of the motherships can fulfil their respective missions within 2 years, due to the long time period of drifting from one plane to another.

Table 4. Mission time for Scenario II.

Mothership	Mission time (years)
1	2.2
2	2.5
3	2.7
4	2.9
5	3.2
6	3.4

For both scenarios, the difference in the mission times of separate motherships is caused by the different waiting time in the injection orbit after the separation from launch vehicle. Based on the results, we can conclude that the mothership architecture can cope with high failure rate scenarios, in which up to 9 targets are distributed in one plane or two adjacent planes, and Δv budget required by a single mothership is less than 1 km/s. In such scenarios, if one mothership takes care of one plane, the mission can be fulfilled within 2 years; however, if one mothership takes care of two adjacent planes, the mission time must be extended to 3.4 years.

Chaser architecture

This architecture is composed of a single ADR servicer spacecraft, named as chaser, which can capture one target at a time and de-orbit it. Before the end of the mission, the chaser will capture one last target, de-orbit it, and re-enter together.

Analogous to the mothership mission, for the chaser mission, we are also focused on the orbit transfer phases, that are, coarse orbit phasing for rendezvous and de-orbiting of target. The detailed orbit transfer steps are as follows.

a. Waiting in injection orbit till reaching target's plane
b. Orbit raising towards target's orbit and coarse orbit phasing for rendezvous
c. De-orbiting target to disposal orbit for target's re-entry

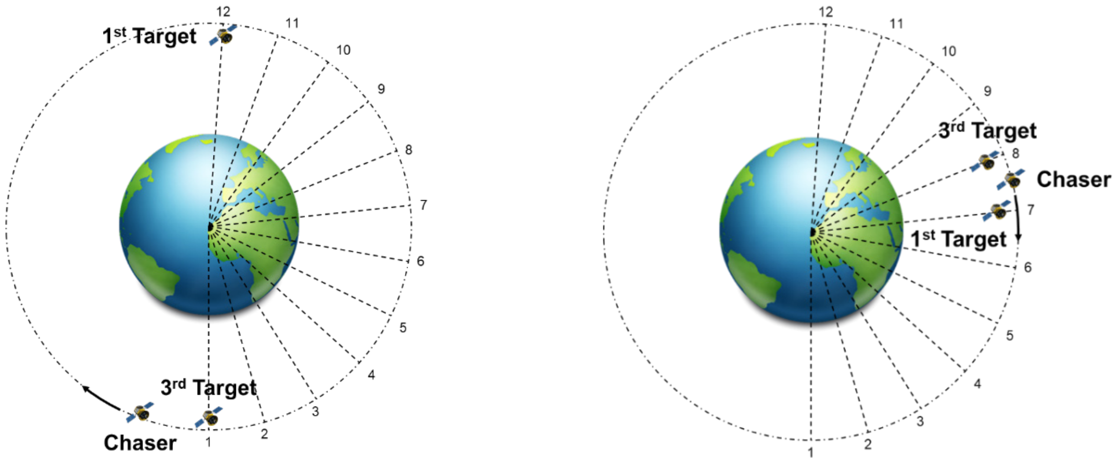
… iteration of Step b and Step c till removing all targets in one plane

d. Waiting in drift orbit till reaching next plane
e. Orbit raising towards target's orbit and coarse orbit phasing for rendezvous
f. De-orbiting target to disposal orbit for target's re-entry

… iteration up to the depletion of propellant

The mission is required to provide 3 services in one or more planes by one chaser, and the chaser shall be compatible with a maximum mission time of 5 years [1]. In this Section only the fuel consumption for the orbit transfer will be shown.

