ESA TECHNOLOGIES FOR SPACE DEBRIS REMEDIATION

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ABSTRACT

Space debris is an existing and growing problem for space operations. Studies show that for a continued use of LEO, 5 – 10 large and strategically chosen debris need to be removed every year. The European Space Agency (ESA) is actively pursuing technologies and systems for space debris removal under its Clean Space initiative. This overview paper describes the activities that are currently ongoing at ESA and that have already been completed. Additionally it outlines the plan for the near future. The technologies under study fall in two main categories corresponding to whether a pushing or a pulling manoeuvre is required for the de-orbitation. ESA is studying the option of using a tethered capture system for controlled de-orbitation through pulling where the capture is performed using throw-nets or alternatively a harpoon. The Agency is also studying rigid capture systems with a particular emphasis on tentacles (potentially combined with a robotic arm). Here the de-orbitation is achieved through a push-manoeuvre. Additionally, a number of activities will be discussed that are ongoing to develop supporting technologies for these scenarios, or to develop systems for de-orbiting debris that can be allowed to re-enter in an uncontrolled manner. The short-term goal and main driver for the current technology developments is to achieve sufficient TRL on required technologies to support a potential de-orbitation mission to remove a large and strategically chosen piece of debris.

Key words: ESA; Space Debris; ADR; Debris Remediation.

1. INTRODUCTION

1.1. The need for active debris removal

In almost 50 years of space activities more than 4800 launches have placed some 5000 satellites into orbit, of which only a minor fraction of about 1000 are still operational today. Besides this large amount of intact space hardware, with a total mass of about 6000 tonnes, several additional objects are known to orbit the Earth. They are regularly tracked by the US Space Surveillance Network and, today, more than 16 000 of them are maintained in their public catalogue, which covers objects larger than approximately 5 cm to 10 cm in low Earth orbit (LEO) and 30 cm to 1m at geostationary altitudes (GEO). Only 6% of the catalogued orbit population are operational spacecraft, while 28% can be attributed to decommissioned satellites, spent upper stages, and mission related objects (launch adapters, lens covers, etc.). The remainder of about 66% is originating from more than 200 on-orbit fragmentations which have been recorded since 1961. These are assumed to mainly have generated a population of objects larger than 1 cm on the order of 700 000. The high impact velocities, which can reach 15 km/s for most missions in LEO, are the reason for the destructive energy, even despite of the small object sizes. So far, there are four recorded examples of collisions (with the latest and most prominent one between the active Iridium-33 satellite and the decommissioned Cosmos-2251 satellite).

Today there is a great concern and consensus that collisions could become the main future source for new debris objects, possibly leading the space debris environment into a chain reaction, rendering some orbital regions with an unacceptably risk for operations. Since the first awareness of the problem in the early 1960s, the global dimension of this problem has been understood today.

While the mitigation measures have been established in order to control the growth of the number of space object, a good level of compliancy by space farers has been assumed as a precondition. However, the recent history of spaceflight has seen many setbacks in this regard. Apart from this an underlying critical status of the current environment has often been suspected. A first analysis on the stability of the current environment independent of human measures was conducted by NASA in 2006 [15], by examining a scenario in which no further object is added to the environment (no launches, no debris release). The results, which are confirmed by ESA's simulations [5], show that the object numbers are growing even under these conditions and in view of a collision rate of one every 10 years. This is a clear indicator that the population of large and massive objects has reached a critical density in LEO. In turn, this means that the number of large and massive (mostly physically intact) objects needs to be controlled. Studies at NASA and ESA [5] showed that the environment can be stabilised when on the order of 10 objects are removed from LEO per year with a removal sequence oriented towards the target mass. Active removal can be more efficient in terms of the number of collisions prevented / object removed, when the following principles are applied for the selection of removal targets:

- The selected objects should have a high mass (they have the largest environmental impact in case of collisions)
- In addition, the objects should have high collision probabilities (e.g. they should be in densely populated regions)
- In addition, the objects should be in high altitudes (where the orbital lifetime of the resulting fragments is long)

1.2. The Clean Space initiative

ESA, with its Clean Space initiative, aims at devoting increasing attention to the environmental impact of its activities, including its own operations as well as operations performed by European industry in the frame of ESA programmes, through the implementation of specific technology roadmaps. The Clean Space initiative, organizes the implementation around four distinct branches:

1. **Eco-design**: the development of tools to monitor and evaluate the environmental impact and legislation compliance of programmes.
2. **Green technologies**: the development and qualification of new technologies and processes to mitigate the environmental impacts of space activities.
3. **Space debris mitigation**: the study and development of affordable technologies required for managing the end-of-life of space assets.
4. **Technologies for space debris remediation**: the study and development of the key technologies for active debris removal.

