SPACE DEBRIS ORBIT MODIFICATION USING CHEMICAL PROPULSION SHEPHERDING

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ABSTRACT

SysNova is an ESA's technology assessment scheme using "technology challenges" and competitions to survey a comparatively large number of alternative solutions. The COBRA concept was proposed as a solution to one of the challenges, and was declared the winner of the SysNova competition.

The COBRA project is a feasibility study of an active debris removal concept which relies on contactless technology to modify the orbit of a space debris object. A ΔV of 50 m/s needs to be imparted on a 100 kg space debris object. Momentum is imparted on the debris object using the exhaust plume of a monopropellant hydrazine propulsion system. The mission concept uses a standard satellite bus with a modified payload bay to suit mission needs.

1 INTRODUCTION

The COBRA project focused three main areas of research: the physics of the momentum transfer, mission analysis & GNC assessment, and spacecraft design and system engineering. The University of Milan has examined the physical mechanism of momentum transfer. GMV has performed the mission analysis and an assessment of the GNC required for the mission. Thales Alenia Space Italy has performed systems engineering and spacecraft design.

Table 1: COBRA mass budget

Element	Mass [kg]
Debris removal payload module	140.3
Service module	472.5
Nominal dry mass	612.8
System margin 20%	122.6
Propellant mass	320
Wet mass	1055.4
Adapter mass	140
Launch mass	1195.4

Table 1 presents the mass budget of the COBRA spacecraft. The dry mass of the spacecraft is 735.4 kg.

The standard platform is equipped with 1N monopropellant hydrazine thrusters, with 1 thruster pointing in the forward direction and two clusters of 4 thrusters pointing in the backward direction.

Figure 1 shows an overview of the COBRA satellite. The satellite is based on the Elite platform from Iridium Next satellite constellation (the service module) and a payload module installed in place of the standard communication payload of Iridium Next.

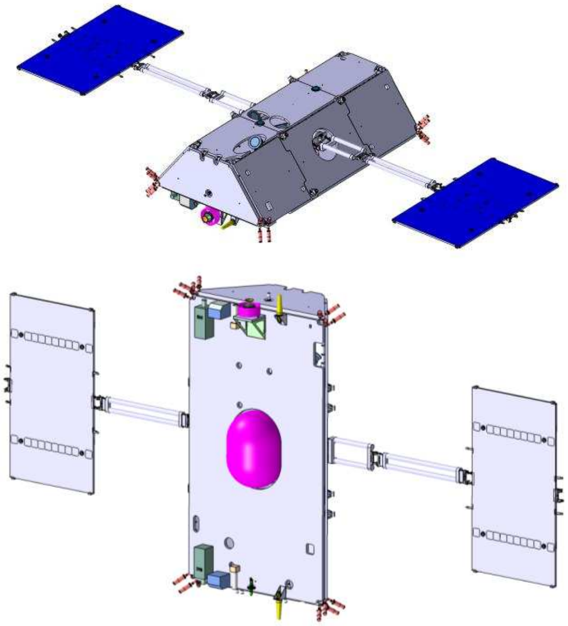

Figure 1: COBRA spacecraft

The use of a standard platform reduces the cost significantly, but it also imposes constraints on the design of the mission. These constraints will be addressed in this paper.

This paper is divided into three main parts. The first part discusses the results of the momentum transfer investigation, the second treats the mission analysis work performed during the study and the third part addresses the mission design.

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2 MOMENTUM TRANSFER

2.1 Momentum transfer models and results

Momentum transfer is achieved through impingement of the gas jet produced by a monopropellant hydrazine thruster. The main desired outcome of the study of the momentum transfer mechanism is the determination of the efficiency of the momentum transfer as a function of the plume characteristics and the distance between the thruster opening and the debris surface. Secondly, the contamination of the sensors and the risk of generating additional debris are assessed. The effect of the impinging plume on the dynamics of the debris object is investigated to determine the need and the feasibility of controlling the attitude of the debris object by pointing the thruster to different areas of the surface of the debris object. The effect of the debris shape and mass on the dynamics and controllability leads to a classification of shapes in terms of their suitability for chemical shepherding.