In the case that targets are distributed in multiple planes, the chaser will have to wait in a drift orbit, exploiting the J_2 effect to passively change the RAAN. As shown in [2], the design of the drift orbit has a significant impact on the mission time and Δv budget in the case of multiple planes. Due to the fact that the launch is rideshared with large constellation operators, two different types of initial positioning are to be considered: the chaser's initial RAAN slot is out of the constellation's planes, and the chaser's initial RAAN slot is between the constellation's planes, as illustrated in Figure 1a and b, respectively, where the constellation's planes are numbered from 1 to 12, the RAAN is measured with the positive sense in the counter clock wise direction, and the arrow indicates the motion of the chaser relative to the constellation.



a) Type I: chaser's initial RAAN slot out of constellation's planes. Worst-case scenario of Type I.

b) Type II: chaser's initial RAAN slot between constellation's planes. Worst-case scenario of Type II

Figure 1. Initial positioning for the chaser architecture mission.

For both types of initial positioning the perigee altitude of the drift orbit is fixed as 500 km, as the one of the injection orbit, while the apogee altitude of the drift orbit is fixed as 1100 km, that is, 100 km below the constellation, to comply with safe operations criteria [2]. The inclination of the drift orbit, it is driven by the 5 years' mission time constraint and the worst-case scenario that takes the maximum mission time.

As shown in Figure 1a, the worst-case scenario of the first type is identified as follows.

- The first and last targets to be captured are in Plane 12 and Plane 1, respectively.
- The second target can be in any plane.
- The chaser is initially a bit behind Plane 1.

In this case, the chaser will have to wait in the injection orbit, drifting for around 180 deg with respect to the constellation, to reach the plane of the first target; after de-orbiting the first target, the chaser will have to wait in the drift orbit, drifting for another 180 deg with respect to the constellation, to reach the plane(s) of the rest targets.

As shown in Figure 1b, the worst-case scenario of the second type is identified as follows.

- The first and last targets to be captured are in two adjacent planes.
- The second target can be in any plane.
- The chaser is initially a bit ahead of the plane of the last target.

In this case, during the entire mission, the chaser will have to wait in the drift orbit for almost 360 deg to reach the planes of all targets.

A Monte-Carlo simulation is performed, considering 3 targets are distributed in one, two, and three planes. Table 5 shows the results in terms of the mission time, Δv budget, and real wet mass [3].

Table 5 Simulation results for 3 target servicing.

Number of planes	Type of initial positioning	Mission time (years)	Δv budget (km/s)	Real wet mass (kg)
1	I and II	≤ 3	1.6519	499.9141
2	I	≤ 5	1.6965	512.4969
2	II	≤ 5	1.7653	527.0289
3	I	≤ 5	1.7411	524.7717
3	II	≤ 5	1.8786	554.7926

The 5 years' mission time constraint is respected for all cases. Especially, the mission can be fulfilled within 3 years if all targets are in one plane. The Δv-budget of the initial positioning I is less than II. If possible, it is suggested to set the initial RAAN slot to the initial positioning I.

Chaser plus station architecture

This architecture is composed of two distinct and independent ADR servicer spacecraft, named as station and chaser. For the chaser, similarly to the chaser architecture, it can capture one target at a time and de-orbit it. For the station, it can transport propellant to the chaser; the chaser is refuelled every time after de-orbiting one target. Before the end of the mission, the chaser will capture one last target, de-orbit it, and re-enter together.

According to the mission definition document [1], two different mission options are to be considered:

- the station and chaser are constrained to remain in the same plane;
- the station and chaser are free to drift with respect to each other.

Hereinafter, these two mission options are called Option A and B, respectively.

Table 6 presents the mission steps of station and chaser. Because for station + chaser architecture, the initial RAAN slot of station and chaser can be freely chosen. Here we assume that after separating from the launch vehicle, the station and chaser are in the first plane to serve, so the chaser will instantly move towards target without waiting. Every time after the chaser removes a target, for Option A, the station will correct its RAAN to remain in chaser's plane, while for Option B, the station will not perform any manoeuvre because it is allowed to freely drift with respect to the chaser. If all targets in one plane are removed, the station and chaser will enter a drift orbit, which is different than the target one, and wait in that drift orbit to passively change the RAAN under the J2 effect until reaching the next plane. In fact, the manoeuvre to enter the drift orbit is performed by the station, and meanwhile, the chaser is attached to the station; after reaching the next plane, the chaser will separate from the station and move towards target, and the station will return to the station orbit.

