Space Debris Pulverization Systems for Low Earth Orbits

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Abstract— **European policy on space debris mitigation is fast evolving to contain the increasing demand for launch of small satellites in Low Earth Orbit (LEO), whose specifications fail to meet ESA latest and more stringent requirements. Referring to the decrease of the maximum permanence in operational orbit from 25 years to 5 years after End of Life (EOL) [1], this research aims at thoroughly reassessing the design concepts currently in development to remove space debris in orbit and introducing a new accelerating paradigm. First, a critical review of the state-of-art of Active Debris Mitigation (ADM) solutions is presented, including magnetic docking capture, plasma-beams and lasers de-orbiting, robotic soft nets, arms and manipulators capture. Secondly, the state-of-art of passive debris mitigation solutions is evaluated, considering deployable or inflatable drag sails, electrodynamic tethers, EOL passivation and Design-for-Demise. Eventually, analysing and synthesizing benefits and limitations of state-of-art solutions, a new in-orbit system is introduced, reducing space debris size from over 10 cm to under 1 mm using a directed energy weapon, like Megawatt Class (MW) space-based lasers, or a docking mechanism with detonator transfer. The new system's competitive advantage consists of its capacity to pulverize multiple pieces of space debris within its operational lifetime via controlled in-orbit explosions, reducing dependency from launch. Its dual applicability would well serve any incumbency of military purposes. Being able to generate a "zero debris corridor" in LEO, where other space vehicles could safely carry human beings, the new system would also support space tourism, lunar and planetary exploration missions. A conclusive comparison with state-of-art concepts is expected to justify further studies on its feasibility.**

Keywords — **Active Debris Removal, satellite fragmentation, space-based lasers, in-orbit explosions.**

I. INTRODUCTION

Space debris is defined by the Inter-Agency Space Debris Coordination Committee Mitigation Guidelines as "all human made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional" [2]. Nowadays hundreds of millions fragments under 1 cm tumble uncontrolled around the Earth with highest concentration in Low Earth Orbits (LEO) [3]. They represent a threat for all functional space assets, mainly due to the damage they generate by collision. A piece of debris with a diameter as small as 0.2 mm could degrade a Space Transportation System (STS) window [4]. For this reason, the research community has been active to study engineering solutions to prevent the formation of new debris and mitigate the risks of its existing presence, while the policymaking community has been developing guidelines in the form of standards and requirements to support effective technical performance. For example, the European Space Agency (ESA) has recently decreased the original "25 years rule" to only 5 years of non-operational life in orbit for newly designed space objects, severely tightening the constraints of satellite End-Of-Life (EOL) design and significantly increasing the number and variety of targets for debris mitigation concepts. Space debris mitigation systems are firstly categorized as active or passive, depending on whether they interact with the target or they are built in the target. Active Debris Removal (ADR) can be further broken down in systems physically capturing and removing the target from its orbit and contactless systems intentionally lowering the target's orbit altitude. Both types of solutions are aimed at accelerating the target's burning return in Earth atmosphere. In some cases, ADR also allows space debris to safely return to the Earth surface. Just-in-time Collision Avoidance (JCA) is a subset of space debris mitigation solutions, including satellites designed to identify approaching debris and to maneuver away from it, as soon as it reaches a certain distance threshold. On-Orbit Servicing (OOS) is considered a form of space debris mitigation, because it allows to lengthen the satellite operational life through refueling, parts substitution or repair. In this paper all the above-mentioned categories will be reviewed and compared with solutions designed under a new paradigm, interpreting the wording of IADC Space Debris Mitigation Guidelines, paragraph 5.2.3, Avoidance of intentional destruction and other harmful activities:

> "*intentional break ups should be conducted at sufficiently low altitudes so that orbital fragments are short live*"

as an opportunity rather than a constraint. The new method is aimed at accelerating the return of space debris, pulverizing it under 1 mm in LEO, where operational spacecraft shielding resists impacts with particles of such size [5] and newly generated micro-fragments would faster de-orbit and be destroyed by the Earth atmosphere [6]. The following section of this paper is dedicated to a state-of-art review of space debris mitigation solutions: ADR contactless methods, such as plasma beams, lasers, gravity tractor, tungsten dust clouds and gaseous clouds; ADR contact-based methods, such as magnetic docking, electro-mechanical docking, orbital debris sweeper, the Slingshot Method, tentacles, robotic soft nets, robotic arms, soft continuum manipulators, adhesives, foams, fibers and electrodynamic tethers; passive debris mitigation concepts, such as deployable or inflatable drag sails, EOL passivation, Design-for-Demise and self-eating satellites; Just-in-Time Collision Avoidance and On-Orbit Servicing. The third section of the paper will introduce the new paradigm of target pulverization under 1 mm proposing two ADR systems: MW-class space-based laser and detonator or packaged charge transfer. The final section will thoroughly and critically compare all the previously described solutions according to key parameters identified by the state-of-art review and will highlight opportunities for further studies on the new paradigm.

II. STATE-OF-ART REVIEW

A. *Active Debris Removal (ADR)*

Active Debris Removal (ADR) consists of solutions aimed at approaching space debris in orbit and either capturing to bring it to an orbit with lower altitude or using directed energy or an appendix to lower its orbit altitude. ADR techniques can be divided between contactless and contact-based methods: contactless solutions use directed energy or material's ejections to interact with the target at distance, while contact-based solutions imply the rendezvous with the target and its capture. Their performance is constrained by the necessity to design the system based on the debris characteristics, such as geometry, mass distribution and rotational speed, which must be assumed or estimated in proximity; their demonstration status is still developing: at present, only Astroscale ELSA-d mission, using magnetic docking with a cooperative client, was validated end-to-end in orbit [7]. The following paragraphs are aimed at describing the most significant ADR solutions currently under development.

❖ ADR Contactless Systems

ADR contactless systems allow non-invasive maneuvering, because they operate at a safe distance from the target. For this reason, the risk of collision and entanglement with the target is reduced with respect to contact-based systems; they also offer a certain degree of scalability, because they are independent from the target interface [7]. However, operating with long ranges requires high energy and the systems' efficiency is inversely correlated with distance [4]. Moreover, technological challenges, such as stability and precision requirements, and regulatory challenges, due for example to their unknown impact on the space environment, prevent their large-scale deployment [7].

➢ Ion Beam Shepherd (IBS)

A satellite equipped with electric thruster ejects a continuous plasma beam towards a target of space debris, transferring momentum to it. Such momentum is aimed at de-orbiting the target, lowering its orbit altitude to accelerate its re-entry. The target can't absorb all the plasma ejected, due to its expansion. Therefore, only a fraction of the force generated by the satellite can transfer momentum to the target. Moreover, the force generates a counterforce, pushing the satellite away from the target. For this reason, the satellite is equipped with a secondary thruster, called *thrust compensation thruster* [4], to keep a stable distance of typically tenths of meters during operations. The resulting net force's direction is tangential to the target's orbital velocity, because the satellite and the target follow a similar quasi-circular orbit. The system is insensitive to the debris' angular motion, enabling the de-orbiting of also rapidly rotating objects; it is theoretically effective with multiple large debris objects sequentially. An electric thruster with xenon propellant can generate a specific impulse of 3000 s [7]; using argon, which is relatively cheap and abundant, the solution has the potential to become cost-effective and scalable [8]. However, the force generated by the primary thruster (called *momentum transfer thruster* [4]) is relatively low, implying long de-orbiting times and high-power requirements. In addition to the complexity of accurate target tracking and control during operations, coordinating the two thrusters is still a technological challenge and the concept has not yet flown.

➢ Lasers

A satellite equipped with laser propulsion directs it toward the target, ablating it. With *direct ablation,* the satellite can completely burn down a small piece of debris. With repeated laser-pulses (*ablation back-jet*), the satellite can de-orbit the target, heating it [4]: under irradiation the target temperature reaches its vaporization point, producing plasma; plasma expansion generates a reaction force, which changes the debris velocity direction and so its orbit altitude, decreasing it. A key project demonstrating ablation back-jet is the Laser Ablative Debris Removal by Orbital Impulse Transfer (L'ADROIT) [4].