The investigation of the momentum transfer mechanism requires the definition of a plume model and a plume impingement model to simulate the interaction of the plume with the debris surface. A literature review has been performed to select the approach most suitable for the COBRA project.

Typical outputs from plume models are temperature, velocity and pressure profiles, heat transfer, condensation, deposits on optical surfaces, impact forces, and chemical species. Two approaches are in use to model thruster exhaust plumes. These are parametric analytical models and numerical models, which can be further divided into deterministic and stochastic models

Parametric analytical models are simple and fast, but do not capture all aspects of plume impingement. Numerical models are used to obtain more accurate results. Conventional fluid dynamics Navier-Stokes (NS) equations are based on a continuum assumption and the Computational Fluid Dynamics (CFD) solvers based on these equations fail to accurately describe rarefied gas effects. Deterministic models for rarefied gas flow use gas kinetic theory based on the Boltzmann equation. The stochastic models use a technique called the Direct Simulation Monte Carlo (DSMC) method, in which gas particles and their interactions with each other and boundary surfaces are simulated directly [1, 2].

Several models are available for the interactions of the gas particles with a surface placed into the plume, amongst others the relatively simple Maxwell model and the more complex Cercigani-Lampis-Lord model.

For the COBRA study the University of Milan developed the following model. Plume state variables are expressed in the following form:

$$\phi(r,\theta) = C \cdot f(\theta) \cdot r^{-2} \tag{1}$$

where

C is a constant determined based on continuity considerations

θ is the angle from the nozzle centerline

$f(\theta)$ is a function describing the dependence of the plume state variable on the angle from the thruster centerline

r is the distance from the nozzle opening

The plume is discretized in 105 beams, randomly generated with a uniform distribution in azimuth (φ = [0 - 2π]) and a distribution in elevation (θ = [0 - α]) respecting a high power cosine law. A Maxwellian collision model was implemented to simulate the plume impingement. The Maxwellian model assumes that a certain fraction of the gas particles impinging on a surface is reflected specularly, while the rest of the particles remain temporarily stuck to the surface and re-radiated with a velocity dependent on the wall temperature.

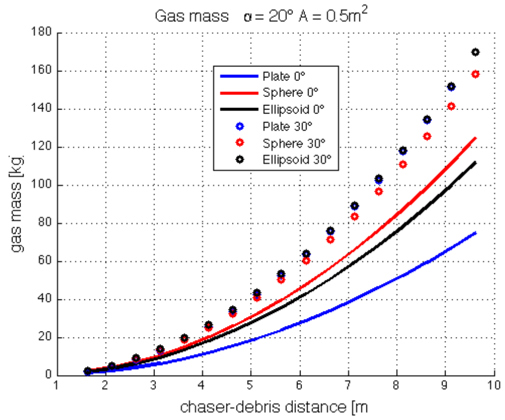

Figure 2: Hydrazine mass needed for imparting 50 m/s

Figure 2 shows the hydrazine mass required for imparting 50 m/s onto the debris object as a function of the distance between the nozzle opening and the debris surface. Three different debris shapes were analysed; a flat plate, a sphere and an ellipsoid. The figure shows that the required hydrazine mass increases quadratically as a function of the distance. The figure also shows that the lowest hydrazine mass is required for flat surfaces oriented perpendicularly to the gas jet. At operating distances between 5 and 6 meters a hydrazine mass between 20 and 65 kg is required.

The main results of the investigation of the physical mechanism are the following. The momentum transfer is defined as the ratio between the force felt by the target object and the force exerted by the chaser spacecraft. It is strongly dependent on the inter-satellite distance; it falls with the square of the distance. As a consequence, the chaser needs to fly as close as possible to the target object in order to achieve a high momentum transfer.

2.2 Debris dynamics and control

For studying the attitude dynamics and controllability of the debris object, another model was implemented based on [4]. The plume model follows a Guassian distribution as a function of the angle from the thruster centreline. Only specular collisions were considered in this second model.

