Small Electric Propulsion Platform for Active Space Debris Removal

IEPC-2013-217

Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013

A. Ruggiero[1], P. Pergola[2], and M. Andrenucci[3]
Alta, Pisa, 56100, Italy

Abstract: It is nowadays clear that future space access and activity sustainability is greatly endangered by the large amount of space debris populating the near Earth region. In the last few years, a number of different Active Debris Removal methods has been proposed and each of them may represent a valuable solution for space debris belonging to specific classes or types, or orbiting in particular space regions. Regardless of the method identified as the most suitable, an Active Debris Removal mission scenario can be thought as composed of different phases in which a deorbiting platform is in charge of approaching a target debris, bringing it to a lower altitude orbit and, in case of a multiple target mission, releasing it and chasing another one. Considering the high total impulse typical of this kind of missions, electric propulsion plays a key role in reducing the propellant mass consumption required for each maneuver, increasing consequently the mass available to deorbit a relevant number of debris per mission. A low power and low cost electric propulsion systems based on the Alta's HT-100 Hall Effect Thruster is here considered with the aim of highlighting the advantages offered by this system for such kind of missions.

Nomenclature

a	=	semi-major axis
$\bar{a}$	=	mean acceleration
Δt	=	maneuver time
e	=	eccentricity
i	=	inclination
m_0	=	spacecraft mass at the beginning of thruster firing
m_p	=	propellant mass
$\bar{m}_{SC}$	=	average spacecraft mass
μ	=	Earth gravitational parameter
T	=	thrust
V	=	orbital velocity

I. Introduction

THE relevant increase in the number of uncontrolled space debris is considered nowadays one of the main threats for future sustainability of space activities and space access. It is now clear that in the near future the access to space might be greatly endangered by the large amount of space debris populating the orbital regions in the vicinity

[1] Research Engineer, Alta, Pisa; M.Sc.; a.ruggiero@alta-space.com.
[2] Project Manager, Alta, Pisa; Ph.D.; p.pergola@alta-space.com.
[3] President, Alta, Pisa; Professor, Department of Aerospace Engineering., University of Pisa, Italy; m.andrenucci@alta-space.com

of the Earth. Currently, about 1000 satellites out of 6000 launched after the Sputnik-1 are still operational and roughly 85% of the 22000 traceable objects space objects represents 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 indeed the current debris population. Due to their high orbital velocity, also small size debris can lead to catastrophic break-ups which have the effect not only of damaging operational spacecraft, but also of increasing the amount of hazardous debris in orbit which can in turn cause further space collisions.

The constant increase in the number of space debris and the associated potential cascade effect led the international space community to adopt specific guidelines aimed at mitigating this phenomenon. This approach, however, might not represent a way out from this problem, hence the implementation of Active Debris Removal (ADR) missions might be essential, especially in those regions where both commercial and scientific space activities typically take place, e.g. Low Earth Orbits (LEO), geosynchronous orbits and Sun-synchronous orbits. Moreover, the European Space Agency itself in the effort of devoting increasing attention to the environmental impacts of its activities, has identified space debris mitigation and the development of technologies for space debris remediation[2] as two of the four branches identified as critical for the reduction of the environmental impact of space programmes. 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].

In the last few years, a number of different ADR concepts has been already proposed and analyzed such as electromagnetic methods (i.e. electrodynamic tethers[4] and magnetic sails), momentum exchange methods[5] (i.e. solar sails and 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. Each method may represent a valuable solution for space debris belonging to specific classes or types, or orbiting in particular space regions and ESA in the framework of the Clean Space initiative has recently focused its interest in the development of technologies for space debris rendezvous, capture and re-entry[9]. The methods selected by ESA for the envisioned ADR mission are based on robotic arm, tentacles, and nets[10]. Nonetheless, regardless of the method identified as the most suitable, a generic ADR mission scenario can be thought as composed of different phases in which a deorbiting platform is in charge of approaching a target debris, bringing it to a lower altitude orbit and then, in case of a multi target mission, chasing another one and then deorbit itself.

Considering the high total impulse typical of these missions aimed at reaching several different targets in a strong central gravity field, Electric Propulsion (EP) definitely plays a key role in reducing the propellant mass consumption required for each maneuver, increasing consequently the mass available to deorbit a larger number of debris per mission.

This study presents, in Sec. II, the concept of operations and the mission scenario of a realistic ADR mission and, in Sec. III, the chaser platform preliminary sizing. The spacecraft is supposed to be equipped with electric thrusters so as to be able to efficiently change its orbit and thus serve multiple targets. The whole design is addressed at subsystem level considering requirements and payload capabilities of small satellites launch systems and launchers auxiliary structures.

Section IV describes the preliminary mission analysis of the proposed active space debris removal method assessed by means of analytical approximations to estimate the velocity increment required to acquire the the target object orbits. The main maneuvers taken into account are changes in semi-major axis, inclination and right anomaly of ascending node. Finally, In Sec. V the performance of the EP-ADR mission is evaluated in terms of the number of missions required to remove all the objects belonging to a representative list of potential space debris. In this latter section, a comparison with the performance provided by a chemical propulsion scheme is also presented.

II. Concepts of Operations and Mission Scenario

The ADR mission proposed in this study is aimed at targeting several different non-functional and uncooperative objects. The mission is intended to be performed by means of a small *chaser* platform equipped with a low mass and low cost EP system. This is driven with some hundreds Watt of power and operates with high specific impulse so that the orbital maneuvers required would not result in a high propellant burden.