ESA has performed several system studies for orbital servicing, such as ROGER, Conexpress, or SMART-OLEV for servicing GEO satellites, as well as CDF studies on active debris removal of large objects. European National Agencies are also addressing active debris removal. An important example is the DLRs Deutsche Orbitale Servicing Mission (DEOS), a demonstrator for in-orbit servicing and active debris removal in LEO that entered in phase-B2 in 2012.

1.3. The challenges of active debris removal

To capture and de-orbit a large piece of defunct space hardware is no small challenge, both technically, legally and financially. Considering that such a large number of targets need to be removed every year, the question raised is how to make it affordable, and who would pay. This again raises the question of whether multiple targets could be removed in a single mission. The ESA investigation of a de-orbitation kit (Section 5.1) aims at facilitating this. Technically, however, a multi-target mission is even more challenging than a single-target one, and even a single target one must be very flexible and adaptable to different targets since ten such missions would need to be launched every year. So it is important that the capturing technologies do not have to rely on specific characteristics or interfaces on the targets. All the technologies presented in this paper are able to deal with a large range of targets as well as target attitudes and spin rates.

But even before capturing the target, it needs to be tracked from the ground, and a rendezvous and target characterisation phase needs to be carried out. Depending on the technology, it may also be required to perform a docking operation. Docking with an uncooperative target has per today never been achieved without involving human astronauts (such as in the case of the rescue of Intelsat VI).

The fact that a target shall be approached, flown around and somehow connected to, requires a complex variation of rotational and translational capabilities of the spacecraft, for which both a much more complex propulsion system and GNC capabilities and sensors are needed compared to what is usually installed in LEO orbiting spacecraft. On the propulsion side, this refers to the number of thrusters, their pointing direction and especially the fluid management of the propellant. So while solid boosters may be the most appropriate for the deorbitation burn itself, due to the required short response time of the above described manoeuvres, chemical-liquid propulsion systems are the best, perhaps the only, option to meet torque and translational force needs of the spacecraft. On the GNC side, both complex algorithms and new sensors are currently investigated through a series of activities at ESA (See Section 5.2) in order successfully achieve rendezvous, target characterisation and, if required, docking.

2. PULLING TECHNOLOGIES

One of the most promising techniques for actively controlling a debris during re-entry or re-orbiting is to attach a tether to it and pull it.

While the dynamics of the tether adds some complexity in both chaser design and controllability, it opens the door for capturing technologies that are nearly agnostic to the target debris shape, attitude and spin-rates, thereby re-

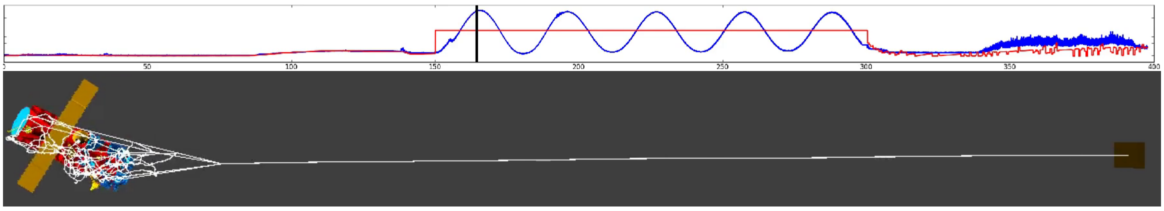

Figure 1. Multibody simulation of tethered pulling of an arbitrary satellite, captured with a throw-net. In the plot can be seen the controlled thrust (red) and the tension in the tether (blue).

moving the high complexity involved in docking with an uncooperative target.