Plume impingement should impart the ΔV in the along-track direction. Undesirable secondary effects are attitude spin-up and motion perpendicular to the direction of the gas jet. Attitude spin-up results if the centre of pressure is not aligned with the centre of mass of the object. Transverse motion can be imparted if the collisions of the gas particles with the surface are partly specular and if the debris surface is not oriented perpendicular to the gas jet. Transverse motion can also result when the centre of pressure is not aligned with the centre of mass of the object. This is because a plume impinging on a surface that is initially oriented perpendicular to the gas jet causes attitude spin-up in case of non-alignment of the centre of pressure with the centre of gravity. Attitude rotation causes the surface to become oriented at an angle with respect to the gas jet. This causes a transverse force on the debris object, such that it will start drifting away from its nominal position.

The analysis of the attitude dynamics shows that the gas jet can spin up a 100 kg homogeneous cube-shaped debris object with a side length of .7 m to 1 rpm in about 25 – 30 s, if the debris is located at a distance of 2 m and the thruster is pointed 1° away from the centre of mass. Simulations indicate that the subsequent transverse displacement is 0.6 m after 30 s. such that the object is close to escaping from the plume altogether, if no station-keeping is performed.

This problem can be addressed in two ways. Firstly, it is possible to perform active station-keeping to follow the object as it drifts away perpendicular to the gas jet. This solution would lead to an increase in the ΔV required for station keeping. Secondly, it may be possible to actively control the attitude of the debris object by steering the gas jet. This would cause the centre of pressure to move with respect to the centre of gravity of the debris object and generate a torque on the debris object. The attitude of the object can be controlled in the directions perpendicular to the thruster boresight.

The study of the controllability also included an assessment of the types of shapes that could be handled by the COBRA concept. The potential debris object shapes were divided into three classes, according to their suitability:

- Suitable shapes: Compact objects (objects with a low surface-area-to-volume ratio) with centre of pressure close to centre of gravity and a low density (high ballistic coefficient), presenting a large surface area and having a low mass

- Intermediate shapes: Flat or elongated objects (or objects with a high surface-area-to-volume ratio). Objects with centre of pressure relatively far from the centre of gravity. Objects with a moderately high density (high ballistic coefficient), presenting a small surface area and having a high mass.

- Unsuitable shapes: Objects with permeable structures, e.g., mesh antennas. Objects with centre of pressure far from centre of gravity. Objects having a low ballistic coefficient. Objects combining both, e.g. satellites with heavy instrument or optics mounted on a boom, or gravity gradient stabilised satellites.

3 MISSION ANALYSIS

From the perspective of mission analysis and GNC, certain aspects of a debris removal mission are within reach of present-day technical capabilities, while other aspects require new developments. The launch, phasing and rendezvous phases have all been performed in previous missions. The main difference for active debris removal is that the target object is uncooperative, and the rendezvous strategy and GNC design need to reflect this. The actual momentum exchange operations form the main challenge. The motion of the debris object in the thruster gas jet is highly unstable. Two options were identified to solve this problem. In the first strategy the chaser simply performs station-keeping with respect to the target and compensates for any transverse motion imparted on the target object. In the second strategy the chaser attempts to control the rotation and the transverse motion of the debris object to maximize the momentum transfer in the along-track direction. Another issue that has been addressed is collision avoidance. A good collision avoidance strategy is required because momentum exchange operations occur when the chaser spacecraft is flying in close formation with the debris object.

3.1 Launch

The Iridium Next constellation will be launched using a Falcon 9 multiple launch, using the Dnepr launch vehicle as a back-up option. The compatibility of the Cobra mission with these launch vehicles is assessed. The Vega launch vehicle is added as a third option.

The standard Iridium Next satellites are launched in batches of 9 satellites using the Falcon 9 launch vehicle. If the Falcon 9 launch vehicle would be used for Cobra, then 1 Cobra satellite would be launched alongside 8

Iridium Next satellites into the injection orbit for the Iridium Next constellation. The study has shown that the change of inclination from the Iridium Next orbit (600 - 800 km circular at 86° inclination) to the COBRA orbit (800 km SSO at 98.6° inclination) is too costly in terms of ΔV.

