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EXPANDING FOAM APPLICATION FOR ACTIVE SPACE DEBRIS REMOVAL SYSTEMS

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The threat represented for space missions by the increasing number of uncontrolled space objects has led to an international consensus regarding space debris mitigation guidelines. Given the naturally increasing debris population, the congestion of some orbits and the risks related to cascading effects following accidental or intentional breakups, systems might be needed to actively remove debris. Concepts for active debris removal have been discussed in the scholarly literature. The present approach is based on a novel, expanding foam system, which serves as a drag augmentation device: the aim is to increase the area-to-mass ratio of debris such that atmospheric drag causes natural reentry from low Earth orbits. The foam-based method realizes the drag augmentation by exploiting the characteristics of foams. These can nucleate almost spherical envelopes around target debris with very limited effort of the spacecraft carrying and applying the foam. The approach offers the advantage over other methods of not requiring any docking systems and the ability to deal with spinning and tumbling debris. The method can also be conceived as a preventive method embedded in future satellites. This paper presents the method and analyses its performance. Special emphasis is given to the key aspects of expanding foams, to the demonstration to specific debris types, leading to sizing of the carrying spacecraft. It is equipped with an electric propulsion system that enhances the performance of the complete mission scenario. With this approach, the specific foam ball radius can be tailored to the debris. Its sizing considers the foam mass, the deorbiting time and the risks related to impact probability of targeted objects. An upper threshold of 10 m radius assures the deorbiting of most of the selected debris within a reasonable time. The approach heavily relies on the foam characteristics, e.g. its density and expansion factor. In this study a low order expanding model is introduced and several assumptions close to state-of-the-art for ground-based foam models are considered. First results demonstrate the feasibility to deorbit up to 1 ton debris within 25 years from 900 km altitude with this method. A high power Hall effect thruster assures to deorbit about 3 ton of cumulated space debris per year. All in all, the study demonstrates the feasibility of the method, even as a relatively short-term application, since most key technology assumptions taken are based on state-of-the-art references.

I. INTRODUCTION

The relevant increase in the number of uncontrolled space debris may represent in the near future the major hazard for space missions in some Earth orbits. The large number and the distribution of space debris leads to debris collision risks with potential cascading effects which impact and potentially prohibit some future human and robotic space activities.

Nowadays, approximately 800 satellites of the 6000 launched after the Sputnik-1 up to 2008 are still operational. Accordingly, roughly 85% of these space objects are uncontrolled debris. Millions of objects[1], considering also launcher upper stages and smaller debris caused by explosions, fragmentations, collisions, accidental discharge and similar events, compose the current debris population. The threat represented by these objects is further increased by their high relative velocities. An energy-to-mass ratio up to 40 kJ/kg can be reached[2], this means that even very small objects could cause significant and, even catastrophic damage to operational satellites.

Additionally, space debris are concentrated in the Low Earth Orbit (LEO) and in the Geostationary Orbit (GEO), which are widely used orbits.

To face this problem, in the recent years, space debris mitigation guidelines have been adopted at international level. These recommendations, though necessary, even if fully implemented, might not be sufficient to solve this problem in the long term.

Active debris removal missions might, indeed, be a necessary step to clean up target space regions where the debris threat is more hazardous both for space missions and for the risk of further debris collisions[3].

A number of active debris removal concepts has been already proposed and described. These can be categorized as: electromagnetic methods (i.e. electrodynamic tethers[4], magnetic sails), momentum exchange methods[5] (i.e. solar sails, drag augmentation devices[6]), remote methods (i.e. lasers[7]), capture methods[8] (i.e. nets) and methods based on the modification of material properties.

This paper presents an innovative active deorbiting system belonging to the class of the momentum exchange methods, in particular to the category of the drag augmentation ones. The drag augmentation is suggested to be performed exploiting the characteristics of expanding foams that can nucleate almost spherical envelopes around debris with very limited efforts of the spacecraft in charge of carrying and spraying the foam.

The method is described in detail in Sec. II where the complete mission scenario is sketched. Sec. III focuses on the key technological aspect of the method, i.e. the foam. Here the foam selection is carried out after a brief survey of foam classes and a first order model to estimate the expansion process in vacuum conditions. In Sec. IV a preliminary sizing of the deorbiting platform is investigated with the aim of outlining mass and power of the main subsystems and identifying a suitable foam ejection device. Finally, in Sec. V the mission concept is applied to representative debris lists. Here also the possibility of tailoring the foam ball to the specific target debris is stressed together with the low thrust mission analysis carried out.

II. DESCRIPTION OF THE METHOD

The conceived method relies on the atmospheric drag influence on a foam ball encompassing the debris.

The foam ejected by the deorbiting platform increases the debris area-to-mass ratio and augments the natural drag effect leading to a considerable reduction of deorbiting time if compared with the natural one. The innovative nature of the proposed method allows overcoming the usual difficulties of active deorbiting systems (in particular the docking phase), though it adds as key technological development step the reliable foam expansion in vacuum and its attachment to the debris (see Sec. III).

The same method, here presented as a remedial method, can also be conceived as a preventive system to be directly embedded in future space artificial satellites.

As the method intrinsically relies on atmospheric drag, it is conceived for the LEO debris population and, considering the high total impulse typical of multiple target missions; electric propulsion has been chosen as main propulsion system for the platform in charge of delivering and ejecting the foam.