The laser-based method offers multiple advantages with respect to the other tested solutions: it is effective for large debris objects, as well as for those smaller than 10 cm; it has the lowest cost per object removed; it is redundant and agile; it can handle tumbling objects; when the satellite and the target are in a similar orbit, it can optically identify fragments of debris as small as 2 cm without prior knowledge [9]; it has additional uses, like preventing collisions, increasing the accuracy of debris ephemerides and controlling large debris impact location. However, it has a high launch cost; it can't be easily repaired in orbit; it requires significant onboard power: for example, ablating 10 cm cube of aluminum necessitates 87,160 kJ and a continuous laser beam of at least 5.38 MW, powered by around 108 MW [7].

The concept can also be implemented from Earth. Multiple ground-based continuous-wave (CW) lasers irradiate space debris when it passes within their field of view. However, the targets must be large and bright enough to be tracked, and their position must be accurately determined for effective re-engagement during their windows of visibility to the laser beams.

➢ Gravity Tractor

A spacecraft hovers near the target with its thrusters angled outwards, leveraging its own mass to impart a gravitational force on the target, thus altering its orbit. The method was conceived to deflect asteroids [10]. It is only minimally influenced by the target characteristics, such as structure, surface and rotation state [4]; it can be adjusted in-orbit [11]; it guarantees high precision [11]; it is simple and feasible [12].

➢ Tungsten Dust Cloud

A satellite, positioned in a similar orbit with respect to its target, injects tungsten dust grains in the opposite direction of the target velocity. The orbit perturbations generated by the Earth irregular gravitational field make the tungsten dust cloud precess and form a shell. When the target encounters the shell during its own precession, it faces increased drag and decreases its orbit altitude. The dust decay rate can be designed based on dust grain size and mass density, and synchronized with the debris decay rate. It is calculated that 30-70 μm diameter tungsten dust grains, released within a narrow dust layer of 30-50 km of width, produce non-negligible drag to eliminate small debris of 10 cm or less from LEO [13]. The method is also effective with untrackable debris, but it is limited by the volume occupied by it. Therefore, it is more effective right after events of fragmentation, when the target pieces are still located in a small volume.

➢ Gaseous Clouds

A satellite generates a transient gaseous cloud with a density sufficient to slow down the debris, accelerating its re-entry. The cloud generation apparatus is a system made of an expellant, a gas generator and a nozzle [14]. The concept is effective with debris having a relatively low ballistic coefficient. Moreover, it can be used to clear multiple areas rather than individual fragments. However, it is not designed for a specific type of debris and its removal speed is directly correlated with the gas density and inversely correlated with the target area width.

❖ ADR Contact-Based Systems

ADR contact-based systems offer the best control during operations. However, they are ineffective for large populations of fragments; they carry a proximity risk, and they require expensive maneuvering [7].

➢ Magnetic Docking

A satellite approaching the target leverages electromagnetic or permanent magnetic attraction to capture it. The concept was demonstrated by Astroscale ELSA-d mission [15], consisting of a servicer equipped with proximity rendezvous technologies and a magnetic capture mechanism, and a client equipped with a docking plate (DP), launched stacked together. Orienting the servicer so that it is always aligned with the target and facing the client's DP requires the ground segment's assistance. The DP, flat and disc-shaped, allows a semi-cooperative capture; it is equipped with optical markers for guidance and navigation, a flat reflective plane for precise distance and attitude measurement, and ferromagnetic material to facilitate magnetic docking. The magnetic capture system consists of a set of extendable and retractable small concentric permanent magnets, designed to perform multiple cycles of docking and undocking. After capturing a target, the servicer can displace it to a lower orbit altitude and let it re-enter faster, or it can initiate a re-entering maneuver, stacked with the target. The concept is effective with multiple targets; with respect to robotic systems and tethers, which will be later described, it has a lower level of mechanical complexity, it can more easily control the target attitude, and it is less expensive. However, it can be used only with cooperative targets equipped with a magnetic docking interface, and so it is more suitable as a debris mitigation solution for space objects to be launched in the future.