The preferred launch option is to use a Dnepr launch vehicle. The Dnepr can launch the COBRA satellite to a circular SSO (98° orbit inclination) with an altitude of 620 km. It is assumed a recurrent cost because a special adapter for twin Iridium Next satellite launch by Dnepr is contemplated for constellation maintenance. The Cobra spacecraft is assumed to make use of a single launch.

The Vega launch vehicle can launch the COBRA satellite into the 800 km circular SSO with an inclination of 98° directly. The cost of a Vega launch is higher than the cost of a Dnepr launch.

3.2 Orbit raising and rendezvous

After launch the chaser performs an orbit raising manoeuvre from the initial 620 km circular injection orbit to a circular phasing orbit at 750 km altitude. Next, the COBRA satellite performs rendezvous with the debris object. An initial estimate of the entire rendezvous is made by considering a Hohmann transfer from a circular 620 km altitude orbit to a circular 800 km altitude orbit. The resulting ΔV is 95.22 m/s.

A more detailed investigation of the rendezvous phase is performed. Based on previous experience, some guidelines for the rendezvous strategy can be defined:

- Out-of-plane manoeuvres should be avoided. This can lead to a saving of 35% of the total ΔV. The natural drift due to J2 should be exploited to correct errors in the right ascension of the ascending node.
- The use of properly aligned thrusters should be maximized and the thruster geometric losses should be minimized. In case of Cobra, this means that:
  - The platform thrusters should be used during the long-range phases
  - Medium & short range phases should be kept short both in time and small in geometrical dimensions, and the number and magnitude of the ΔV's should be minimized

During the definition of the rendezvous ΔV budget, the following aspects need to be taken into account:

- Thruster geometric losses need to be taken into account during the relevant phases
- A GNC margin of 20% needs to be taken into account over the rendezvous ΔV. This margin is not applied to the orbit raising, because more accurate dynamics models will be used during this phase.

The rendezvous strategy makes use of a phasing orbit 50 km below the target orbit. The Hohmann transfer to raise the altitude of the circular orbits from 620 km to 750 km phasing orbit requires a ΔV of 68.19 m/s.

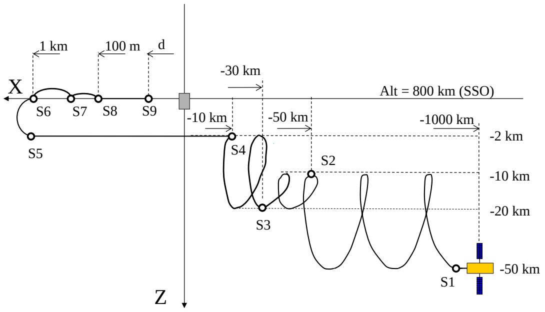

Figure 3: Rendezvous strategy

Figure 3 shows the rendezvous strategy defined for the COBRA mission. The ΔV associated with each of the manoeuvres is reported in table 2. The rendezvous makes use of drifting trajectories between S1 and S6, radial hops between S6 and S8 and a forced motion from S8 to S9. The magnitude and timing of the orbit raising manoeuvres between S1 and S4 is determined by the along-track distance when the target debris object is found, and by the desired arrival time at the debris object.

Table 2: Rendezvous ΔV budget

#	Element	ΔV_{ideal} [m/s]	ΔV_{geom} [m/s]
S1	From circular (750 km) to elliptic (750x790 km)	10.45	10.45
S2	From elliptic (750x790 km) to elliptic (780x790 km)	7.84	7.84
S3	From elliptic (780x790 km) to elliptic (780x798 km)	2.08	2.08
S4	From elliptic (780x798 km) to circular (798 km)	4.68	4.68
S5	From circular (798 km) to elliptic (798x800 km)	0.52	0.90
S6-1	From elliptic (798x800 km) to circular (800 km)	0.52	0.90
S6-2	Start a hop of 600 m along Vbar	0.16	0.28
S7-1	Stop the 600 m hop	0.16	0.28
S7-2	Start the 300 m hop	0.08	0.14
S8-1	Stop the hop 300 m hop	0.08	0.14
S8-2	Start the final approach	0.1	0.17
S8-S9	Forced motion	0.2	0.35
S9	Stop at the operational distance	0.1	0.17
	Total	26.97	28.38
	GNC margin 20%	5.39	5.68
	Total ΔV for the Rendezvous phase	32.36	34.06

The orbit raising manoeuvres from points S1 to S4 are performed using the platform thrusters that are oriented in the direction of flight. The manoeuvres that follow use the rendezvous thrusters, which incur some geometric losses. The ΔV including thruster geometric losses are shown in the rightmost column of table 2. The ΔV for orbit raising and rendezvous 68.19 m/s and 34.06 m/s respectively, leading to a total ΔV of 102.25 m/s. This agrees well with the initial estimate.