The technologies that ESA has identified as being the best for this capture, and which are currently under investigation through the Technology Research Programme (TRP) and the General Support Technology Programme (GSTP) are throw-nets and harpoons.

In the course of a recent CDF study [2], multibody simulations with several thousand degrees of freedom were performed parametrically for the whole de-orbitation cycle. This included the capture operation with a net and the subsequent pulling phase. It also simulated the scenario where multiple burns are performed and the system must therefore recover to a stable situation after the burn.

The outcome of the study showed that de-orbitation by pulling an object by a tether is plausible, both in the single- and multi-burn scenario, given that the tether is very elastic. The elasticity helps in multiple ways, firstly it simplifies the controller design, but also it makes it possible to retain control authority at the end of the burn by appropriately timing the shut-down of the apogee kick motors.

Figure 1 shows a screen-shot from a simulation as well as the thrust and tension curves associated with it. First, the tether is tensioned with pulsable but low-thrust engines to a controlled tension. Then the apogee kick motors are fired. These have a fixed thrust, and induce a lateral oscillation in the tension of the tether and the distance between the spacecraft. There is no risk of collision or entanglement due to the pre-tensioning phase. So long as these oscillations are *not* damped out, it is then possible to shut down the motors at the point of minimal tension and retain control authority with the pulsable low-thrust engines. If the oscillations are damped out, or the kick motors are turned off at the wrong time, the residual tension in the tether will pull the spacecraft together into a regime where the tether goes slack and in the worst case where the spacecraft collide.

2.1. Capture of debris using throw-nets

In July 2012, ESA carried out the e.Deorbit [2] study in its Concurrent Design Facility. One of the two short-listed options for capturing space debris was the throw-net.

The idea is simple, a net ejector mechanism ejects a net from a canister. The net is pulled open by the inertia of a number of corner masses that have a high mass relative to that of the net as well as a radial velocity. Figure 3 shows the net being ejected from its canister.

The concept was studied as thoroughly as it could be within the framework of the CDF. This included performing multi-body simulations both of the capture phase and the de-orbitation phase. The simulations were performed in order to address key concerns related to using a net and tether for space debris capture and deobritation. In particular whether the net would properly entangle the target, whether it would slip off, what level of force is transmitted to the target, and how the compound system affects the dynamics of the subsequent pulling phase.

In the study, the net itself was baselined to be a 16 by 16 meter net with a mesh size around 20 centimetres. The net would be constructed from a high strength-to-weight ratio material such as Dyneema®. In each corner of the net would be a mass. The purpose of these masses is to pull the net open during deployment. It would be deployed using a mechanism derived from the concept shown in the *ROGER* study from Astrium [1]. In this concept, there are four ejector tubes on an angle with the container holding the net itself in the middle. One modification from that concept is that the net itself, and not just the masses, would be ejected towards the target to avoid a back-and-forth oscillation, and to ensure that it can reach its maximum size. Figure 2 shows the modified net ejector concept.

The net would reach its full size just prior to impacting the target debris, and would wrap around it passively - the motion driven by the inertia of the corner masses (Figure 4). However, while the simulations show that a fully passive net closure are likely to be sufficient, it is also possible to implement a simple closing mechanism consisting in winches in two of the corner masses and a thread between them. This concept is similar to the mechanism described by Benvenuto[6].

Once the target debris is fully wrapped up in the net, the tether would be tensioned by the chaser and the de-orbitation burn would commence.

The simulations performed were quite detailed and identified no show-stoppers for the concept. On the contrary, it was identified as a very promising capture mechanism

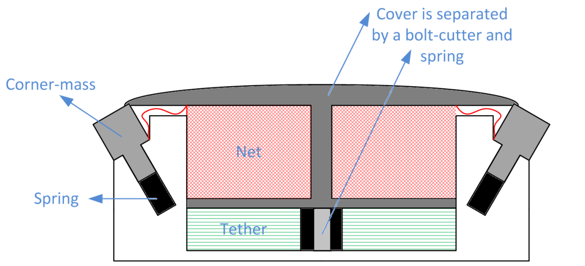

Figure 2. Section through canister holding the net and tether and the ejector mechanism. Note that the center of the net and the tether are both attached to the cover.