➢ Electro-Mechanical Docking

A study proposed the concept for the removal of two large pieces of debris from LEO, namely the Cosmos-3M second stages [16]. A satellite, equipped with a Hybrid Rocket Engine (HRE) as primary propulsion, attaches to the targets a Hybrid Propulsion Module (HPM), which is remotely ignited and performs the de-orbiting. The debris capture is composed of two systems: a Soft Docking System, using electrostatic adhesion to establish the initial contact with the target at the divergent nozzle border and dampen the impact loads; a Hard Docking System, using a special corkscrew to perform the structural connection inside the target's nozzle. The method doesn't require a specific docking interface, and it is effective with multiple targets. However, a solution like the special corkscrew increases the mechanical complexity and is still at conceptual level.

➢ Orbital Debris Sweeper [17]

A satellite is equipped with relatively thin large-area rotating panels, connected to the spacecraft core by radially extendable and retractable arms or booms; it estimates the size of approaching debris fragments using a tracking device and, depending on a threshold, either sweeps them away by impact with the panels or lets them pass without collision. The rate of removal can be controlled depending on the debris size changing the arms' length, and so the moment of inertia of the panels and consequently their rotating velocity; it can be further increased installing a propulsion device on a panel. However, the system requires a large operational area and is not suitable to remove large pieces of debris.

➢ Slingshot Method

A satellite, equipped with extendable and retractable rotating arms attached to semispherical collectors, is designed to capture space debris and leverage the arms' spinning motion to direct it towards Earth. The concept was presented with Sling-Sat Space Sweeper, developed at Texas A&M University [4]. The plastic collision between a debris fragment and its collector generates momentum, which is leveraged by the satellite propulsion system to reach the following target, reducing fuel requirements. The method is suitable to remove medium and large debris from LEO, and it is effective with multiple targets. However, it can remove only debris whose mass can be estimated upon capture by observing the satellite's angular momentum variation. Moreover, it requires high power to control the arms' length and has structural challenges with dampening vibrations and impact loads.

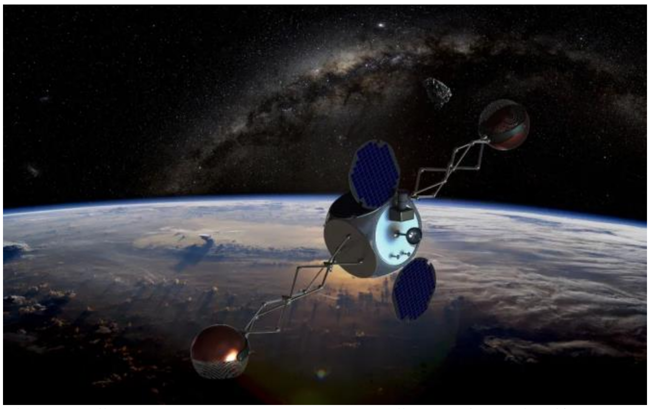

Figure 1. Sling-Sat Space Sweeper. Image credit: Jonathan Missel/Texas A&M [18].

➢ Tentacles

A satellite equipped with flexible appendages grasps debris at several points. If the appendages are robotic arms, they are equipped with a clasping mechanism; if they are not robotic, they are equipped with a docking mechanism, designed according to their target shape [4]. After the debris capture, the satellite performs a re-entry maneuver. Despite being expensive due to mechanical sophistication, the concept is easy to test and has reached a high Technological Readiness Level (TRL). It will be demonstrated by ESA with ClearSpace-1 mission in 2029 [19, 20].