The whole ADR mission scenario can be broken down into six different mission phases:

1) *Launch and commissioning*: The platform in charge of targeting and deorbiting the debris is launched into an initial orbit close to the one of the first target debris. In particular, the chaser is assumed to be released into a neighboring orbit laying down underneath and behind the one of the non-functional satellite with a true anomaly placing the platform few km below and behind the target[11].

2) *Debris rendezvous and capture*: In this phase the chaser performs the final rendezvous maneuver required to reach the target debris and the actual capture procedure takes place. During this stage the capture device is activated and operated together with the chaser propulsion, attitude and orbit control system to perform the necessary approach and grasping maneuvers. The most suitable debris capture configuration is autonomously and accurately identified by means of the onboard 3D vision and image processing system assumed to be embedded into the capture device.

3) *Low-thrust spiraling:* after capturing the debris, the propulsion system of the chaser platform is operated with the aim of slowly decreasing the semi-major axis of their orbit. During this phase, the atmospheric drag exerts a beneficial effect increasing the altitude decrease rate.

4) *Debris Release and Deorbiting*: as soon as the c*haser-debris* system reaches an orbital altitude of 300 km, the debris is released and it begins its own natural orbital decay.

5) *Targeting of next debris*: the chaser platform, operating its EP thrusters, performs a set of orbital maneuvers aimed at the interception of the next target debris, i.e. next debris rendezvous. Steps 2-4 are thus repeated.

6) *Platform self-disposal*: Once the platform has completed its mission (making use of all propellant available or running out of capturing devices) the thrusters can be used to lower the orbit perigee and deorbit the spacecraft within the 25 *years* limit stated by the IADC guidelines[12].

Figure II–1 shows the profile and the most relevant phases of the envisaged ADR mission with the chaser equipped, by way of example, with a capture device based on a robotic arm.

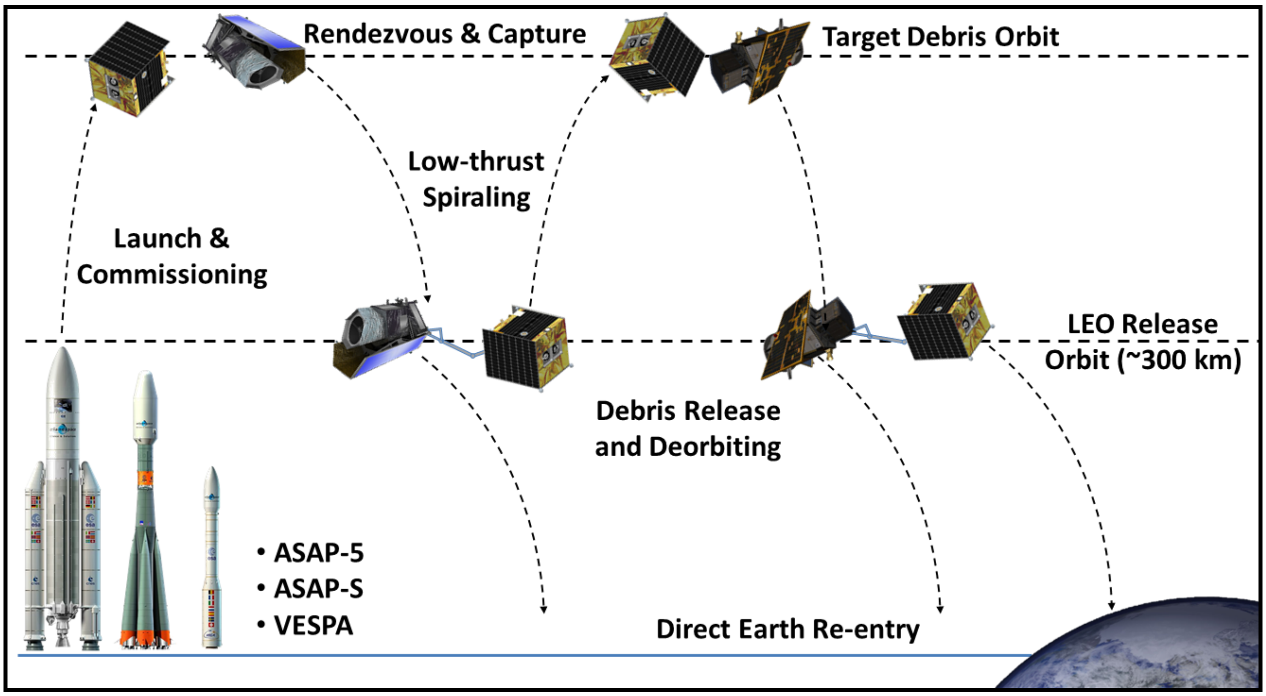


Figure II–1: Complete profile of a possible multi-target ADR mission.

III. Preliminary Spacecraft Design

The preliminary design of the spacecraft has been carried out by considering a maximum launch mass of 200 kg in order to meet the requirements of many small satellites launch systems and of the most relevant secondary payload adapters. In particular, the design of the platform is compliant with the requirements and the payload capability of the Ariane Structure for Auxiliary Payloads on Soyuz launcher (ASAP-S) and on Ariane 5 (ASAP-5) and with the ones of the Vega VESPA (VEga Secondary Payloads Adapter).