Table 6 Mission steps for the station + chaser architecture.

Step	Description: Station	Description: Chaser
1	staying in station orbit	orbit phasing for coarse rendezvous with target
2	staying in station orbit	close-proximity operations and capture of target
3	Option A: correcting the RAAN of station Option B: staying in station orbit	de-orbit of target
4	staying in station orbit	orbit phasing for coarse rendezvous with station
5	staying in station orbit	close-proximity operations and refuel of chaser
… iteration of steps 1 to 5 until removing all targets in one plane		
6	entering and waiting in drift orbit until reaching the next plane	
7	returning to and staying in station orbit	orbit phasing for coarse rendezvous with target
… iteration of steps 1 to 7 until removing all targets in all planes to serve		

The mission is required to provide 25 services multiple adjacent planes, and the ADR servicer spacecraft shall be compatible with a maximum mission time of 5 years [1]. The mission time and Δv-budget is mainly driven by the design of the station orbit and the drift orbit.

Table 7 presents the results of the station orbit design. For Option A, considering that chaser's mission objective is to remove target, the chaser is desired to follow the motion of target. Therefore, the constraint to remain in chaser's plane is converted to the constraint to remain in target's plane. Here we choose the station to stay in the injection orbit. Such a choice is justified by the following reasons:

- the inclinations of the injection and target orbits are the same, so the station can remain in target's plane without performing inclination change, which is usually expensive in terms of the Δv-budget;
- the altitude of the injection orbit is 100 km below the target one, thus minimising the difference in RAAN drift rates between station and target while complying with safe operations criteria.

For Option B, the station is chosen to stay in a circular orbit whose RAAN drift rate is the same as the target one. Such a choice is economic because the station does not have to perform RAAN change, which is usually expensive in terms of the Δv-budget, neither does the chaser. Here the altitude of the station orbit is set to 100 km below the target one, and the inclination of the station orbit are calculated so the RAAN drift rate of the station orbit equal the respective target one. Such a station orbit can lead to a minimum Δv budget for chaser's moving between target and station orbits while complying with safe operations criteria.

Table 7 Results of station orbit design for the station + chaser architecture.

Option	Altitude, km	Inclination, deg
A	1100	87.9
B	1100	87.995

Table 8 presents the results of the drift orbit design. Basically, the design of the drift orbit is driven by the following three factors:

- the constraint of 5 years' mission time
- the requirement of the number of serviceable targets
- the requirement of the number of serviceable planes

Table 8 Results of drift orbit design for the station + chaser architecture, for Option A and B.

Number of planes serviceable	Altitude, km	Inclination, deg
2	1100	87.850
3	1100	87.705
4	1100	87.660
5	1100	87.415
6	1100	87.269
7	1100	87.124
8	1100	86.979
9	1100	86.833
10	1100	86.688
11	1100	86.543
12	1100	86.397

Here the altitude is set to 100 km below the target one to comply safe operations criteria, and depending on different numbers of planes serviceable, the inclinations are different; these inclinations correspond to the minimum inclination change between station and drift orbits.
Finally, the results of the Δv-budget are shown in Table 9. In terms of chaser's Δv-budget, Option A is smaller than Option B. This is because in Option B, the station and target orbits are at different inclinations, and thus the chaser spends more Δv for inclination change when moving between station and target orbits; while in Option A, the station and target orbits are at the same inclination. In terms station's Δv-budget, Option A is larger than Option B. This is because in Option A, the station must correct its RAAN after every service. In terms of total Δv-budget, Option A is larger than Option B.

Table 9 Results of Δv budget for "station + chaser" architecture.