The deorbiting platform has to be able to chase the target debris and realize a foam ball around or attached to it increasing its area-to-mass ratio such that the atmospheric drag can exert a significant influence to decelerate the debris. In this way, debris that would have deorbited in hundreds of years would re-entry in a much shorter, prescribed time frame.

A complete mission of this kind can be thought as composed of three main phases (see Fig. 1):

- *Target Debris Chasing*: after the launch, the platform has to approach each target debris in a preset order. In the following it has been assumed that the platform initial orbit is the one of the first debris, thus the first maneuver the platform has to perform is the first debris rendezvous.
- *Foaming Process*: in this phase the target debris, reached by the deorbiting platform, undergoes the actual foaming process. The foam is ejected by an ad-hoc device mounted on the platform and sticks on debris surfaces growing in volume.
- *Debris Deorbiting*: the debris is partially or fully encompassed in an assumed spherical envelope of foam. The area-to-mass ratio of the object has been increased and the atmospheric drag naturally causes the debris to spiral down for re-entry. The platform is ready to approach the next debris exploiting its electric propulsion system.

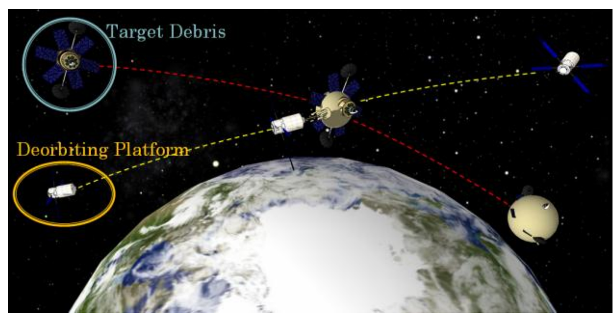


Fig. 1: Schematic representation of the three main mission phases. From left, the debris chasing, the foaming process and the debris deorbiting/next debris targeting. The deorbiting platform path is highlighted in yellow, the target debris one in red and the only encounter point between the two is during the foaming process

At the end of the last mission, the platform is able to de-orbit itself. This can be done firing the electric thruster or exploiting the remaining foam.

The most remarkable advantages of the proposed method are the absence of a docking mechanism, the possibility of an uncontrolled re-entry, the relative sturdiness of the resulting foam, the absence of potential hazards related to ground based systems. Moreover, the capacity of the foam-based method to intercept several minor debris and drag them into the foam or stuck to its surface, as a sort of domino effect has also been demonstrated[9]. This side effect would enable to remove, besides large dead spacecraft, also small debris deriving from spacecraft collisions or fragmentation.

III. FOAM IDENTIFICATION AND MODELING

The development of a foam able to expand in vacuum condition represents the key technology to be matured for the applicability of the proposed method. In the following, starting from a brief overview of the characteristics of existing foam types, a suitable candidate and its physical characteristics are identified.

III.1 Foam Classes

Foams can be described as biphasic materials with polydisperse cells (hollow regions or gas bubbles) surrounded by a firm lattice[10]. The structure of this lattice strongly influences the final physical characteristics of the foam. It is possible to discriminate between closed-cell foams, usually characterized by a significant value of the volume ratio before and after the foaming process (i.e. the expansion factor), and open-cell foams, typically exhibiting superior mechanical properties. Since the resulting properties of the foam are mostly influenced by the material they are composed of, open-cell foams have been identified as the most suitable for our purpose and a more detailed investigation of the material that can be used to nucleate a foam has been carried out[9]. In particular, glass and ceramic foams have been analysed and considered unsuitable for the proposed method for their brittleness and issues related to the manufacturing process. Metallic foams would have represented a good candidate for the proposed method for their mechanical properties but their typical high density represents a significant limiting factor. All in all, polymeric foams turn out to be the most light and versatile foam family offering the best combination of characteristics for the considered application. Polyurethane foams, in particular, have been chosen due to their reasonably high expansion factor (typically), flexibility and their relatively simple manufacturing process.

III.2 Expansion Model

An analytical or numerical assessment of foam expansion at different external pressure levels is essential to estimate the final foam characteristics in vacuum conditions. Considering the foam as composed of a polymeric matrix and an expanding gas developed by the reaction between two pre-polymer components, its final volume can be obtained studying the expansion of a single bubble enclosing all the initial bubble nuclei. This analysis is based on the classic Rayleigh-Plesset equation[11]:

$$\rho_l\left(R\ddot{R}+\frac{3}{2}\dot{R}^2\right)=-\frac{2\sigma}{R}+P-P_\infty-4\mu\frac{\dot{R}}{R}\,, \quad [1]$$

where ρ_l is the density of the liquid, μ its viscosity, σ the gas/liquid surface tension, R the instantaneous bubble radius, P the pressure of the gas inside the bubble and P_∞ the pressure in the liquid matrix which is constant in time and equal to the external pressure. Few simplifying assumptions can be used to obtain a simpler description of the growth of the bubble radius as a function of time, which will have to be substantiated during further maturation phases of the concept:

- fluid viscosity with respect to surface tension is negligible, thus the first term on the right hand side can be neglected;
- the ratio between inertia effects and the viscous ones, i.e. the Reynolds number ($Re \ll 1$), is not relevant, therefore the term on left hand side can be also neglected[12];
- polymer mass represents a very large thermal inertia with respect to the gas, thus a constant temperature for the whole gas reaction can be assumed