3.3 Proximity operations

The proximity operations are all those phases that involve forced motion and station-keeping close to the target debris object. The proximity operations include the debris characterization phase, during which the debris object is monitored with camera and LIDAR and the actual debris pushing phase, during which the pushing thruster is active. The objective of the proximity operations is to impart a ΔV of 50 m/s to the target debris object. GMV proposes to use the ΔV of 50 m/s to achieve an elliptic orbit with a perigee height that is as low as possible. The burns need to be concentrated at a single point in the orbit or that the burns need to be performed at the same point every orbit if the burn is split because the thrust level is low. Splitting the large burn into smaller ones performed at the same point every orbit leads to a reduction in gravity losses.

The selection of the thrust level and the operational distance has a strong relation with the safety of the pushing operations. Figure 4 shows the relations between these concepts schematically. The thrust level determines the duration of the pushing operations. The higher the thrust level is, the shorter the pushing operations take. The shorter the mission takes, the less ΔV is required for compensating perturbations. The less time the Cobra spacecraft spends in a risky situation such as the pushing operations, the safer the mission is. In contrast, a high thrust level leads to a shorter reaction time in case of thruster failure, but also higher controllability. The thrust level does not have an effect on the momentum transfer efficiency.

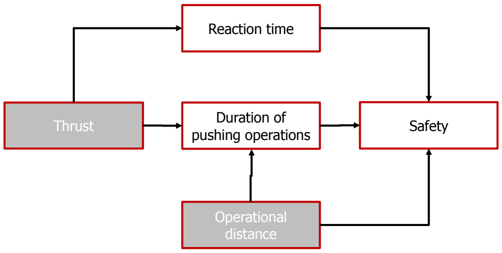

Figure 4: Thrust level, operational distance and safety

The second parameter that can be selected is the operational distance. The lower the operational distance is the greater is the efficiency of the momentum transfer and the shorter the duration of the pushing operations. The shorter the duration, the safer the mission is. On the other hand, operations closer to the target object introduce a higher level of risk because of shorter reaction times.

For the selection of the thrust level of the pushing thruster for the Cobra mission, the thruster layout of the Elite bus should be taken into consideration. The standard Iridium Next platform has a single 1 N thruster in the forward direction, and 8 x 1 N thrusters in the backward direction. The line of force of these thrusters lies approximately through the centre of gravity. Minimal modifications should be made to the platform in order to avoid requalification. This means that any additional thrusters need to be mounted on the payload bay face. In this case, the thruster line of force would not pass through the centre of gravity, and additional thrust would need to be provided to compensate for the torque generated by such a thruster. For this reason the forward platform thruster is used for debris pushing operations. This fixes the thrust level at 1 N.

Several aspects have been explored in the determination of the operational distance. The maximum operating distance is determined by the amount of propellant that can be accommodated, and by the thruster lifetime of 60 hours. It was found that the propellant mass is the critical constraint. The minimum operating distance was determined by considering the minimum safe distance used in other formation flying mission, the dimensions of the spacecraft and the debris object, and the reaction time associated with operating at a certain distance.

One of the critical parameters that influence the selection of the operating distance is the momentum transfer efficiency. Figure 5 shows the momentum transfer efficiency as a function of distance, computed for a cube with a surface area of 0.5 m^2. The transfer efficiency has been computed for plume half cone angles of 15° and 40° and specular and diffuse collisions of the gas particles at the debris object surface. The vertical black line indicates the distance at which the COBRA satellite touches the debris object.