More in detail, the Arianespace System for Auxiliary Passengers (ASAP-S) is the Soyuz internal carrying structure dedicated to auxiliary passengers and it allows embarking up to 4 micro satellites of the 200 kg class on 4 external positions and 1 mini satellite of 400 kg class in central position[13]. Similarly, the Ariane 5 Structure for Auxiliary Payload (ASAP-5) is capable of embarking up to 8 micro auxiliary payloads (mass <120 kg), 4 mini

Auxiliary Payload (120 kg < mass <300 kg), or a combined configuration with up to 2 mini Auxiliary Payloads and 6 Micro auxiliary payloads[14]. VESPA is the Vega solution for secondary payloads and allows 1 mini auxiliary passenger or up to 2 micro auxiliary passengers[15]. The chaser platform has been designed considering Commercial Off-The-Shelf (COTS) components to the larger extend to provide a state of the art design, to reduce the mission costs shortening at the same time the duration of development and qualification phases.

The core system of the chaser envisaged is the EP system. Several EP technologies have nowadays demonstrated their effectiveness and reliability in mission requiring high total impulse as the one here investigated aiming at reaching several different targets in a strong central gravity field. The low thrust level provided by these systems with relatively high power–to–thrust ratios allow for a sufficiently high acceleration level on small platforms. Despite the mass penalty derived by the growth of the Power Generation System (PGS), the resulting propellant mass saving, offered by the characteristics of such a kind of thrusters, enables a significant increase in terms of number and mass of the debris that can be targeted and deorbited per each mission.

A low-power spacecraft propulsion system based on the Alta hundreds class Hall thruster HT–100[16] has been considered with the aim of highlighting advantages and drawbacks offered by this kind of technology for such kind of missions. The HT–100 operates between 150 and 350 W with 31% of maximum total efficiency. The thruster uses permanent magnets and requires at its nominal working point about 175 W generating 8 mN with 1000 s of specific impulse and efficiency close to 22%. Nonetheless, the power level considered in the analysis of Sec. V is of 330 W with a corresponding thrust larger than 15 mN and a specific impulse of 1283 s. The total system mass, including the thruster, the propellant management assembly and it's the electronic units, is about 5 kg. Table III–1 shows the most relevant characteristics of the Alta HT–100 Hall propulsion system.

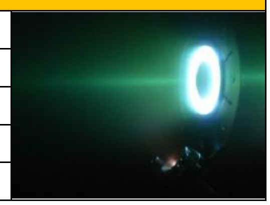
Alta HT–100		
Thrust [mN]	**6–18**	
Specific Impulse [s]	<1300	
Efficiency	<31%	
Power [W]	150 –350	
Dry Mass [kg]	0.5	

Table III–1: Most relevant characteristics of the Alta HT–100 Hall effect thruster.

The chaser PGS has been sized by considering the power consumption of the EP system, of the payload and of the other spacecraft subsystem. The worst case scenario is during the debris capture phase as both the capture device and the imaging system are operated while the spacecraft propulsion subsystem and the Attitude and Orbit Control System (AOCS) are in charge of maintaining the relative attitude and orbital position of the chaser with respect to the target debris. More in detail, three solar panels (one body mounted and two deployable solar arrays) are in charge of producing up to 500 W EOL by means of space-proven triple junction GaAs/Ge cells with 28% efficiency at begin of life[17].

The Energy Storage Subsystem (ESS) consists of two space-proven Saft Li-ion micro sat battery pack[18]. This battery pack generates 2.5-4.8 V with a discharge current of 5.6 Ah a mass of 4.5 kg and a total of 465 Wh of stored energy with a specific energy of about 103 Wh/kg. With such a sizing, the on-board available energy results to be sufficient to operate the thruster and the spacecraft systems also during eclipse periods avoiding an excessive battery discharge that would relevantly shorten their life. Numerical simulations suggest that the maximum battery depth of discharge is 35%.

SAFT MicroSat Li-Ion Battery Pack		
Nominal energy [Wh]	465	
Nominal capacity [Ah]	16.8	
Width [mm]	220	
Length [mm]	170	
Height [mm]	95	
Mass [kg]	4.5	

Table III–2: Most relevant characteristic of SAFT MicroSat Li-Ion Battery Pack.

The chaser AOCS is based on 4 Sinclair Interplanetary 0.06 Nms Reaction Wheels[19] (225 g each) mounted in redundant tetrahedral configuration to obtain a 3-axis zero bias control. One SSTL Earth horizon sensor (500 g)[20] and three SSTL Sun sensors (35 g each)[21] complete the system. The chaser is also equipped with a total of twelve Alta Xenon-fed resistojets[22] (see Table III–3) for the desaturation of the reaction wheels. These thrusters allow to take advantage of most of the existing gas supply and feeding system of the main EP system and avoid the installation of an additional propellant tank. Accordingly, despite the relatively low specific impulse provided by these thrusters (~60 s), the overall system performance is increased whereas the spacecraft system complexity, costs and streamlining ground assembly, integration and validation activities are reduced.

Alta XR-100 resistojet		
Specific Impulse [s]	63	
Thrust [mN]	125.00	
Mass [kg]	0.15	
Power [W]	75	

Table III–3: Most relevant characteristics of the Alta XR-100 resistojet thruster.

The Spacecraft Communication System (SCS) and the on-board Command & Data Handling (C&DH) are based on standard commercial space proven components including one primary computer, one data recorder, two micro patch low frequency omnidirectional antennas and one medium gain helix antenna.