Number of planes serviceable	Δv budget, km/s					
	Option A			Option B		
	Chaser	Station	Total	Chaser	Station	Total
2	11.991	0.972	12.964	12.290	0.037	12.327
3	12.035	1.059	13.094	12.321	0.148	12.469
4	12.077	1.143	13.220	12.351	0.256	12.607
5	12.232	1.454	13.686	12.494	0.591	13.086
6	12.387	1.764	14.151	12.637	0.925	13.562
7	12.578	2.146	14.724	12.816	1.332	14.148
8	12.806	2.603	15.409	13.032	1.812	14.845
9	13.073	3.135	16.207	13.286	2.369	15.655
10	13.375	3.739	17.114	13.576	2.998	16.574
11	13.714	4.418	18.132	13.904	3.700	17.604
12	14.091	5.173	19.264	14.269	4.480	18.749

Architecture trade-off

A summary of the three architectures considered is reported in Table 10. We can do some considerations on them based on the number of failure rates and the location and distribution of the failed satellites within the constellation geometry. In general, we can say that for high-failure rate scenarios Architecture I – Mothership + kit is to be preferred; for medium to high failure rate in several planes the baseline option can be considered the Architecture III – Chaser + station, why for few failures, no matter where the failed satellites are within the constellation geometry the premium option is the Architecture II – Chaser. For the following part of the Sunrise project, considering the foreseen number of failures within the constellations to be serviced and the business case performed by D-Orbit SpA on the ADR service to be offered and the system requirements, the baseline option was chosen to be Chaser architecture.

Table 10. Architecture trade-off for light-case scenario.

Architecture I – Mothership + kit	Architecture II – Chaser	Architecture III – Chaser + station
	Chemical propulsion	
Mothership captures one target at a time and attach one kit to the target.	Chaser captures and de-orbits one target at a time.	Chaser captures and de-orbits one target at a time. Station transports propellant.
9 services in one plane mission time ≤ 2.0 years, Δv ≤ 1 km/s 9 services in two adjacent planes mission time ≤ 3.4 years, Δv ≤ 1 km/s	3 services in one plane mission time ≤ 3 years, Δv ≤ 1.65 km/s 3 services in two or three planes mission time ≤ 5 years, Δv ≤ 1.70 km/s chaser's initial RAAN slot out of constellation's planes	25 services in multiple adjacent planes mission time ≤ 5 years Chaser and station are free to drift with respect to each other.
High failure rate scenario (9 targets in one or two adjacent planes)	Premium option for few failure (no matter where the failure is)	Baseline option for many failure in many planes

RENDEZVOUS AND CLOSE PROXIMITY OPERATIONS PRELIMINARY DESIGN

In this Section, the Rendezvous and Proximity Operations (RPOs) preliminary design are described and discussed. According to the mission architectures options discussed in the previous Section, two main types of rendezvous are envisioned:

- Uncooperative and non-collaborative rendezvous to failed target to capture.
- Cooperative and collaborative rendezvous to dock with the station.

The focus of this section will be placed on the design and feasibility study of the uncooperative and non-collaborative rendezvous with the failed target, being the most challenging in terms of close-proximity operations and common to all the mission architectures. While on the other hand, the cooperative operations to dock with the station are characterised by a strong heritage.

Proximity operations concept of operations

The RPOs will start at the edge of the Approach Ellipsoid (AE), defined considering the first detection of the target with the chaser onboard sensors. The operational phases defined for the uncooperative rendezvous are reported in Table 11 and Figure 2.

Table 11: Close proximity operation concept of operations.

Phases	Separation
Far range rendezvous	From 50 km to 1 km
Mid-range rendezvous	From 1 km to 500 m
Inspection	From 500 m to 75 m
Contactless detumbling	~20 m
Forced motion	From 75 to 4 m
Robotic operation	~4 m

In the next part, the preliminary design and analysis of each phase is presented, after a brief description of the sensor suite selected for the uncooperative approach.