Under these hypotheses and assuming that the inflating gas obeys to the perfect gas law, the time evolution of the bubble radius is expressed by[13]:

$$R(t)=R_B\left[\left(1-\frac{P_B}{P_\infty}\right)e^{-\frac{3P_\infty}{4\mu}t}+\frac{P_B}{P_\infty}\right]^{1/3} \quad [2]$$

where the initial bubble radius R_B can be obtained from the value of the expansion factor of a specific foam. In particular, considering a commercial two-component polyurethane foam (ESPAK 90), the ratio between initial polymer mass and the mass of the gas generated during the reaction is 2%[9]. This value can be used to validate the model with the data provided by foam producers and to predict the expansion factor of each particular foam in vacuum conditions. It is worth noting that this polymer-gas mass ratio is peculiar to each foam but its value may slightly differ from the one obtained.

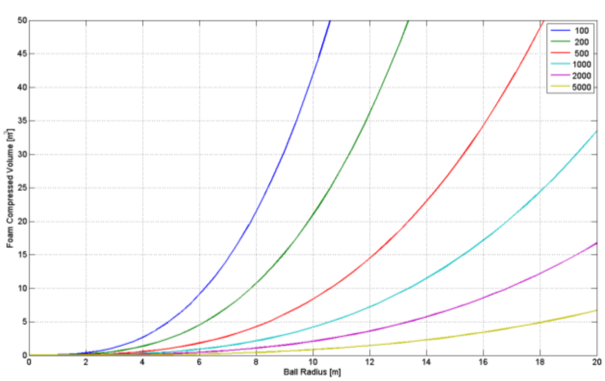
Even if this analysis results in an infinite expansion factor for $P_\infty = 0$, for an external pressure equal to 0.001% of the atmospheric pressure the model implemented results in an expansion factor of 1.2e6 and a final density value close to 1e-3 kg/m^3. The considered external pressure corresponds approximately to the pressure in a low Earth orbit of around 100 *km* altitude and can be intended as a reference value highlighting foam characteristics change with respect to external pressure. Moreover, since the values here obtained are the results of a low order analytical model and the characteristics of an ad-hoc space-developed foam could differ significantly, more conservative values have been used to assess the performance of the deorbiting method.

II.I Characteristics of the Candidate Foam

The most suitable foam for the method proposed should satisfy several fundamental requirements:

- it has to be sticky, such that the foam and the debris become a single object and additional debris caused by foaming process are avoided;
- the foam has to be able to expand, polymerize and harden in vacuum;
- at the end of the expansion phase, the foam should have an high expansion factor and a low density;
- the foam should not degrade too fast during the atmospheric re-entry;
- it has to be not hazardous for human and for the on-board equipment. The foam should be environmentally innocuous, if burning up in the atmosphere, or crashing in waters or on the ground.

Moreover, starting from the results of the described expansion model, a parametric analysis aimed at the identification of candidate values for the foam density and expansion factor has been carried out[9]. This analysis follows a reference foam ball radius of 10 m, which is able to deorbit a 2.5 tons debris from 800 km within 13 years and. Depending on foam characteristics the mass of this foam ball may significantly vary. In particular, the most suitable foam expansion factor and expanded foam density values have been studied starting from foam state-of-the-art values for ground application[14], see Fig. 2.



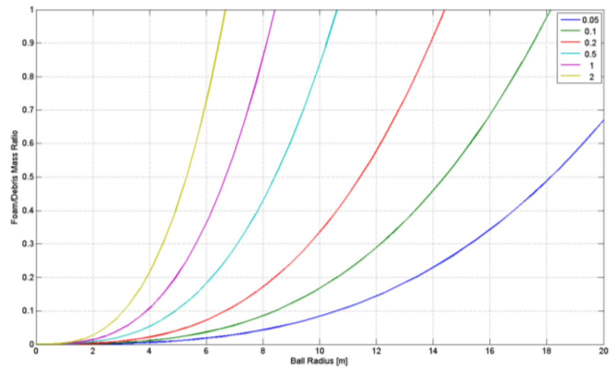


Fig. 2: Top: Foam compressed volume with respect to ball radius for different expansion factor values. Bottom: Foam-deorbited-debris mass ratio with respect to foam ball radius for different values of the expanded foam density.

From the top plot of Fig. 2, it is clear that, in the considered range, an expansion factor greater than or equal to 1000 times enables a significant reduction of the original volume. Similarly, considering the bottom plot of Fig. 2, an expanded foam density of 0.2 kg/m^3 can be identified as the one giving a significant mass saving, if compared to larger values. Given that low density foams are already available with densities in the range 1-6 kg/m^3, a relatively conservative foam density value of 1 kg/m^3 (at the end of the expansion phase) has been identified and will be used in the following analyses.

IV. DEORBITING PLATFORM SIZING

The method performance, in terms of debris deorbited mass per year or per mission, depends on the specific deorbiting platform characteristics. In order to analyze the method on the three debris lists considered (Sec. V) in this section a rough sizing of the conceived platform is carried out.

As reference value for the platform launch mass we are assuming some metric tons to be delivered in LEO. At this stage we are not precisely assessing any payload mass (i.e. foam), as this results from some iterations between mission analysis and system design.

An analysis on the available European launch vehicles, led to consider a medium size launcher (e.g. Soyuz) as the most suitable for our purpose. As the largest part of the considered debris lies approximately in the SSO region at approximately 800-900 km, the reference launch mass is defined assuming the Soyuz launcher performance into a SSO of this altitude (4600 kg)[15].