Figure 3. From left to right shows the ejection of the net from its canister.

that could work without adaptation to a large range of target sizes, shapes, attitudes and spin rates.

ESA released on 4 April 2013 an Invitation To Tender (ITT) for a TRP activity to further simulate, and validate in a parabolic flight, the net capture operation.

2.2. Capture of debris using Harpoons

While not included directly as one of the options studied during the e.Deorbit CDF study, the Harpoon concept was identified as having many of the same advantages in dealing with uncooperative targets as the net. The actual de-orbitation phase is identical.

The concept has already achieved some maturity through work carried out at Astrium Stevenage. They built a prototype harpoon (Fig 5) and tested it repeatedly against representative satellite material to test both its penetrating ability, resistive strength when getting pulled and the potential generation of additional fragments during the penetration [19].

None of these issues have so far been identified as show-stoppers. For this reason a GSTP proposal has been accepted and a tender is expected to be released in the course of 2013 to take the concept up to TRL 4 or 5.

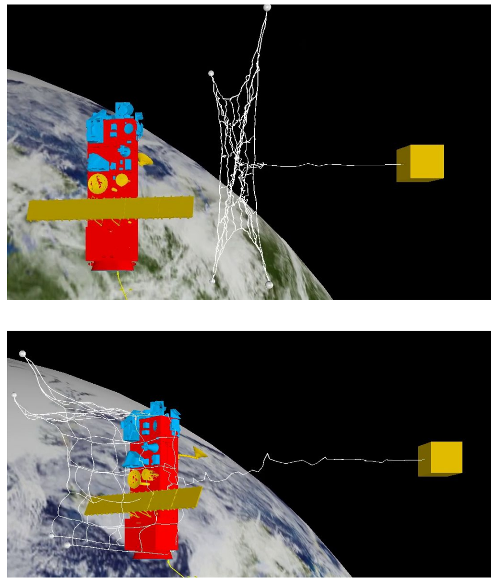

Figure 4. Multibody simulation of net being ejected and grasping an arbitrary satellite.

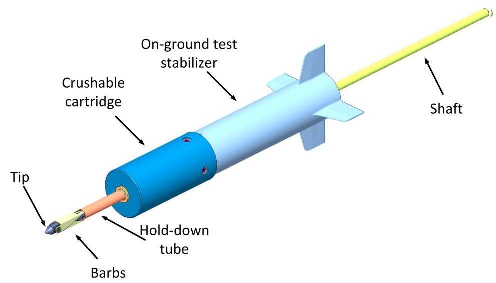

Figure 5. Harpoon concept for capturing space debris as developed by Astrium Stevenage [19].

3. PUSHING TECHNOLOGIES

An alternative to the pulling strategy could be to push the target to into the ocean. This strategy faces difficulties in the rendezvous phase and during the capturing process, while the de-orbiting phase is expected to be easy. The chaser should during the final rendezvous phase, be controlled in the target body reference-frame, something that becomes difficult in case of a large tumbling motion or in the presence of numerous appendages on the target. Secondly, it requires accurate sensors that are able to measure the relative positioning and velocities between the chaser and the target.

This approach derives its concepts from the various docking mechanism that have been studied over the 30 past years [12, 13]. The clamping mechanism on board on the chaser is dependent on the shape of the target.

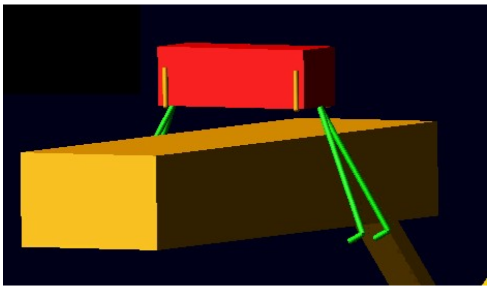

Figure 6. Clamping concept analysed with MSC-ADAMS. The chaser is in red and the target in orange. After clamping, the pushing rods are lowered to rigidify the connection.

The most promising approach consists in a "capture before touching strategy" and means that the clamping mechanism should ideally embrace the target before touching it (Figure 6). The "capture before touching strategy" is able to cope with:

- the capability of the attitude & control sub-system to handle a "Collision Avoidance Manoeuvrer",
- switch-off the closed loop of the Attitude & control sub-system during the capture process.