A. Payload: The Debris Capture System

The mission scenario described in Sec. II strongly relies on the exploitation of a debris capture system capable of aiming, capturing and towing the target uncooperative object. A number of different studies have been carried out in the last few years for the development of systems capable of performing the required tasks and, in general, three categories of capture systems have been identified as he most promising:

1) Rigid chaser–debris connection (robotic arms and grasping mechanisms)
2) Flexible chaser–debris connection (nets and harpoons)
3) Contactless capture systems (foam projection, or Ion–beam shepherd)

The first class of debris capture systems corresponds to rigid mechanical interface with a full 6 degrees of freedom control between platform and target debris. Robotic arms and grasping mechanisms have already been extensively tested and demonstrated in space for a number of applications and their implementation for an ADR mission would require a limited effort[23,24]. These solutions have the clear advantage of enabling a complete control (both in attitude and position) of the platform over the debris but they also require a complex de–tumbling procedure in case of uncooperative targets with unpredictable spin and attitude[25].

Nets, hooks and harpoons belong to the second kind of capture systems providing a flexible mechanical interface between the chaser platform and the debris. These solutions have the advantage of enabling a simple link solution suitable for a wide range of spacecraft materials and partly affected by the target attitude providing, nonetheless, a limited control of the Chaser–Target assembly. The Technology Readiness Level (TRL) of these solutions is in fact lower than the one of the previous class but significant progresses have been achieved (e.g. the work done by Astrium about net capture[26] and harpoon[27] systems[28]).

The last group corresponds to solutions where no mechanical interface with the debris is required, as in the case of the Ion Beam Shepherd[29] or of the electrostatic tractor[30], which produce uncontrolled debris re-entry. These systems have low TRL and do not represent the most suitable solution for LEO ADR but they are perfectly adapted to the re-orbiting of large GEO satellites[28].

A preliminary overview of suitable debris capture technologies has been performed with the aim of identifying small and lightweight devices requiring limited power. The three devices identified as the most promising candidates for the envisaged ADR mission are the Debris Collecting Net (D-CoNe) developed by the Department of Aerospace Science & Technologies of the Politecnico di Milano, the Kraken deployable Robotic Arm designed and manufactured by Tethers Unlimited, and the Astrium Harpoon Capture System.

1. Net-based capture system

The D-CoNe is a net-based debris capture system easily scalable on the basis of debris mass and significant length. The system is composed of a pyramidal/conical or plane net stowed in a canister with four masses (bullets) attached to the vertexes of the net. The bullets are positioned in a pneumatic or spring-driven ejection mechanism which can be easily tuned to finely control the launch of the bullets for symmetric net deployment[31]. After the deployment (and the debris capture) the net is connected to the chaser platform by means of a tether. Table III–4 shows the most relevant characteristics of the D-CoNe system considering two different values for the target debris mass.

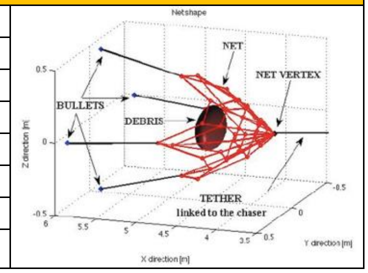
Debris Collecting Net (D-CoNe) System			
Debris mass [kg]	200	1000	
Debris Maximum length [m]	2.3	3.9	
Net mass [kg]	0.3	0.84	
Bullets mass [kg]	4 x 0.45	4 x 1.27	
Structure and mechanisms mass [kg]	12.83	13.09	
Tether (100 m), reel and C.U. [kg]	2.4	2.4	
Sensors and data handling [kg]	4.8	4.8	
Total System Mass [kg]	**22.13**	**26.21**	

Table III–4: Most relevant characteristics of the D-CoNe System and simulated debris capture (right).

2. Robotic Arm/ Tentacles

The Kraken Robotic Arm is a small and lightweight robotic manipulator designed by the American Tethers Unlimited with the aim of enabling mini– and micro–satellites to perform challenging missions such as on-orbit assembly, satellite servicing, and debris capture. The system is designed so that two arms can be stowed in a total volume of 3 liters and unfolded providing a high–dexterity 2 m diameter hemispherical workspace per arm[32]. Thanks to its modular nature, a longer version of the arm can be obtained by assembling more than a single arm.

Tethers Unlimited Kraken Robotic Arm		
Arm length [m]	2	
Degrees of Freedom	up to 11	
Stowed Volume [l]	3	
Repeatability	±10mm	
System Mass [kg]	**4.2 for 7 DoF arm**	

Table III–5: Most relevant characteristics of the Tethers Unlimited Kraken Robotic Arm and simulated debris capture (right).

3. Harpoon

The Astrium harpoon system is one of the various capture technologies investigated by Astrium in the last few years with the aim of identifying the most suitable device for catching space debris. The harpoon has been identified as an attractive candidate thanks to a number of advantages over other systems such as the compatibility with different target types (rocket bodies or satellites) the possibility to easily test it on ground and the relative insensibility to the spin rate of the target or to the presence of a specific grappling point[33]. The whole capture device is composed of the harpoon itself, a firing system, and a tether[34]. The harpoon (see Table III–6) consists of a barbed tip to prevent pull-out after impact, a crushable, controlling penetration depth, a shaft to interface with the firing system, and a stabilizer for ground testing. The harpoon firing system is based on compressed nitrogen and can be used for releasing several harpoons mounted on the same platform. The chaser is in charge of the accurate pointing and, after the firing, it remains attached to the harpoon and to the target debris by means of a Dyneema tether which is stored in a spool container. Such a tether is sized for a maximum force of 1.6 kN.