Considering the platform launch mass, the first step in platform preliminary design is to size a suitable electric thruster for the deorbiting application and a specific reference thruster to assess the mission scenario performance. A qualitative analysis of all electric thruster methodologies can easily identify the best candidate thruster from a technological point of view[16]. Electrothermal thrusters may have a small specific impulse, thus the resulting propellant mass would be too high. Field electric emission thrusters, although offering a very large exhaust velocity, provide level of thrust that would result in long transfer duration in-between debris. Magneto-plasma-dynamic devices would require too much power to work in their optimal range. Hall effect thruster, instead, naturally operate at some mN of thrust with specific impulses between 1000 and 4000 s. Ion thrusters would have been the second-best choice. Although they usually have slightly better performance in terms of mass consumption, they require on average higher power levels to operate. Moreover their size and weight is generally larger than the ones of Hall effect thrusters, mainly due a lower thrust density, causing also significant thermal problems[17].

Among the Hall effect thruster category, a representative thruster with medium-high performance has been taken as reference thruster, the SNECMA Moteurs PPS-5000 Hall effect thruster. This thruster operates at a nominal power of 5 kW, it is able to provide around 3000 s of specific impulse with an efficiency larger than 50%[18]. This means that (conservatively) a single PPS-5000 provides a thrust of 200 mN. Moreover, as larger solar power generation systems are feasible for the considered orbits, two identical thrusters are chosen to be operated simultaneously. This thruster, furthermore, can be also considered for the attitude control and relative platform-debris pointing during the foaming phase.

The mass and power requirements of the remaining subsystems are sized by means of a top-down approach In particular, a dry mass of 1 ton, demonstrated a-posteriori to be a reasonable value, has been assumed to start the analysis and, relying on statistical data on the state-of-the-art technology, a percentage of this mass has been allocated to each subsystem. The Attitude Determination and Control System (ADCS), the Command and Data Handling subsystem (C&DH), the Telemetry, Tracking, and Command (TT&C) subsystem and the spacecraft structure represent respectively 10%, 3.4%, 6% and 20% of the platform dry mass. The Energy Storage System (ESS) has been sized to provide the maximum power required by the spacecraft also during eclipse phases. Moreover, assuming 20% of contingency for each subsystem, about 3600 kg result to be available for the propellant mass, the foam with its tank and the foam ejection device. In a preliminary (but conservative) estimation, this mass is supposed to be equally divided (1.8 tons each one) between the payload, composed of the foam itself and by the foam ejection device, and the propellant. This assumption represents a reference value, indeed foam and propellant mass fractions depend on the specific mission scenario and, in general, their value depends on the size and the spatial distribution of the targeted debris population. The platform power generation subsystem (PGS) is composed of 40 m^2 of independent, deployable, Sun-tracking solar panels capable of providing up to 12 kW. The power required by each subsystem, similarly to their mass, has been determined on the basis of statistical data on the state-of-the-art technology. The pie charts in Fig. 3 show the relative weight in terms of mass (top) and power (bottom) of the different subsystems with respect to total mass (4.6 tons) and available power (~12 kW). The identified power level is required to operate both the thrusters and the other subsystems during the foam ejection phase, which is the most power-demanding phase of the mission.

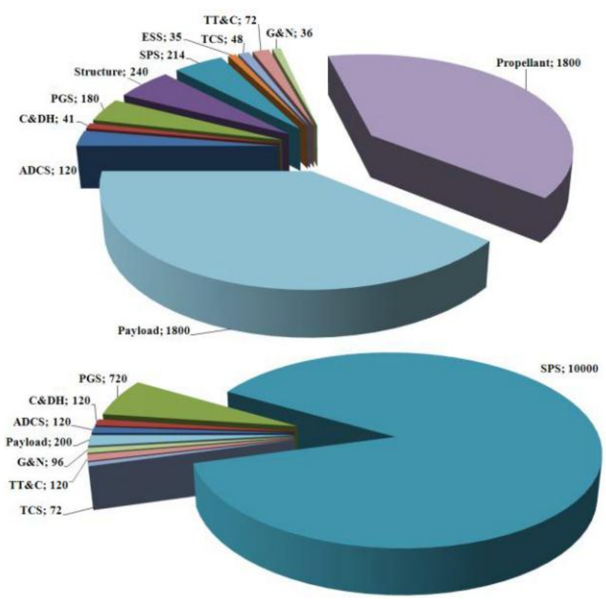


Fig. 3: Top: Mass of deorbiting platform subsystem and their relative weight with respect to spacecraft wet mass. Bottom: Power required by each subsystem with respect to total incoming power.

It is worth mentioning that the mass and power required by the foam nucleating system have been determined after a brief comparison among four foam nucleating device options[9]. The best candidate in terms of technological issues, costs, reliability and effectiveness is the “Foam Ejection Nozzle”. This device consists of a nozzle from where foam is ejected on the debris surface, two pre-polymer component reservoirs, the pumping system and a pipe flushing system. In order to reach the debris in a more precise way and cover its surface from various positions, it may also be combined with a robotic arm mounted on the spacecraft, see Fig. 4.