➢ Robotic Soft Nets

A satellite ballistically launches a robotic soft net towards debris to capture it. Upon capture, the satellite performs a re-entry maneuver. Most studies propose passive or minimally active net control, while ESA developed the simulation of a 4-satellites formation at the corners of the net to remove Envisat, one of the largest pieces of debris in LEO [21]. The method achieves high compliance and has relatively low weight with respect to other ADR solutions. However, there is a high probability of breaking the target at contact and generating further debris [5]. Moreover, the method is not compatible with tumbling objects.

- Robotic Arms

A satellite, equipped with a robotic arm with sensors and end-effectors, approaches and grasps a targeted debris, equipped with a custom-designed marker. After stabilization, the satellite initiates a controlled re-entry maneuver to de-orbit the target. Before capturing the target, the system uses a pre-processing technique to de-tumble and decelerate it: for example, it leverages the dampening effect of a deployable and retractable flexible beam or brush. Robotic joints are protected from impact loads during capture by a Spring Damper Buffer Device (SDBD) [4]. The concept can also be used in dual-arm configuration to increase contact stability and operational efficiency, with one arm controlling the debris trajectory and the other one compensating for its reaction forces. It is highly reliable and scalable. However, it faces technological challenges with highly rotating targets, because the robotic joints get damaged after impact, and dynamic coupling is developed between the robotic arms and the satellite base. Moreover, it is not effective with non-cooperative targets with unknown shape and size; the computational complexity is high, because precise control is required; there is a risk of unwanted collisions; robotic arms can't execute complex tasks, because their degrees of freedom are restricted; shielding robotic arms is expensive. For these reasons, the system is still at a conceptual or simulation stage [7].

- Continuum Space Manipulators (CSMs)

A satellite equipped with Continuum Space Manipulators (CSMs) [4] approaches and grasps the debris, then initiates the re-entry maneuver, de-orbiting it. These soft continuum manipulator arms are cable-driven and made of a super-elastic central backbone (e.g. nickel-titanium alloy) with evenly spaced support discs. They are flexible and dexterous with respect to traditional robotic arms, also called Articulated Space Manipulators (ASMs) [4]. Moreover, they have infinite degrees of freedom. Therefore, they enable full-arm operational capabilities, including “whole-arm grasping”, i.e. the manipulator surrounds the target to control capture; they are effective with non-cooperative, large and irregularly shaped targets in confined spaces; they are reliable for long duration missions; they can cooperate with other robotic systems. Recent studies are developing robotic manipulators' multisensory capabilities, like the combination of visual imagery and tactile sensing [5]. The concept is mechanically complex, both kinematically and dynamically; it requires extensive testing and validation; technical challenges remain with non-cooperative targets.

- Adhesive Method

A satellite, equipped with four symmetrical flexible arms made of a dry anisotropic adhesive microstructure, approaches and adheres to a piece of debris, capturing it. Then, it initiates a re-entry maneuver to de-orbit its target. The adhesive can be fabricated by two-photon polymerization (2PP) and replication molding techniques, using for example polydimethylsiloxane (PDMS) [4]. The concept is purely mechanical: it leverages van der Waals forces to attach to debris and a passive triggering system with tension and compression springs to guarantee stability of contact during operations. It is adaptable to multiple types of debris. However, it faces technical challenges with the arms' bending stiffness and the adhesive material's surface energy density. Recent studies have explored the use of micro-patterned dry adhesives (MDAs) to extend the concept to both flat and curved surfaces without a favorable interface for capture.

- Foam-Based Method

A satellite approaches and flies around a piece of debris, ejecting foam until its target becomes all covered. Since the debris' area-to-mass ratio is significantly increased by foam, the debris faces increased drag, decelerates and decays to an orbit with lower altitude, accelerating its re-entry. The foam is designed to resist the impact loads with the target; its material and thickness determine the debris' variation of velocity and thus the reduced debris' de-orbiting time. When equipped with an electric propulsion system, the satellite can perform the foaming process with multiple targets within a single mission. The concept is effective also with large, highly rotating and non-cooperative targets. However, it is expensive for large targets, because a high quantity of foam is required, unless the target's configuration includes controlled re-entry. Moreover, it has not yet been tested in microgravity [22] and its highest TRL achieved is 4 [4].