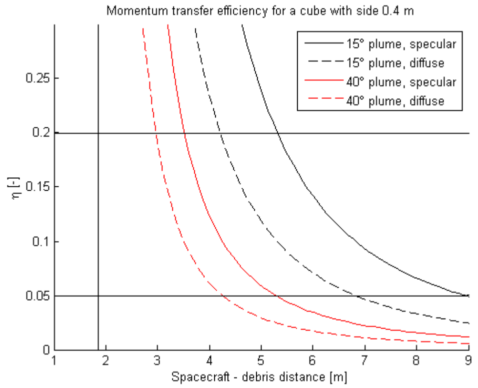

Figure 5: Transfer efficiency as a function of distance

The figure shows that to achieve a transfer efficiency of 20% the chaser needs to maintain a distance of 5.5 m in the best case, and 3 m in the worst case.

Table 3 summarizes the operational distance selection. A transfer efficiency of 20% is aimed for. This transfer efficiency occurs at between 4.9 and 6.3 m distance (for a 1 m^2 debris surface area), which is the range of operating distances that is selected for this study.

Table 3: Operating distance selection

distance selection criterion	min D [m]	max D [m]
minimum momentum transfer efficiency 5% according to propellant mass	8.3	11.2
realistic momentum transfer efficiency 20%	4.9	6.3
thruster operational lifetime	10.3	14
minimum distance in HARVD study	3	-
collision risk based on spacecraft geometry	2.19	4.4

Table 4 shows the ΔV required for the proximity operations as a function of the transfer efficiency. Also included are the operating distances for diffuse (D_1) and specular (D_2) collisions of the gas molecules on the debris object surface.

Table 4: Transfer efficiency, operating distance and ΔV

η [-]	D_1 [m]	D_2 [m]	ΔV total [m/s]
0.04	9.1	12.3	506.42
0.06	7.7	10.3	367.99
0.08	6.9	9.1	296.27
0.1	6.3	8.3	252.38
0.15	5.4	7.1	192.83
0.2	4.9	6.3	162.60
0.3	4.3	5.4	132.05

The ΔV for a transfer efficiency of 20% is 162.60 m/s.

3.4 Collision avoidance

Collision avoidance manoeuvres are required to protect the system against collisions when operating at the closest ranges (< 100 m). The CAM strategy for Cobra is inspired on the collision avoidance strategy for the ATV, with the exception that drag effects are negligible at 800 km altitude, such that no preferred direction exists for the drift after the CAM. The CAM manoeuvre requires a ΔV of 0.2 m/s in the along-track direction after the CAM. Application of a ΔV of 0.2 m/s in the along-track direction leads to a drift of 3.6 km per orbit. The recovery strategy after the CAM is similar to the rendezvous strategy from point S5 in figure 3 and table 2. The total ΔV for a CAM and the recovery is 6.56 m/s. This value includes the CAM ΔV, the ΔV required to stop the motion and the ΔV required for the recovery.

3.5 De-orbiting

After the pushing operations are completed, the Cobra satellite and the target debris object will both be in an elliptical orbit with dimensions 611 x 800 km, due to the application of 50 m/s of ΔV. The Cobra satellite re-entry orbit is 300 x 800 km, from which re-entry occurs after about three and a half years [5]. The debris object remains in the 611 x 800 km orbit. The de-orbiting of the Cobra satellite requires a ΔV of 85.70 m/s.

3.6 ΔV budget

The platform can provide a ΔV of 762.04 m/s. Table 5 shows the ΔV budget for a transfer efficiency of 20%. Each of the elements of the ΔV budget has been discussed in previous sections, except for the ADCS contribution. A fixed ΔV of 10 m/s has been added for reaction wheel offloading and perturbation compensation. In this case, the total ΔV required is 458.62 m/s.

Table 5: ΔV budget for 20% efficiency transfer

Mission phase	ΔV m/s
Orbit raising	68.19
Rendezvous	33.32
Proximity operations	162.60
CAM and recovery (4 CAMS)	22.37
De-orbiting	85.70
ADCS	10.00
System margin 20%	76.44
Total	458.62

The ΔV required for a 6% efficiency transfer is 705.13 m/s, which fits with the mass budget of the Iridium platform. The minimum efficiency of the transfer needs to lie between 5% and 6%.