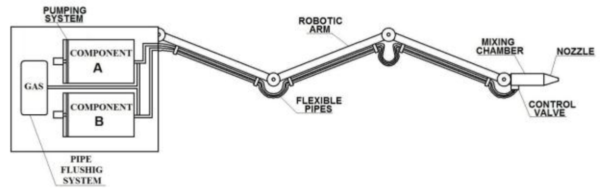


Fig. 4: Schematic representation of the "Foam Ejection Nozzle" on the extendible robotic arm.

V. APPLICATIVE CASES

A set of three space debris lists is presented and described in this section together with the methodology used to assess method performance. The deorbiting platform described in Sec. IV is considered in the mission preliminary analysis to estimate the cost in terms of required velocity increment (ΔV) and propellant mass needed for each phase of the mission scenario depicted in Sec. II. The low-thrust manoeuvres necessary to acquire target debris orbits have been assessed by means of analytical approximations under some simplifying assumptions. In particular, platform and debris orbits are always accounted as circular and no orbit phasing is considered to adjust the platform true anomaly. The orbits of debris are considered as unchanged during all platform transfers and the cost of each low thrust manoeuvre is obtained as the maximum velocity increment between the one necessary to perform the combined semi-major axis and inclination change and the one for the RAAN change. Moreover, at the beginning of each mission, the platform is supposed to be released by the launcher at the exact orbit of the first target, thus the only task to be performed, in this case, is the debris foaming.

V.1 Debris Lists

The orbital and physical characteristics of current space debris population cannot be easily described due to the different nature and origin of these man-made objects. For this reason, in this study three different lists have been taken into account and for each of them the simulation of an active space debris removal mission campaign have been carried out. In particular, the list considered in this study are:

- *Filtered DISCOS list*: This list, based on the ESA Database and Information System Characterizing Objects in Space (DISCOS)[19], embraces 59 objects obtained by means of subsequent filters on the original DISCOS list. These objects lie in almost circular orbits with an altitude between 700 and 900 km, and have an average cross sectional area larger than 1 m^2 and a mass larger than 500 kg. Only objects launched before 2000 and rocket bodies (regardless of the launch date) have been taken into account and just one of the 78 satellites of the *Iridium* Constellation has been considered as representative for the whole constellation.

- *Proprietary SSO list*: This second list presents a more focused description of the near-Earth region and in particular of the Sun-Synchronous Orbit (SSO). More stringent filters in terms of orbital parameters have been assumed and only objects with orbital altitude between 600 and 900 km, inclination between 97 and 100 deg and eccentricity smaller than 0.035 lie in this list.

- *UCS Tracked Object list*: This third list is intended to provide a broader description of the space debris environment. It is based on currently tracked objects whose characteristics are published in a database (downloaded at November 2010) made available by the Union of Concerned Scientists (UCS)[20]. These objects are mainly active spacecraft but, under the assumption of no mission extension, the object launch date and its expected lifetime allows to obtain a list of potential current or future debris. Two additional upper thresholds on object mass (2000 kg) and orbital altitude (1000 km) provide a list of 237 objects, covering a possible future scenario of debris objects in LEO.

Figure 3 shows the orbital altitude (top plot), the debris mass (centre plot) and the inclination (bottom plot) for the three lists described. In particular, the leftmost series (blue dots) represents the debris of the SSO list, the red squares in the centre symbolize the DISCOS list and the rightmost green triangles are the debris of the UCS list.

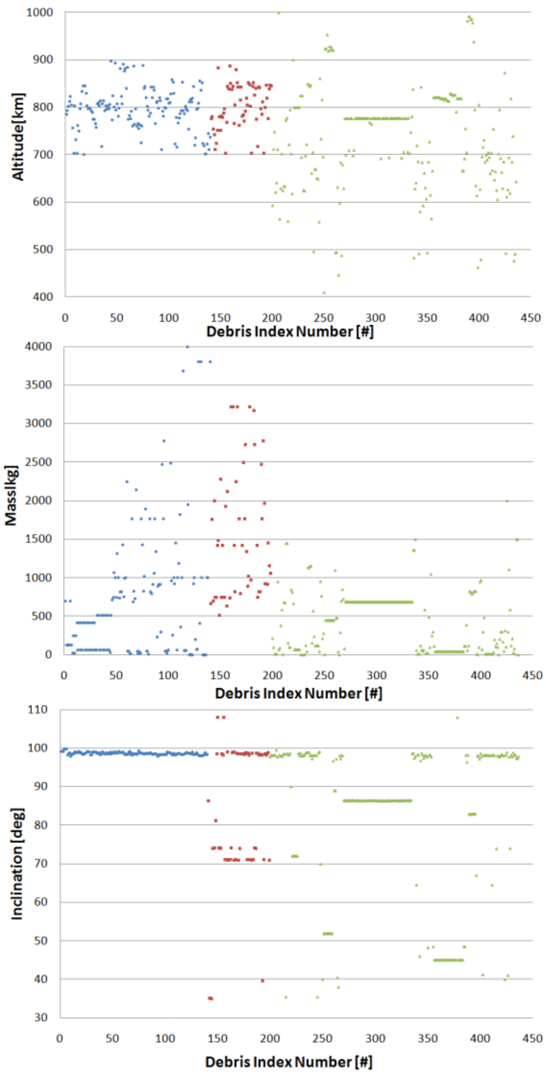


Fig. 5: Orbital altitude (top plot), the debris mass (centre plot) and the inclination (bottom plot) for the DISCOS (blue), SSO (red) and UCS (green) lists.