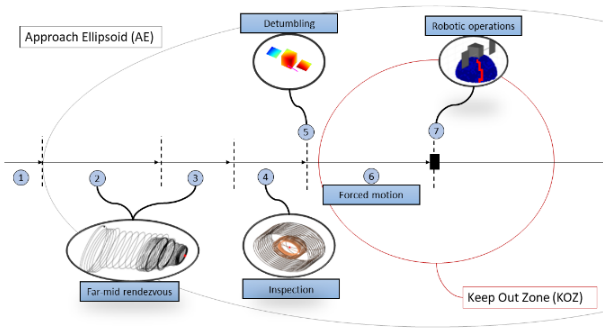


Figure 2: Concept of operation phases of the approach to the failed uncooperative constellation satellite.

Sensor suite preliminary definition

Prior the preliminary definition of the approach strategies and Guidance Navigation and Control (GNC) design of the proximity phases, a technological trade-off has been performed to select the appropriate sensor suite. According to the requirements, the suite defined is reported in Table 12. The present sensor suite can support the navigation functions during the whole approach, with the sufficient redundancy and robustness to illumination conditions.

Table 12: Chaser sensor suite selected for the uncooperative approach, with preliminary characteristics and sensors' range of operations.

Sensor	Range [km]	Mass [kg]	Power [W]
VIS NFOV camera	50-close	~1	~10
VIS WFOV camera	10-close	~1	~10
IR camera	3-close	~1	~10
Flash LiDAR	5-close	~5	~50

Far- and mid-range rendezvous

After the first detection of the failed target satellite, starting from about 50 km, the relative GNC system takes over and initiate the approach to the target. The guidance and control of this phase is managed in a decoupled fashion, from the heritage of [4, 9]. In the Relative Orbital Elements (ROE) domain, the guidance defines the ROE jumps solving an optimal control problem with a fixed time horizon in an analytic form. The objective function used in the guidance algorithm optimisation is reported in [4]. The impulsive manoeuvres to achieve the required ROE jumps are obtained suing the optimal four impulsive manoeuvres scheme of [4]. Particularly, the four manoeuvres scheme is composed by three tangential and one normal manoeuvre.

The navigation function during the approach is performed using the angles only navigation solution in the far and mid-range and with and Extensive Kalman Filter (EKF) [5, 7]. In the cases of separation of about 500 m, also a full 3D navigation with the range information retrieved from the ranging device (i.e., LiDAR) is simulated.

The present GNC design is adopted to guarantee the autonomous operations during the approach, thanks to the limited computational resources required. Additionally, the GNC algorithm is already flight proven [9].

A simulation of the approach can be seen in Figure 3, where the ROE states and estimated ROE history are shown.

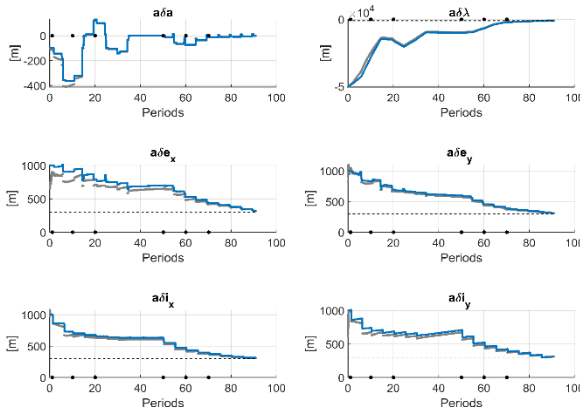


Figure 3: ROE time history during the far range rendezvous. In blue the true state and in grey the estimated state output of the navigation filter.

Inspection phase

At 500 m of separation, the inspection phase is performed where the target is observed with the onboard sensors. At the end of this phase, the 6 degree-of-freedom state of the target must be known and checked from ground to proceed with further proximity operations. The design of the inspection trajectories uses a walking safety ellipse approach which guarantee passive safety and a satisfactory fly-around of the target for inspection. An example of the trajectory is shown in Figure 4, where three different safety ellipses are used during 80 orbital periods, approximately 6 days. The width of the walking safety ellipse, in terms of relative eccentricity and inclination vector can be adjusted according to observation constraints. For instance, the separation in the case of heavy target, in terms of safety and required resolution in the observation of the failed spacecraft can be increased.