Other objectives of the clamping mechanism are, after the capture process ;

- to obtain a stiff composite (mated chaser and target) to ease the de-orbiting process,
- to ensure the de-orbiting thrust will be performed through the centre of mass of the composite.

Some initial concepts have been evaluated internally within ESA and were based on existing qualified actuators and sensors. A large effort in multi-body simulations is necessary to evaluate the size, speed of the mechanism as a function of the the relative positioning and velocities between the chaser and the target. Several promising configurations have been identified by using MSC-ADAMS software (Figure 6). It was emphasised that the capture operation should be as fast as possible (meaning that a control via the ground station is not realistic).

A great part of the validation can be done on ground, by using a robotic arm to simulate the relative motion between the chaser and the target. Depending on the sensor performances available for the end rendezvous, it is expected that fine iterations between multi-body simulations and ground test will be necessary.

The Agency has released an ITT for a TRP activity to further study and simulate the capture of space debris using clamping mechanisms.

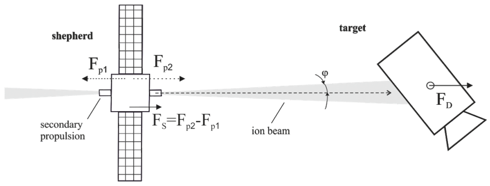

Figure 7. Schematic of ion beam shepherd satellite

4. CONTACT-LESS TECHNOLOGIES

Docking to well-known and cooperative orbiting objects is a technological challenge mastered only by few space-faring nations. Capturing or otherwise attaching to a non-cooperative orbiting object in space, which characteristics are not fully know in advance is an even bigger challenge, especially if the uncertainty involves both the physical state and the attitude of the un-cooperating object. This is however a likely scenario for many foreseeable active space debris removal missions. This section describes a few concepts which avoid this complication. These are usually classified under the summary term of "contact-less" methods, even though the term is not entirely accurate.

Contact-less methods furthermore have some intrinsic limitations due to the type of momentum transfer. In case of a requirement for a fully controlled de-orbit due to the likely intact survival of massive parts of the spacecraft during atmospheric burn up and the potential consequences for caused damages on Earth, such concepts are less suitable, due to the difficult to achieve high atmospheric re-entry angles.

4.1. Ion-beam shepherd

Expelling charged particles via the Lorentz or Coulomb forces at high velocities is one of the most propellant-mass efficient ways to accelerate spacecraft. An extension of this concept has been proposed for the transfer of momentum to non-cooperative space debris objects [9, 11, 14, 20, 24] and studied in 2010 in the frame of an ESA Advanced Concepts Team (ACT) *Ariadna* study together with the Universidad Politécnica de Madrid under the name of "ion beam shepherd" [3, 7–10]. The concept relies on directing the plasma accelerated by an ion thruster (or similar plasma propulsion device) towards the surface of a target object to exert a force (and depending on its impact area a torque) upon the target from a distance (Figures 7 and 8). The force transmitted comes from the variation of momentum of the plasma ions (typically Xenon) impacting against the surface of the object and penetrating its outermost layers before being stopped.

During a typical mission profile the IBS would rendezvous with the target debris and, while co-orbiting at constant distance have one of its ion beams constantly pointed at its surface to produce a small continuous drag

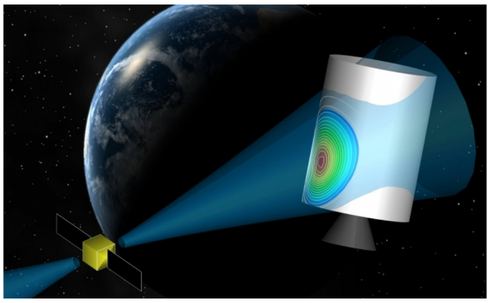

Figure 8. Artist impression of an ion beam shepherd satellite, transferring momentum onto an upper stage.

force while the other ion beam would point at the opposite direction to keep the relative distance constant. This way the IBS can be used to remotely manoeuvre space debris without physical contact (docking), and can be repeated for multiple targets. In [7] Bombardelli et al., published different numerical assessments of the dynamics and control of a space debris co-orbiting with an ion beam shepherd satellites. They conclude that a three-axis proportional-derivative controller on the shepherd satellite can provide stable relative motion for both spherical and cylindrical debris. The more complex behaviour analyses an ion-beam perturbed cylindrical debris, an aluminium cylindrical shell of 1500 kg mass, 6.5 m height and 2.4 m radius co-orbiting at 15 m nominal distance from a 300 kg IBS satellite.