The top plot in Fig. 5 clearly shows that the debris of the first two lists has similar altitude distributions but while the DISCOS list includes debris with inclinations from 35 up to 108 deg and masses from 500 to 3250 kg, the SSO list contains debris from 1 to 4000 kg with a narrower inclination distribution (97.9 deg< i <99.8 deg). On the contrary, the UCS list offers debris with orbital altitude from 400 up to 1000 km with an inclination distribution similar to the one of the DISCOS list. Moreover, the values of orbit Right Ascension of the Ascending Node (RAAN) for the debris of the three lists are equally distributed from 0 to 360 deg. It is worth highlighting that, considering all the debris of the three lists, the average orbital altitude is 777.5 km, the average debris mass is 1261.7 kg and the average inclination is 87.81 deg.

V.2 Foam Ball Tailoring

Debris orbital and physical characteristics can be used to take advantage of one of the main benefit of the proposed method: the possibility to tailor the foam ball on each specific target debris. The quantity of foam used for each target debris results in a different final area-to-mass ratio and hence in a different duration of the deorbiting phase. Nevertheless, high values of the drag-exposed cross sectional area cause a high number of potential impacts with other debris or even active spacecraft, i.e. a high impact probability. For this reason, the assessment of these two quantities (deorbiting time and impact probability) with respect to foam ball area is essential for the determination of the most suitable foam ball size.

The deorbiting time of the system composed by foam and debris can be assessed by means of the Gauss form of the Lagrange Planetary Equations[21]. These equations model the time evolution of the classical orbital parameters (semi-major axis a, eccentricity e, inclination i, RAAN Ω, argument of pericenter ω and mean anomaly M) under the influence of an external acceleration besides the Keplerian one. As the most relevant perturbation affecting debris in the Low Earth Orbit (LEO) is the atmospheric drag, its expression[22] can be directly substituted with the non-conservative perturbation term. Focusing on the instantaneous rate of change of the semi-major axis and by means of substitutions for the relative velocity and the eccentric anomaly rate of change, it is now possible to obtain an expression for the influence of the atmospheric drag with respect to eccentric anomaly (E):

$$\frac{da}{dE} = -\rho \frac{C_d A a^2 \left(1 + e\cos\left(E\right)\right)^{3/2}}{m\sqrt{\left(1 - e\cos\left(E\right)\right)}} \qquad [3]$$

Note that the atmospheric drag also affects orbit eccentricity but its main effect is to decrease initial orbit eccentricity to the minimum value of 0. Since initial orbit eccentricity values for all the considered debris are rather small, the atmospheric drag net effect on orbit eccentricity is also minor. An integration based on the adaptive Lobatto quadrature of the atmospheric force over the eccentric anomaly[23], together with the identification of a proper model for the atmospheric density variation with the orbital altitude, allows to assess the orbital lifetime of each target debris with respect to debris mass, area and initial altitude. In particular, since our scenario does not assume a specific mission starting date or duration, a static atmospheric density model, the Harris-Priester model[22], has been assumed.

The impact probability, required to avoid a high number of potential impacts with other debris or active spacecraft, is obtained integrating the debris flux, given by the NASA90 model[24], together with Eq. 3. The debris flux (i.e. the cumulative number of impacts on a spacecraft in circular orbit per m^2 and per year on a randomly tumbling surface[24]) is obtained as function of the minimum impactor diameter, the considered orbit altitude and inclination, the mission epoch and the solar radio flux.

In order to obtain one single curve, expressing the relevance of both the described quantities, a guideline value for each parameter has been assumed as a non-dimensional number. This curve, representing a trade between the two criteria, is obtained as the sum of deorbiting time and impact probability weighted with the maximum allowable impact probability value (1e-3)[25] and with a desirable deorbiting time value (5 years), respectively. Thus, the minimum of this curve provides the sought foam ball radius for a given debris.

Figure 6 shows the deorbiting time (blue line) and the impact probability (red dashed line) with respect to drag exposed area for the debris number 26 of the DISCOS list.

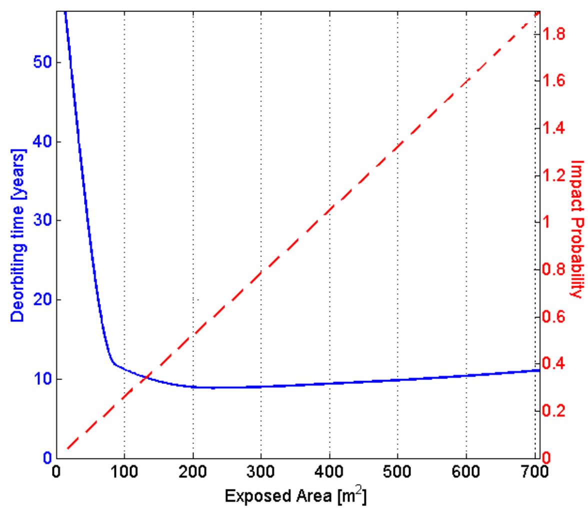


Fig. 6: Deorbiting time (blue line) and impact probability (red dashed line) with respect to drag exposed area for the 26th debris of the DISCOS list.

In general, allowing a larger impact probability, the foam ball radius increases, augmenting accordingly the foam mass, and the deorbiting time decreases. On the contrary, reducing the allowed impact probability and allowing a lower gain in the deorbiting time, the foam ball can be reduced, thus the foam mass decreases and even more massive debris can be targeted by this method.