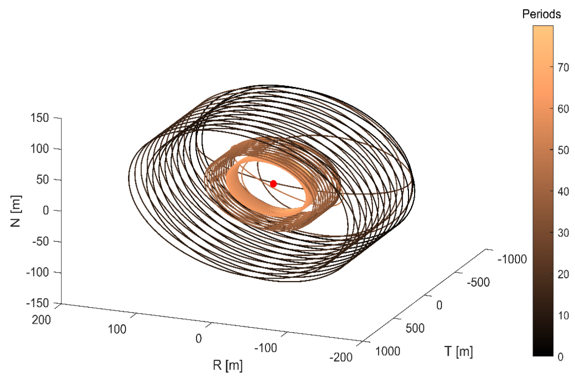


Figure 4: Inspection trajectories around the target. Colormap represent the time along the inspection routing in periods.

Close approach to a tumbling target

A failed asset of the constellation may be characterised by a tumbling motion which increase the difficulties in the approach and capture operation. In the phase A of the sunrise mission, a safe threshold of target tumbling rate to safely synchronise to the target motion is defined as 1 deg/s. This threshold is defined considering the chaser acceleration levels required during synchronisation and the 22 N thrusting capability of the thrusting assembly. To this aim, a simple linear quadratic tracking control is used to estimate the mean and maximum acceleration required in the tracking fly around at different distances. The results for multiple distances and multiple tumbling rate tracking control simulation are shown in Figure 5. Considering that the safe distance where the chaser must be synchronised in front of the target is considered at least two times the longest target's dimension, taken as 8 m considering the case of light-case target. The 1 deg/s threshold is defined considering the thrusting capabilities in relations with the acceleration level required and chaser mass class, together with the consideration of avoiding the full thrusting in such close-proximity for collision avoidance and safety reasons.

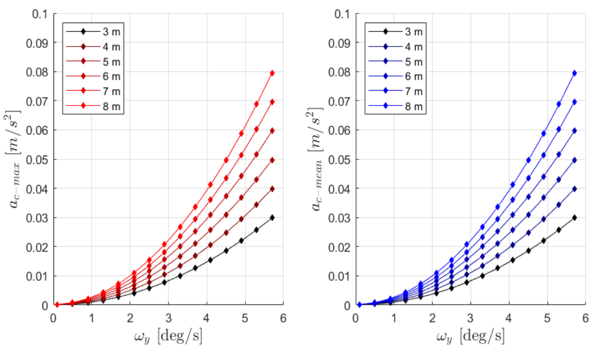


Figure 5: Acceleration levels required for the synchronization and fly-around to the target attachment point at various distances and tumbling rates.

In the cases where the target is characterised by a higher tumbling rate, a contactless control strategy is envisioned. Particularly, a plume impingement strategy is selected thanks to simplicity and no need of an additional subsystem onboard the chaser. In fact, the chaser thruster will be employed to control the rotational dynamics of the failed satellite. A feasibility study on this phase control is performed, and two different control strategies have been tested and proven. Particularly the detumbling of the target angular rate, the reorientation control to reduce the tumbling motion to a pure spin and reorient the spin axis towards a fixed inertial direction. The control algorithms employed are reported in [6]. Some simulation results for the detumbling and spin axis orientation control simulations are shown in Figure 6, Figure 7 and Figure 8.

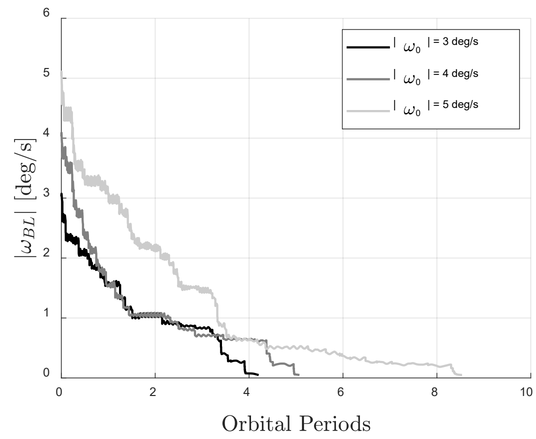


Figure 6: Time history of the angular rate of the target during the detumbling routine using plume impingement for various initial tumbling rates.