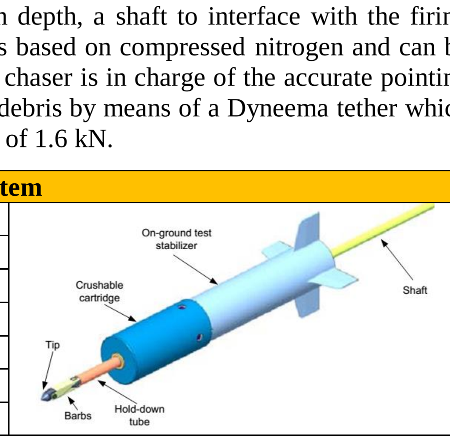
Astrium Harpoon Capture System		
Target mass	up to 9 tons	
System Dimensions	585 x 400 mm	
System Power	20 W	
ΔV to the Chaser	~0.01 m/s	
Accuracy	<5 cm at 10 m of distance	
Firing Distance	≥10 m	
System Mass	**8 kg (2 harpoons) +1.3 kg for each harpoon**	

Table III–6: Most relevant characteristics of the Astrium harpoon and CAD model of the harpoon (right).

Apart from the capture device itself, the payload of the chaser platform is completed by a 3D vision and image processing system such as the Kayser-Threde VIBANASS System[35] to accurately and autonomously determine the best capture pose. Considering that the number of targeted object per mission is not a priori defined, the overall mass of the chaser device, whether we consider the net, the robotic arm or the harpoon system, of the sensors, and of the data handling system is considered to be around 30 kg.

Moreover, in view of the low TRL of the whole system 20% margin has been applied to the overall payload mass whereas 5% contingency has been used for COTS subsystem and 10% margin added to those subsystem only requiring minor modifications.

Figure III–1 shows the mass budget of the 195.8 kg chaser platform. The final chaser mass breakdown has been obtained considering the mass of the above described subsystems, the one of the Thermal Control System (TCS) and 56.1 kg of propellant which can be stored in a 11 kg COTS tank. The resulting platform is equipped with four HT-100 thrusters which can provide to the platform a total ΔV larger than 4 km/s.

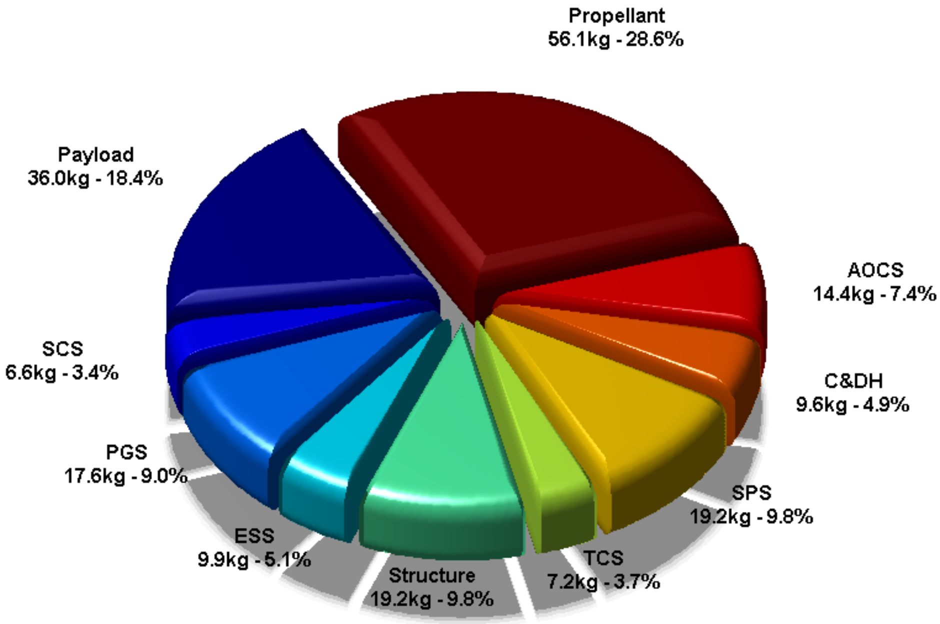


Figure III–1: Preliminary mass breakdown of the Chaser platform for ADR mission.

IV. Mission Analysis Approach

A preliminary mission analysis is here carried out to estimate the performance of an ADR mission performed with an EP-equipped chaser platform. Considering the large number of potential targets and their broad spatial distribution, in this analysis the number of debris deorbited per mission is not defined in advance. More in detail, a set of ADR mission is simulated and, considering the amount of propellant required to move from the orbit of a generic debris to the LEO release orbit and then to the orbit of the next target, the duration of the whole mission and the number of deorbited debris per mission is determined.

In order to implement the preliminary low thrust mission analysis, a set of preliminary assumptions has been adopted:

- At the beginning of each mission, the chaser platform is released by the launcher on the exact orbit of the first target, so no orbital maneuver has to be performed. This means that, for the first targeted debris, the only tasks to be performed are the final rendezvous and the debris capture.
- The orbits of debris are considered unchanged during all the ADR missions, i.e. no drag or Earth oblateness perturbation (J2 effect) is considered during the low thrust transfers neither for the debris nor for the platform.
- The platform orbit is always accounted as circular and, as also debris orbits are very circular (see Sec. V), accordingly the argument of perigee change maneuver has been neglected.
- The cost in terms of velocity increment of the chaser-debris rendezvous is neglected with respect to the cost of the orbit transfer maneuver. This assumption seems reasonable, since an elaborated orbital transfer thrusting strategy would allow avoiding this maneuver.