For the sake of completeness, Fig. 7 shows the deorbiting time (left) and the impact probability (right) values obtained using the foam ball size values identified with the described method. In particular, it turns out that 93.7% of the considered debris could be deorbited with the proposed method within 25 years, 71.6% within 10 years and 42.4% within 5 years. Moreover, about 47% of the debris in the three lists has an impact probability below 0.001 and only 18% of them larger than 0.01.

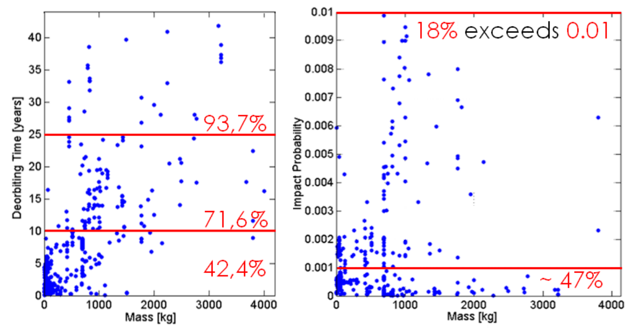


Fig. 7: Deorbiting time (left) and the impact probability (right) for the debris of the three described lists.

IV.III Low Thrust Mission Analysis

Method performance, in terms of average number of targeted debris per year and per mission, can be assessed considering the orbital and physical characteristics of the debris of the three considered lists. The most relevant simplifying assumptions used for the implementation of the preliminary mission analysis are:

- Debris orbit are considered unchanged for the whole time needed to target each debris, i.e. neither atmospheric drag nor Earth oblateness perturbation (J2 effect) are considered during the low thrust transfers both for the debris and the platform.
- The platform trajectory is obtained by the semi-major axis and inclination change manoeuvre followed by a RAAN change.
- The total manoeuvre cost is obtained as the maximum velocity increment between the one necessary to perform the combined semi-major axis and inclination change and the one for the RAAN change manoeuvre.

The last assumption still provides reasonable results considering that natural RAAN drift is neglected for the whole analysis both for the platform and for the debris. Considering the listed assumptions, the mission profile has been described as a sequence of transfer manoeuvres. The selection of target debris sequence is based on the manoeuvre cost obtained by means of analytical approximations. In particular, the semi-major axis and inclination modification manoeuvre is assessed by means of Edelbaum approximation[26]:

$$\Delta V = \sqrt{V_0^2 - 2V_1V_0\cos\left(\frac{\pi}{2}\Delta i\right) + V_1^2} \quad [4]$$

where V_0 and V_1 represent, respectively, the orbital velocity on the initial and final orbit and Δi is the desired inclination change angle. The RAAN change maneuver can be analytically approximated by[27]:

$$\Delta V = \frac{\pi}{2}\sqrt{\frac{\mu}{a}}\left|\Delta\Omega\right|\sin(i), \quad [5]$$

where $\Delta\Omega$ is the desired change in RAAN. Thus, Tsiolkovsky equation[28] can be used to compute the mass of propellant required to perform the whole transfer. Moreover, the manoeuver time, under the assumption of constant acceleration, is obtained by means of:

$$\Delta t = \frac{\Delta V}{\bar{a}} = \frac{\Delta V}{T}\bar{m}_{SC} = \frac{\Delta V}{T}\left(m_0 - \frac{m_p}{2}\right) \quad [6]$$

where $\bar{m}_{SC}$ is the average spacecraft mass, m_0 the value of the spacecraft mass at the beginning of thruster firing and $\bar{a}$ the resulting average acceleration on the spacecraft.
The mass of foam required to deorbit each targeted debris can be computed considering the foam density (ρ_F) and the volume of the ejected foam. Since the debris is assumed spherical before and after the foaming process, the required foam mass is given by:

$$M_F = \rho_F \frac{4}{3}\pi\left(\frac{A_F - A_D}{\pi}\right)^{\frac{3}{2}} \quad [7]$$

where A_D and A_F represent the average exposed area of target debris before and after the foaming process, respectively.

V.3 Results

By means of the described procedure for the preliminary mission analysis, each one of the considered debris list can be used to obtain a realistic assessment of the method performance. In particular, Fig. 8 shows the propellant mass consumption (top left), the time required for each manoeuvre (top right), the total mass of the debris in orbit (bottom left) and the foam mass (bottom right) for the debris of the DISCOS list. Each vertical red line represents the end of a debris removal mission and, considering each mission to start at the end of the previous one, 7 missions and 30.4 years are necessary to target the 50 DISCOS list debris. On average, 1.65 debris (2.57 tons) can be targeted per year and each mission could target 11.2 tons of debris with an average mission duration of 4.34 years.

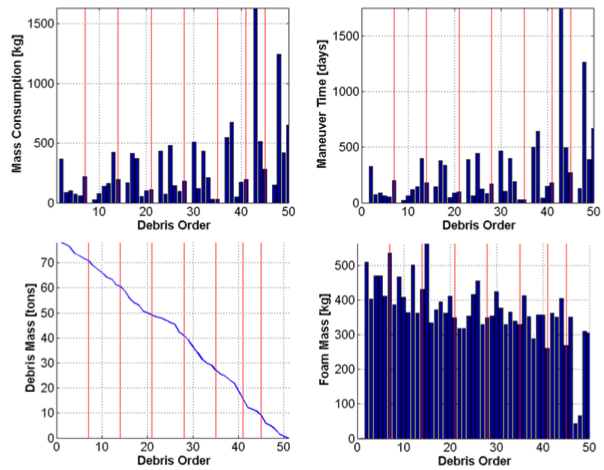


Fig. 8: Propellant mass consumption (top left), the time required for each manoeuvre (top right), the total mass of the debris in orbit (bottom left) and the foam mass (bottom right) for the DISCOS list.