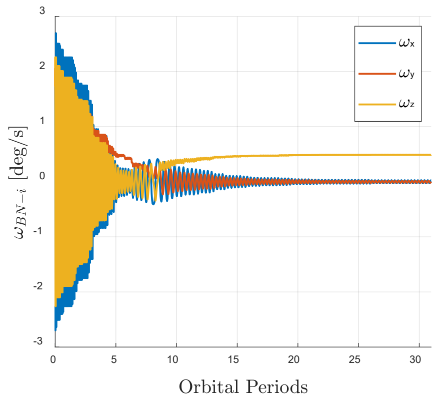


Figure 7: Time history of the angular velocity components during the spin reorientation control routine with plume impingement.

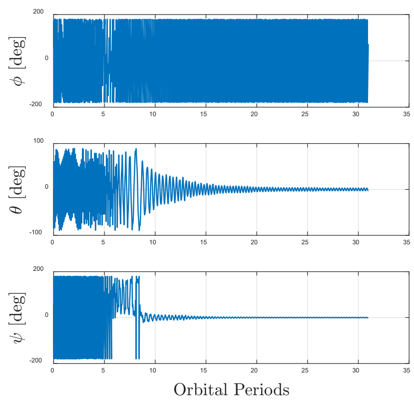


Figure 8: Target's Euler angles in LVLH frame during the spin reorientation control routine with plume impingement

Robotic arm analyses

Finally, the robotic arm phase is studied. The arm architecture selection was based on multiple-criteria evaluation, considering space heritage, dexterity, folding, wrist and complexity. Both a kinematic analysis, calculating of the reachability and dexterity map limited to the selected arm architecture were performed. Moreover, a preliminary sizing of the selected arm architecture was done with a multibody analysis (see).

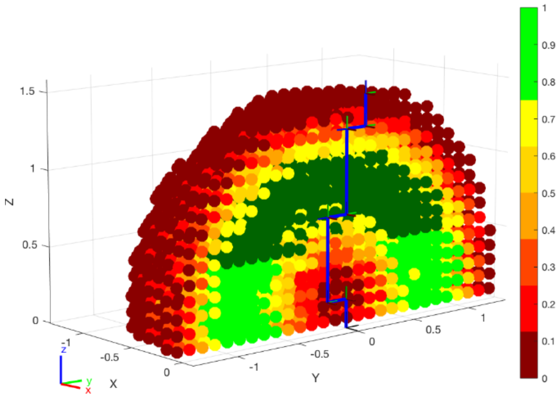


Figure 9: Robotic arm analysis.

SYSTEM DESIGN

The design of the chaser and station spacecrafts leverage on the D-Orbit SpA proprietary "ION Satellite Carrier Vehicle (ION SCV)" spacecraft (see Figure 10) [10]. Both chaser and target system bus are composed by two physically- and functionally-distinct modules: the platform (PLT), which includes the general spacecraft subsystems (OBDH, COM, EPS, AOCS, TCS and propulsion subsystems), and the payload bay, which hosts those specific for the ADR mission: the robotic arm, the docking mechanism and the relative navigation sensors suite, and the kits deployer structure for the mother only.