4 MISSION DESIGN

In order to satisfy the budget requirements, the Iridium Next platform has been selected. This platform is designed for operations in LEO at 800 km and only minimal modifications are required. The debris removal equipment can be hosted in the payload bay and the chaser spacecraft can be launched on the Dnepr or the Vega launch vehicle.

4.1 Platform design

The Cobra flight segment (the satellite) will be basically composed by a Service Module, the Elite platform from Iridium Next satellite constellation, and a Payload Module installed in place of standard communication payload of Iridium Next. The Service Module presents an Iridium standard interface respect to launcher, compatible with multiple launch with dispenser of single/twin launch with DNEPR or Vega. A modularity concept will be considered for the design of the Satellite in order to allow parallel development of SVM and PLM modules.

Figure 6 provides an overview of the Cobra configuration elaborated in Sysnova short study. This configuration study has been performed via CAD models of Elite and developing a payload module CAD model. Particular care has been paid to the layout of thrusters and position of metrology equipment.

The satellite service module features a propulsion system for momentum transfer to debris and pure translation of satellite. Rendezvous is possible by the means of a network of 16 thrusters (including redundancy) of 10 N each added to the payload module. This configuration has been elaborated to avoid modification of Elite platform. An additional thruster of 1 N pointing backwards is considered for momentum transfer, because the set of eight thrusters of Elite platform are not effective for the proximity operations. This system is complemented by an opportunity payload based on the Helicon Plasma Hydrazine (HPH) technology

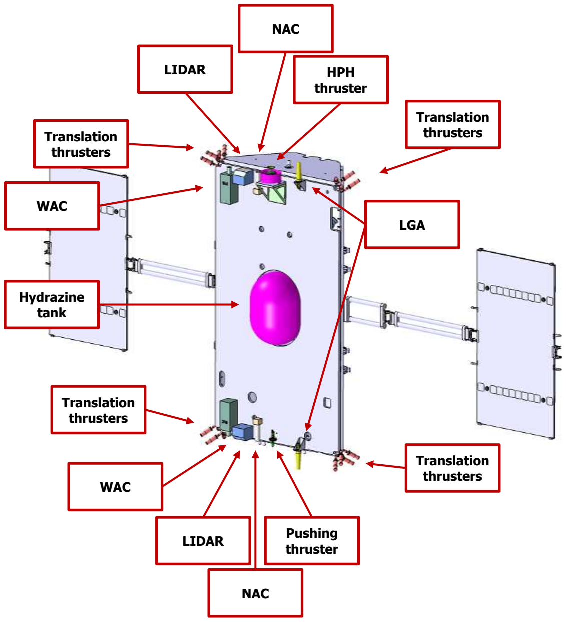

Figure 6: Payload module layout

The optical metrology used for rendezvous and proximity operations consist of a Wide Angle Camera (WAC), a Narrow Field Optical Camera (NFOC) and an RVS LIDAR. All metrology equipment is redundant.

This set of units allows the in-flight debris position identification from remote to proximity position. Data of the metrology set will be used on-board and on-ground for the debris removal operations.

Finally the satellites features a set of service equipment, composed of the payload module structure, the payload thermal control component set, an IMU for measurement of acceleration and an S-band low gain antenna.

The use of Elite appears compatible with the Cobra mission profile. It is relevant to highlight that from this preliminary assessment no relevant hardware modification, jeopardising the platform qualification, are envisaged. However the main aspect of platform adaptation to be considered with care is the new software to be implemented.

4.2 GNC system design and development

This section provides a brief overview of the required new developments in GNC software. The elements of the GNC software are at different Technology Readiness Levels (TRL). The elements of the GNC software are the sensor processing and the GNC for autonomous rendezvous and proximity operations. The TRL for these elements are shown in table 6.