Similarly, Fig. 9 shows the results of the analysis of the mission campaign targeting the debris of the Proprietary SSO list. A total of 21 missions is required to target 140 debris. On average 4.32 debris are targeted per year, assuming to perform the mission in sequence, with an average mass value of 3.51 tons of deorbited debris. Each mission targets on average 5.41 tons of debris (6.7 debris).

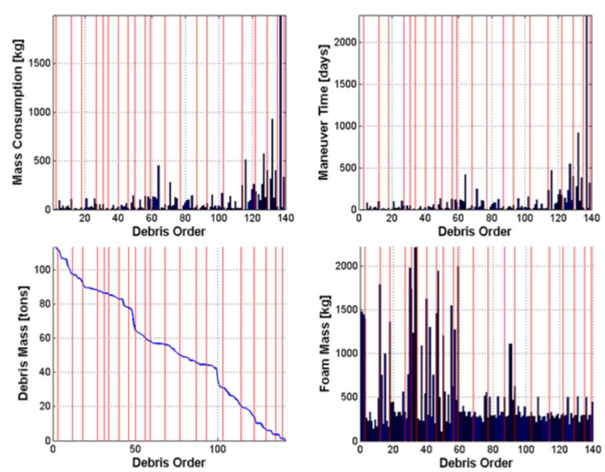


Fig. 9: Propellant mass consumption (top left), the time required for each manoeuvre (top right), the total mass of the debris in orbit (bottom left) and the foam mass (bottom right) for the Proprietary SSO list.

The more crowded UCS list, requires 34 missions in order to reach all the 237 debris. Assuming again to perform one mission after the other, 3.28 debris can be targeted each year on average with a corresponding value of the debris mass per year of 1.38 tons/year, so each mission is sufficient to target 2.93 tons of debris (~7 debris). The results of the active debris removal mission campaign for the UCS list are shown in Fig. 10.

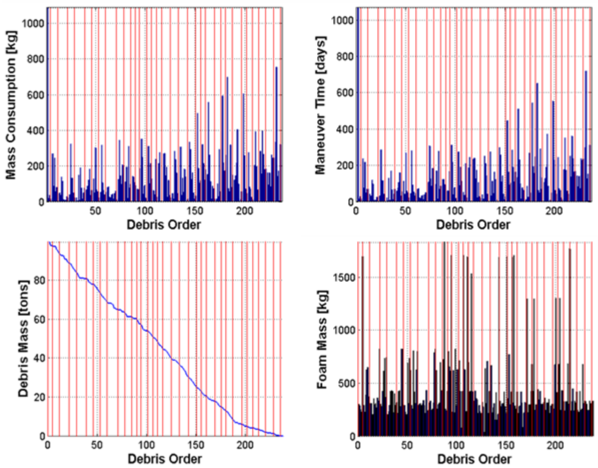


Fig. 10: Propellant mass consumption (top left), the time required for each manoeuvre (top right), the total mass of the debris in orbit (bottom left) and the foam mass (bottom right) for the UCS list.

VI. CONCLUSIONS

In this work an innovative active debris removal method has been described. The expanding-encompassing-foam concept proposed aims to augment the drag acceleration acting on a given debris such that an uncontrolled re-entry can take place with the complete burn up of the object in the atmosphere within a given time frame.

One of the most remarkable advantages of this method is that the foam mass depends on the specific debris and the ball can be tailored according to the required deorbiting time. The approach followed to compute such a radius consists in identifying, for each debris, the minimum of the curve given by the sum of non-dimensional deorbiting time and impact probability.

In absence of the requirement for a docking phase, the key technological aspect of the method is the foam expansion and bond to the target debris in vacuum conditions.

A survey of the state-of-the-art available foams led to consider the polymeric class as the more suitable for our purpose. The expansion phase has been modelled by means of a first order model and the obtained foam density has been used for the subsequent mission analysis assuming, conservatively, 1 kg/m^3.

An electric thruster equipped platform, in charge of carrying and spraying the foam has been sized both from the mass and power point of view. The proposed platform is a 4.6 tons spacecraft to be launched in LEO or SSO by means of a Soyuz-class launcher. The electric propulsion system, based on 5 kW Hall effect thrusters, allows a significant propellant mass saving and a reasonable increment in the transfer times from one debris object to the next. This scenario requires a large total impulse, thus the preference for electric propulsion options over chemical solutions.

Based on the assumed bi-component polyurethane foam and the low-thrust equipped platform, representative mission analyses have been carried out to assess the system performance. The proposed missions depend on the debris object lists (three here considered), the space region they cover and the number of targets considered. In general, up to several tons debris (1.4-3.5 tons) can be deorbited per year with an average reduction of the original deorbiting time of the order of 85%. Considering heavy debris (> 1 ton), however, the required foam mass might exceed (depending on its density) the debris mass making this method not the preferred choice for such debris objects.

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