- The time needed to perform the debris capture is neglected with respect to the time needed for orbital transfer maneuvers.
- Each transfer maneuver is approximated by considering the combined semi-major axis and inclination change maneuver followed by a RAAN change. The total velocity increment (ΔV) required for the maneuver is obtained as the sum of the ΔV required to perform the combined semi-major axis and inclination change and the one for the RAAN change maneuver. This assumption provides a conservative estimation of the amount of propellant required since the three orbital elements change maneuver could be performed by means of a combined and more effective thrusting strategy and moreover, the orbital perturbations such as RAAN drift and atmospheric drag could even be favorable in some specific case.
- The mass of the spacecraft is considered constant during each orbital manoeuver and its value is estimated as the average between the mass at the beginning and at the end of the thruster operations.

Considering the above assumptions, it is possible to describe the mission profile as a sequence of predefined maneuvers, each one assessed by means of analytical approximations to actively target each debris. The selection of the debris sequence is performed by comparing the ΔV required for all debris in a given list. In particular, the ΔV required for the combined semi-major axis and inclination change is assessed by means of the analytic Edelbaum approximation[36]:

$$\Delta V = \sqrt{V_0^2 - 2V_1V_0\cos\left(\frac{\pi}{2}\Delta i\right) + V_1^2} \tag{1}$$

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. It considers a constant acceleration to compute the low thrust transfer velocity increment between two circular inclined orbits by linearizing the Lagrange Planetary Equations around a nominal circular orbit. The other maneuver that is modeled is the RAAN change. It can be analytically approximated by[37]:

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

where $\Delta\Omega$ is the desired change in RAAN. This maneuver is performed by using out-of-plane thrusting with burn arcs centered about the apices (i.e., the maximum and the minimum latitude points) under the assumption of almost circular orbits. Once assessed these figures, the propellant mass needed can be computed by means of the Tsiolkovsky equation. It is, moreover, possible to assess the time required for each manoeuver, under the assumption of constant acceleration, by means of:

$$\Delta t = \frac{\Delta V}{\bar{a}} = \frac{\Delta V}{T}\bar{m}_{SC} = \frac{\Delta V}{T}\left(m_0 - \frac{m_p}{2}\right) \tag{3}$$

where $\bar{m}_{SC}$ is the average spacecraft mass, m_0 the spacecraft mass at the beginning of thruster firing and $\bar{a}$ the resulting average acceleration on the spacecraft.

V. Results

The orbital and physical characteristics of the current space debris population cannot be easily described due to the different nature and origin of these man-made objects. Moreover, space debris lists rarely are open database and the exact number and nature of tracked objects is often covered by military intelligence. For these reasons, in this study a reference list of space debris has been assembled by considering currently tracked objects whose characteristics are published in an open database (downloaded at August 2013) made available by the Union of Concerned Scientists (UCS). These objects are mainly active spacecraft but, under the assumption of no mission extension, the object launch date and its expected lifetime allows obtaining a list of potential future debris. Two additional upper thresholds on object mass (3000 kg) and orbital altitude (1000 km) provide a list of 405 objects with an average altitude of 763 km and an average mass of 580 kg, representing a possible future scenario of debris objects in LEO. Heavier objects are not considered in the present study as we are assuming that dedicated missions would represent the most suitable option to dispose these objects.

Figure V–1 shows the altitude, eccentricity, inclination and mass of the objects used to simulate the ADR missions. The majority of these objects has nearly zero orbital eccentricity and moves in a Sun–Synchronous Orbit

(SSO) with orbital inclination between 90 and 100 deg. This crowded region, already identified as the one of the more interesting candidate for active space debris removal missions[38], is one of the most important regions for commercial and scientific purposes.