The preliminary investigations have concluded that there were no fundamental show-stoppers for the concept to work and confirmed some of the preliminary advantages of the IBS:

- an IBS of a few hundred kg is able, if properly controlled, to de-orbit the largest Earth orbiting debris (=10 ton) from 1000 to 300 km altitude in less than a year,
- a 10-15 m along track distance allows jet momentum transmission to a large-size debris with minimal efficiency losses due to divergence,
- stable, non-trivial, attitude configurations of beam-propelled cylindrical body exist,
- the beam force has a stabilising effect in the along track direction and a destabilising affect in the (already unstable) radial direction.

4.2. COBRa

In 2012 ESA launched a new initiative under its General Studies Programme (GSP), called SysNova, in order to get the most brilliant proposals for the development of new technologies in the space field. It is a technology assessment scheme that uses "technology challenges" and competitions to survey a comparatively large number of alternative solutions. Within the 2012 SysNova Announcement of Opportunity, one of the proposed challenges was to deflect space debris using contact-less technology. GMV, TAS-I and Politecnico di Milano put forward the COBRa mission concept. This relies on the use of a conventional chemical propulsion system to modify the orbital velocity of a 100 kg man-made metallic object in SSO.

The concept is very similar to the ion-beam shepherd (Section 4.1), except that it uses chemical propulsion rather than electrical propulsion. The innovation of the concept consist of a self-contained technology payload plugged in a standard platform to build the chaser. A piece of space debris is impinged by the exhausted gas of the chemical thruster from a distance of 4-6 meters. Another chemical thruster practices a force in the opposite direction of the impinging plume in order to counteract the effect of the first thruster (similarly to what is shown in Figure 7).

The COBRa concept is currently object of study in the Concurrent Design Facility in ESTEC with the aim of designing a technology demonstration mission.

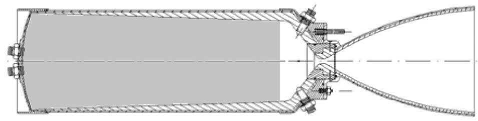

Figure 9. Cigarette burning SRM to be used in clusters for de-orbitation kits. [21]

5. OTHER DEVELOPMENTS

5.1. Solid propulsion de-orbitation kit

Solid propellant de-/re-orbiting is a promising solution to clean up old satellites [22]. Figure 9 shows a conceptual design of a solid rocket motor with a cigarette burning propellant grain [21] to be used in a variety of clusters to de-/re- orbit different types of spacecraft. A cigarette burner is the only suitable propellant grain type when applying gentle low acceleration forces (several minutes of burn time) to a spacecraft.

While the motors could and should be included in future spacecraft design to deal with their end-of-life, similar motors could also be used in cluster packages that could be combined with the capturing technologies already presented in this paper to achieve multi de-orbit missions. They could be clamped to the defunct satellites in order to push the spacecraft down or could serve the role of the de-orbiting chaser in the net/harpoon/tether scenarios. In a multi de-orbit mission, the host spacecraft would provide all the complex manoeuvres and release the solid rocket motor cluster just prior to firing in a sort of "fire and forget approach". This solid rocket motor cluster is then providing the main de-orbit ΔV in order to enter the Earth's atmosphere half an orbit later over a remote area of the planet. Small thrust vector control systems, a spin-in from the military domain, possibly combined with spin stabilisation, would keep the cluster on its track.

ESA is currently running several activities related to the determination of suitable size cluster motors for de-orbiting and re-orbiting spacecraft. The SPADES study, running in ESAs Concurrent Design Facility, will investigate the impact of solid propellant de-/re-orbiting on the host satellite as well as the impact of the host spacecraft on the required motor design (e.g. maximum thrust level). The activity shall contribute to an optimum motor design that can be used in clusters on a variety of spacecraft for de-/re-orbiting, but also on multi de-orbit missions to bring down large varieties of space debris. New aluminium free solid propellants, that do not generate and deposit in space hard metallic oxide particles or slag, are being investigated and tested in a full scale demonstrator solid propellant rocket motor. Simultaneously, TVC systems and system autonomy are also being investigated for this application.