Table 6: TRL for GNC software elements

Element	TRL
Far range image processing	4
Short range image processing	2 – 3
LIDAR processing	2 - 3
GNC for autonomous rendezvous with uncooperative target	4 - 5

The LIDAR and short range image processing require the greatest development effort. LIDAR and short range image processing require basic filtering (to reduce noise etc.), 3D feature extraction and pose estimation by matching to a shape model stored in the database. The main difference between short range image processing and LIDAR processing is that the LIDAR point cloud already is a set of three-dimensional points.

The new developments within the autonomous rendezvous GNC and formation flying software for Cobra should focus on incorporation of lessons learned from previous projects, adaptation of navigation function to the COBRA sensor set, and the development of a station keeping debris pushing mode.

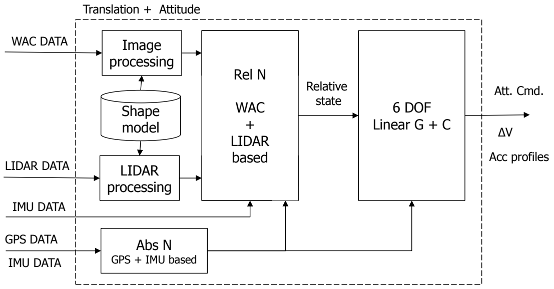

Figure 7: GNC for proximity operations

Figure 7 shows the GNC system for these proximity operations. An 8 DOF controller is used for controlling the attitude and relative position of the Cobra spacecraft, and for controlling the 2 attitude degrees of freedom of the target that can be controlled. The attitude of the target object is controlled by pointing the gas jet onto different points of the target debris object. For this reason, the shape and mass model is used in the guidance and control function as well as in the image and LIDAR processing functions. The guidance and control functions use the shape model to predict the effect of the pointing of the gas jet on the target object.

4.3 Operational concept

The COBRA concept features a high level of on-board autonomy, up to level E3 according to the ECSS standards. Ground involvement is required for commissioning and for the demonstration of the debris pushing. During these phases, the ground would increase the on-board autonomy in a step-wise approach.

Table 7: Mission timeline

Phase	Sub-phase	Activities
Pre-launch preparation		Debris TLE lookup
LEOP		Launch, early operations, deployment of solar arrays, platform activation
Commissioning		Platform and rendezvous payload check-out
Rendezvous	Phasing and orbit raising	Orbit raising using nonlinear guidance
	Search phase	Target searching using NAC
	Far range rendezvous	Approach using nonlinear guidance
	Medium range rendezvous	Approach using linear relative guidance
	Short range rendezvous	Approach using linear relative guidance
Debris characterization		Forced motion Station-keeping at 30 m Observation with LIDAR and WAC
Debris de-orbiting demonstration		Station-keeping at 10 m Demonstration of forced motion approach / retreat Demonstration of debris pushing
Debris de-orbiting		Station-keeping at 10 m Forced motion approach / retreat Debris pushing
Cobra de-orbiting and passivation		Perform de-orbit burn to re-enter the Cobra spacecraft within 25 years, passivate Cobra spacecraft

Table 7 shows the mission timeline. Only those elements that are most relevant to the debris removal mission are listed in the table. Before the actual mission starts, so before launch, a debris object is selected, and two-line element (TLE) set for the object is obtained the from NORAD (or comparable data from a future European debris tracking system) and a suitable injection orbit for Cobra is established. The best knowledge of the debris shape and mass are compiled into a preliminary model to be stored on-board the Cobra spacecraft. The TLE set for the object needs to be updated up to the moment the object can be tracked by means of the NAC and relative navigation can be performed. The total duration of the mission is 4.5 to 6 months.

5 CONCLUSIONS

The study has shown that it is feasible to impart a ΔV of 50 m/s by means of momentum transfer exchange using a monopropellant hydrazine thruster. The momentum transfer efficiency needs to be better than 5%. In worst case conditions (20° plume divergence angle and inelastic collisions of the gas molecules on the debris surface) the distance between the thruster and the debris surface needs to be 5 m or less.

The demonstration mission can be performed at low cost using a modified payload module on an otherwise standard satellite platform. The use of a standard platform means that the mission is feasible in the near-term. The main technology development needs lie in the development and testing of a high-fidelity plume impingement model and the on-board GNC software for performing the rendezvous and proximity operations, including the debris pushing.

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