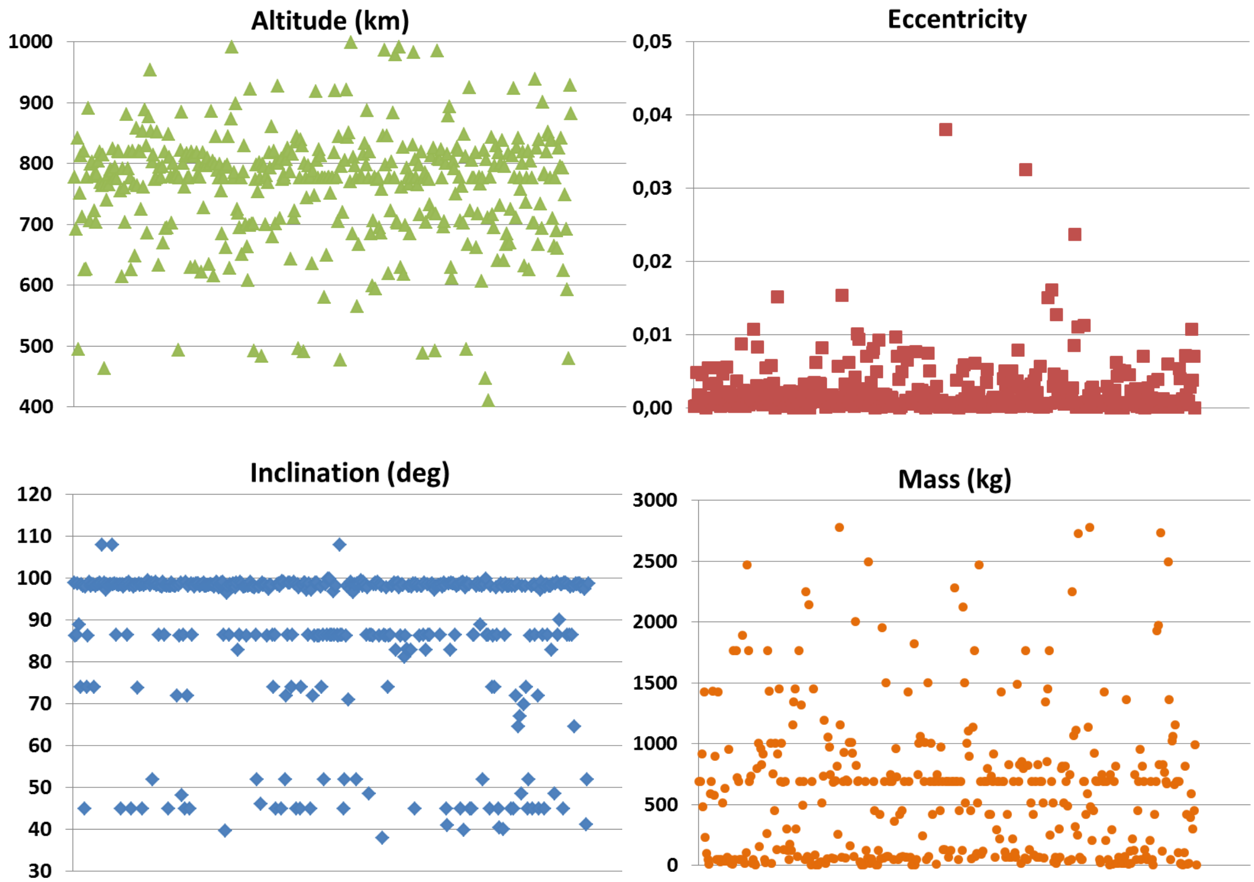


Figure V–1: Orbital altitude (top left), eccentricity (top right), inclination (bottom left) and object mass (bottom right) of the representative space debris list utilized in the study.

The described list of debris has been used to assess the performance of the ADR mission by means of the procedure described in Sec. IV. In particular, a total of 131 missions are necessary to target and deorbit all the objects of the list and Figure V–2 shows the decrease of the mass of orbiting debris thanks to the ADR missions and each vertical red line represents the end of an ADR mission.

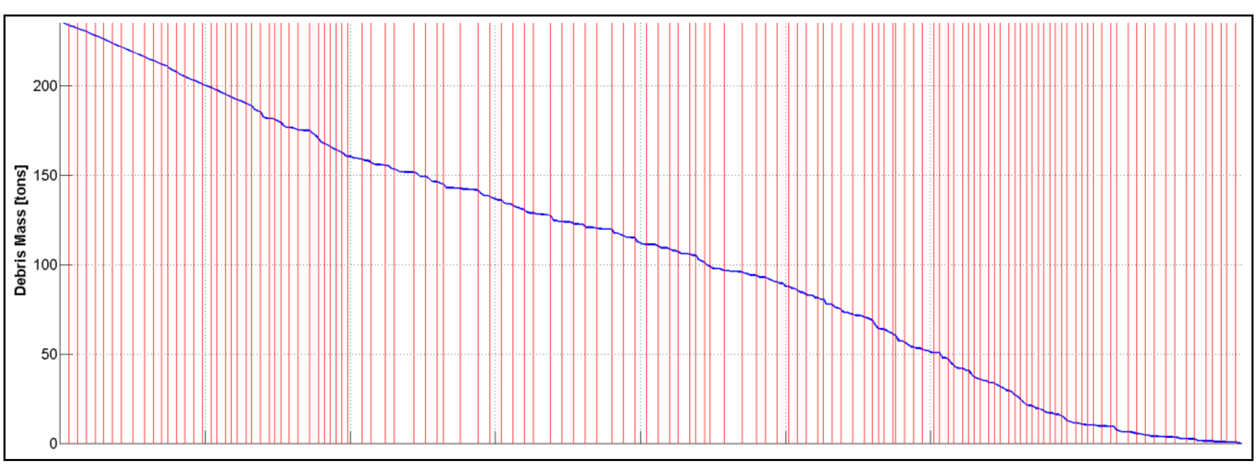


Figure V–2: Mass of orbiting debris. Each vertical red line represents the end of an ADR mission.

The average duration of each mission is slightly smaller than 1 year and each mission, on average, is capable of capturing and removing 3 different debris. Up to 5 debris can be deorbited per year with an average mass of debris deorbited per mission of about 1.8 tons. Moreover, 1.86 tons of debris can be deorbited on average each year and in some cases, one single mission is even capable of removing from the LEO region several tons of debris. Figure V–3 shows the total mass of the debris targeted and deorbited by each ADR mission.