- Fiber-Based Method

A satellite, equipped with a specialized device based on technologies like extrusion, chemical vapor deposition, blow forming or mechanical shaving [4], produces fibres, which are then coupled mechanically together and form an interceptor able to capture a piece of debris. After capture, the satellite initiates its re-entry. The fibres' thickness is under 100 microns in diameter to avoid breakage during the impact with the target, while their material can be aluminium or a polymer like nylon [4]. The concept is effective with multiple targets at the same time and can safely bring a target to the Earth surface [23]. However, it is only theoretical.

- Electrodynamic Tethers (EDTs)

A satellite deploys a long, thin, flexible and electrically conductive wire, which is oriented towards the Earth's centre by the Earth gravity gradient field. The geomagnetic field induces a voltage and generates a current within the wire, which then generates a decelerating Lorentz' force. The tether attaches through a mechanism to a piece of debris and the Lorents' force is leveraged by the satellite to de-orbit it. Expendable systems incorporate up to 10 small EDTs, each targeting an individual piece of debris, while reusable systems repetitively attach to, de-orbit and detach from individual targets [4]. The solution requires low power; it is efficient and lightweight; it has a relatively low weight and volume; it has a few Attitude and Orbital Control System (AOCS) requirements; it doesn't require thrust vector control; it has inherent safety, because of the satellite distance from the target during operations; it is effective with multiple targets, rotating targets, targets with different shapes and large ranges of motion; it shows high compliance with the configuration and tumbling state of the target (high portability); it is cost-effective. However, the power requirements increase for reusable systems; the generated thrust is very low; the de-orbiting times are long (from several months up to a year) [4]; the concept faces technical challenges due to advanced mechanisms (e.g. the risk of generating further debris if the tether's end is a harpoon or similar mechanism); it faces safety challenges, due to a complex re-entry, which requires sophisticated flight control techniques; it has an impractical length during the de-orbiting phase; it carries the risk of entanglement and unwanted or untimely deployment; it is still unproven at full scale. The concept can also be used passively, with a satellite at EOL or an upper rocket body deploying a free tethered mass to accelerate their decay (e.g. the "Terminator Tape", described later).

B. Passive Debris Mitigation

The main advantage of using passive techniques is that they are relatively less expensive with respect to ADR solutions, because they do not require interaction with a satellite chaser nor a propulsion system. However, being the debris re-entry uncontrolled, they carry the risk of material ablation and of ground impact.

- Deployable or Inflatable Drag Sails

At EOL a satellite remotely deploys or inflates a sail, which increases drag and leverages the solar radiation pressure, accelerating re-entry, so that it is compliant with the 5-years rule. Also the drag's orientation towards the Sun is remotely controlled by a ground station [4]. The solution is reliable and inexpensive. However, it may require propellant for the AOCS, significantly increasing the satellite mass requirements, and it carries a risk of orbital collisions due to the sail's wide area.

- Terminator Tape

At EOL a satellite ejects an electrically conductive tape ending with a plate. The gradient gravity force orients the tape towards the Earth's centre and the geomagnetic field generates a drag Lorentz' force along the tape. The combination of these forces decelerates the satellite and accelerates its decay. At low altitudes, when the aerodynamic drag becomes more significant than the electrodynamic drag, the tape's width is leveraged to enhance drag and accelerate re-entry. The system consists of a flat box, made of a cover plate, a restraint/release mechanism, a bottom plate and a length of tape, connected to both plates and folded up [24]. Tethers Unlimited, Inc. (TUI) qualified the technology with two configurations of tape: 7,5 cm wide x 10 m long and 15 cm wide x 70 m long [24]; three satellites have already been equipped with the solution. The concept is scalable and it carries a lower risk of orbital collisions with respect to drag sails. However, it shows some of the EDTs' limits: it has an impractical length during the de-orbiting phase and it carries the risk of entanglement and unwanted or untimely deployment.