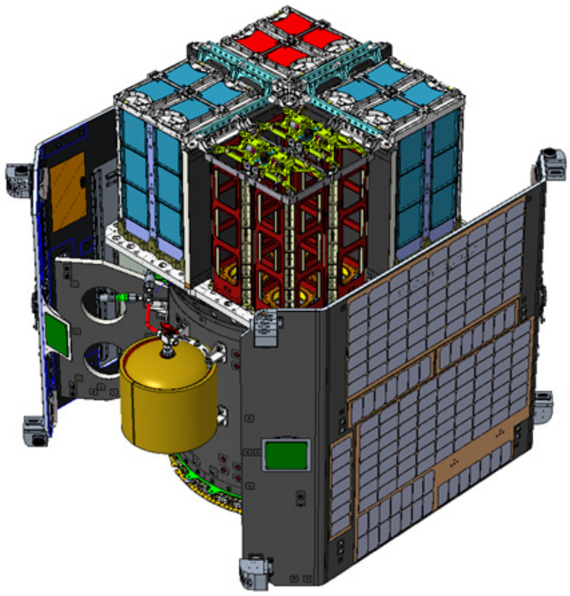


Figure 10: ION SCV spacecraft overview.

The kit architecture (see Figure 11) is designed to be compatible with the 16U form-factor of CubeSat standard, equivalent to 2Ux2Ux4U CubeSat units. The kit system comprises all the basic subsystems of a typical spacecraft, like a chaser or a mother. However, they are reduced and simplified to the maximum extend to contain the overall mass and size, hence cost, of one kit.

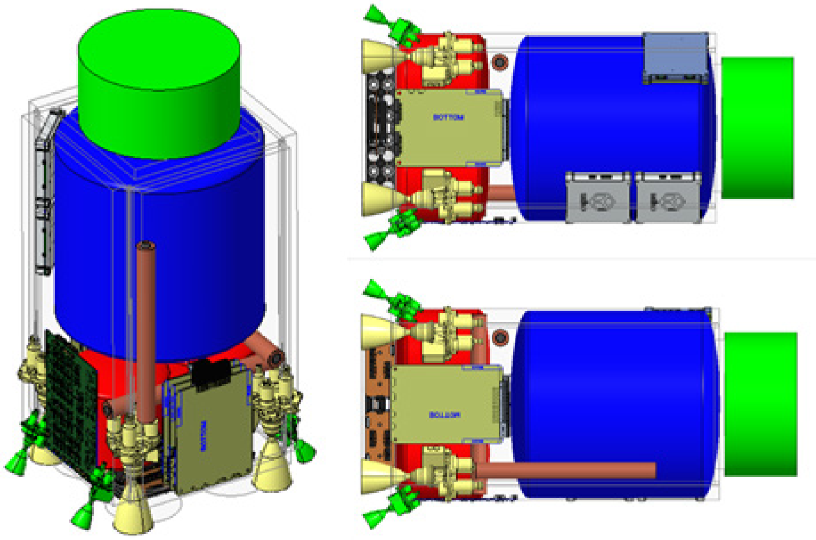


Figure 11. Kit spacecraft preliminary sizing, 16U volume is visible in grey transparent.

The station mission objective is to extend the operational capabilities of the chaser by providing refuelling capabilities, therefore it is designed to carry as much propellant compatibly with the capacity of the F9 launch vehicle (several launch vehicles have been considered in the trade-off analysis, with Space X F9 selected as baseline hence presented in this study). The station structural design is therefore similar to the upper stage of a launch vehicle, based on a sandwich cylindrical structure made of CFRP and aluminium honeycomb, with the spacecraft avionics and the other bus subsystems placed in the lower part, inside the LVA ring, and the propellant is allocated inside the central cylinder. The refuelling is allowed via a modified F&D valve accessible on the external surface of the spacecraft, close to the docking port with the chaser. The propellant selection allows to employ orbital temperature differential between the two spacecrafts after docking to allow for self-regulated propellant transfer.

CONCLUSION

The mission analysis and system design of an ADR mission for large constellation is presented. The mission analysis and the following mission architecture selection is driven by the importance of providing a service to several customers. For this reason, it is the driven by the need to be efficient, ready, reliable and to offer the ADR service at a reasonable cost. These requirements, proper of commercial services have strongly affected the selected design.

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