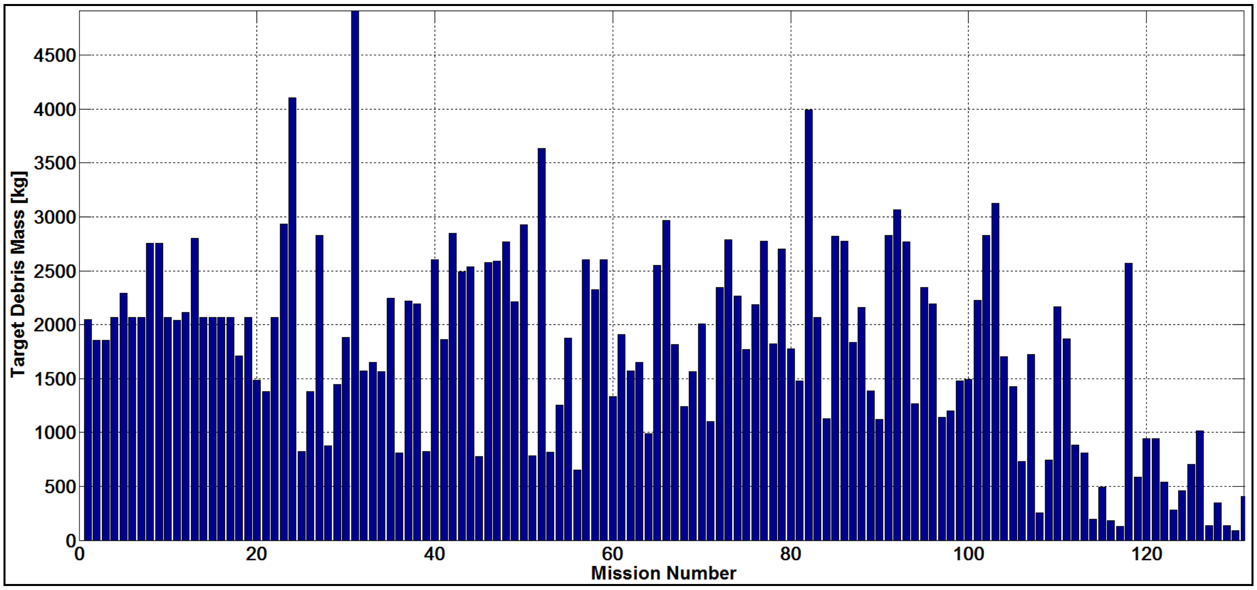


Figure V–3: Total mass of the debris targeted and deorbited by each ADR mission.

For the sake of completeness, a brief comparison between an ADR mission performed by means of a small chaser platform equipped with an EP system and a platform equipped with a COTS chemical propulsion system is also carried out. In particular, considering the preliminary mass breakdown presented in Sec. III (see Figure III–1), the sizing of a 200 kg platform with the same payload of the EP equipped chaser has been performed by assuming that the SCS, the C&DH, the AOCS and the thermal control systems do not depend on the specific propulsion scheme chosen.

For the chemical propulsion configuration a specific impulse of 230 s is assumed considering the performance of the ECAPS HPGP green propulsion system[39]. The comparison is then performed by considering a smaller amount of mass allocated for the PGS, ESS and the SPS. In particular, 10 kg are estimated to be sufficient for the PGS and ESS thanks to the lower power consumption of the chemical propulsion subsystem which has a dry mass, excluding tank and propellant, of 4.3 kg[40]. The resulting dry mass of the chaser is 117.2 kg and considering a propellant feed pressure of 2.2 MPa at 20˚C[41] and a tankage factor of 2500 m[42], a total of 73.7 kg of ADN propellant can be stored in a 9 kg 60 l tank. Accordingly, the maximum velocity increment that can be imparted to the spacecraft after the capture of a 580 kg debris which is the average mass of the objects in the list is about 224 m/s which is enough to deorbit the object from an altitude of about 700 km, but it is not sufficient to target more than one debris per mission.

VI. Conclusion

In this work the preliminary mission analysis and spacecraft design of a small platform equipped with an electric propulsion system for an active debris removal mission has been carried out. In particular, after defining a proper mission and operations scenario, the chaser satellite has been sized considering a total launch mass on the order of 200 kg to meet the requirements of most of the existing secondary payload launch systems.

The spacecraft has been sized considering to the larger extend COTS components for the most relevant subsystems so as to reduce the mission costs and the duration of the development and qualification phases. A set of suitable debris capture payload has been described and the Debris Collecting Net (D-CoNe) developed by the Politecnico di Milano, the Tethers Unlimited Kraken robotic arm, and the Astrium harpoon capture system have been identified as the most promising candidates for the envisaged ADR mission.

A reference list of 405 space debris representing a possible future scenario of debris objects in LEO has been assembled by considering an existing list of currently tracked objects with some filters on the maximum object mass (3000 kg) and orbital altitude (1000 km).

Considering the physical and orbital characteristics of the above mentioned list, it has been demonstrated that the significant propellant mass saving enabled by the use of a high specific impulse electric propulsion system such as the Alta HT-100 Hall Effect Thruster allows to target and deorbit up to 5 different debris per each mission. On average each mission is capable of targeting and removing 3 different debris corresponding to an average mass of debris deorbited of about 1.8 tons and in some cases, one single missions is even capable of removing from the LEO region more than 3 tons of debris. Moreover, it has been also demonstrated that a platform with the same initial mass and equipped with a chemical green propulsion system would be capable of deorbiting only one 1 ton debris per mission. Nonetheless, an ADR mission performed by means of a chaser equipped with a chemical propulsion system presents a number of advantages in terms of total duration of the mission, complexity of the deorbiting phase and overall probability of impact with other objects during the deorbiting phase. Moreover, the implementation of one dedicated mission for each orbiting debris would allow to realize a controlled deorbiting for each object but would also results in a significant increase in the cost of the whole operation.

The outcome of the preliminary mission analysis can be significantly improved both by means of an optimization approach for the design of minimum propellant mass maneuver from a debris to the next one and including the main perturbations typical of the LEO region. Moreover, a major refinement of the present work would be obtained performing a detailed mission analysis on a set of real orbiting targets with an exhaustive investigation of the close-approach and capture phases.

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