5.2. Guidance, navigation and control

GNC activities contributing toward the objective of Active Debris Removal are being developed in the areas of sensors, image processing, and advanced guidance and control techniques.

The goal of sensor development is to upgrade and adapt sensors to rendezvous missions with uncooperative targets. These sensors can be passive (2D cameras, visible, or infra-red) or active (scanning or flash LIDARs). Typically camera navigation would be used at medium distances (from 10 km down to few meters) to spot and track the targeted object, while active sensors would work at close distance for shape identification, tumbling rate measurement and relative position navigation. Time-of-flight 3D cameras will be also considered since they can work at a faster rate than a scanning LIDARs [18]. Several GNC technology activities have been proposed under the ESA's GSTP-6 programme. One of these activities is the *Infrared Camera Breadboard for Rendezvous with non-cooperative Target*, that uses on-board image processing techniques such as shape or pattern recognition for object identification and relative navigation. Another GSTP study will be held on *Image Recognition and Processing for Navigation* which would incorporate data from either 2D or 3D camera to estimate position, attitude and angular rate of uncooperative targets. The advanced guidance and control techniques domain will include phases from phasing and rendezvous, fly-around, capture/mating, and subsequent de-orbitation of the compound chaser-target. A TRP activity named as *Advanced GNC for ADR* is underway to be initiated. It will focus on the dynamics modelling and controller design, with particular emphasis placed on the control of the coupled system during de-orbitation (two spacecraft connected by a tether), and the demonstration of global stability during its controlled re-entry.

5.3. Expanding foams

A completely different Active Debris Removal concept, also studied in the form of an *Ariadna* study of ESA's Advanced Concepts Team in 2010, relies on the transfer of a sticky expanding foam to a debris. The underlying principle of the method is to increase the area-to-mass ratio of debris in sufficiently low earth orbiting debris in order to increase their natural atmospheric drag and thus substantially decrease their natural orbital lifetime leading to their natural re-entry.[4, 16, 17] The system requires the foam carrying spacecraft to perform a rendezvous with the debris and remain in relatively close proximity formation flight with it, but without requiring physical docking since the expanding foam is intended to be sprayed from a distance to the debris, onto which it is assumed to stick while expanding. As an alternative application, it was also suggested that the same method can also be conceived as a preventive system to be directly embedded in future spacecraft. The key technological aspect is the specific type of foam; it has to significantly expand its original volume, stick and remain attached to the debris, not create additional, non-attached objects and be as light as possible. In [4] Andrenucci *et al.* conclude that this approach is able to de-orbit any kind of debris below a certain orbital altitude, studying its ability to de-orbit, as a worst case scenario, the a 1 ton debris within 25 years from 900 km. An active space debris removal mission with a 5 ton, 5 kW electric propulsion, Soyuz-launched spacecraft would be capable to de-orbit about 3 tons per year. Detailed information has been published by Andrenucci *et al.* [4, 16, 17]

5.4. HybridSail

In the frame of a 2010 *Ariadna* study of ESA's Advanced Concepts Team, Visagie *et al.* from Surrey University studied a concept for a scalable de-orbiting spacecraft that makes use of a deployable drag sail membrane and deployable electrostatic tethers to accelerate orbital decay. The study included the identification of design and external parameters that influence the de-orbit times, proposed docking and attitude control methods. While the combination of electrostatic tethers with a drag sail increases the altitude range for such a concept, it adds complexity and according to the preliminary analysis by Visagie *et al.* actually increases the total collision probability (large surface area for quicker de-orbit times). [23]

6. CONCLUSION

ESA, mainly under its Clean Space initiative, is currently undertaking a number of technology developments and studies within its GSTP and TRP programmes. Along with activities running under the GSP programme, they aim to increase the TRL of key technologies so as to enable a potential mission to de-orbit a large and strategically chosen debris in the near future.

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