- EOL Passivation

According to IADC Space Debris Mitigation Guidelines, all satellite on-board sources of energy are "depleted or safed when they are no longer required for mission operations or post-mission disposal" [2], a process called "passivation" [25]. The process can be leveraged to de-orbit the satellite, if it is designed so that the energy discharge generates a variation of velocity, bringing the satellite to a lower orbit altitude. The solution carries a reduced risk of break-up in orbit with respect to ADR solutions. However, the full propulsion system's passivation must be designed at an early stage; the remaining quantity of fuel at EOL cannot be accurately measured by sensors; there is risk of creating single points of failure during the mission, if the process gets started inadvertently or at the wrong time; the concept requires the minimization of highly survivable materials to keep a low risk of breakage and collisions during the de-orbiting phase.

- Design-for-Demise

The approach is based on designing the satellite to be compliant with Space Debris Mitigation Guidelines from the early stages. A notable example is designing the satellite structure in wood [26]. Wooden structures reduce the metal vapor in Earth atmosphere; they have a lower cost, because they can sustain an uncontrolled re-entry; they don't interfere with radio signals; they perform better vibrations' absorption. However, the reaction of wood with electric particles in space is still unknown and a protective coat is necessary in vacuum.

- Self-Eating Satellite

A satellite is equipped with an autophagic propulsion system, which burns most of its tank structure [27]. The system can be leveraged to passivate the satellite and bring it at EOL to the desired initial re-entry orbit. The concept was developed, for example, by the University of Glasgow, as a structure made of a plastic tube, which is burnt with gaseous oxygen and liquid propane as propellants [28]. The propulsion system has already been tested on Earth and there are plans to launch a satellite in the future [29]. The solution is light and efficient, but it is still at PDR phase, as it incorporates complex systems of autonomous self-deconstruction and it faces ethical challenges related to its long-term safety impact [4].

C. Just-in-Time Collision Avoidance (JCA)

Whenever two large non-maneuverable debris objects reach a certain threshold of collision's probability, a sounding rocket equipped with a gas and particle generator is launched to deflect one of the debris objects to avoid collision. The generator derives from a Solid Rocket Motor (SRM) and fires at apogee in anti-flight direction, near the debris' trajectory and just before the debris' transit time [4]. It imparts a small variation of velocity to the debris, altering its orbit as much as the probability of collision with the other debris object is gradually decreased. JCA operations must be authorized by an international body and the sounding rocket is launched by a spaceport located at high northern latitudes, to maximize the number of firing windows. The concept is ineffective with current observational capabilities: one or two higher orders of magnitude of accuracy in the calculation of debris' ephemerides are required for the solution to be reliable.

D. On-Orbit Servicing (OOS)

Approaching EOL or in case of technical failures, a satellite is refueled, repaired or upgraded by a space vehicle in orbit, which extends the satellite operational lifetime [30]. The space vehicle performs a rendezvous and docking to transfer fuel to the satellite, repair it or upgrade it, then undocks and initiates a re-entry maneuver. Using this tactic reduces the rate of debris creation, but the solution requires supply from Earth, which is complex and expensive to coordinate. It is envisioned to supply satellites with lunar in-situ resources in the future.

III. NEW ADR PARADIGM: DEBRIS PULVERIZATION

In very Low Earth Orbits, at altitudes below 500 km [6], the intensity of aerodynamic drag, radiation and orbital perturbations requires any space object to be shielded. Moreover, under 200 km of orbital altitude small pieces of debris re-enter within days [4]. For these reasons, this study proposes to consider debris pulverization under 1 mm at very LEO as a new paradigm for ADR solutions. Using NASA Standard Breakup Model [31], the preliminary design of a satellite whose 99% fragments upon pulverization are smaller than 1 mm can be designed. The complete satellite fragmentation can be achieved with an energy-to-target-mass-ratio (EMR) above 40 J/g [32]. The pulverizing systems should be designed to deliver at least 50 J/g to reduce the uncertainty of empirical studies. Two pulverizing systems are proposed by this study: a Megawatt class (MW) space-based continuous laser and a detonator or packaged charge transfer.

➢ MW Space-Based Continuous Laser

According to the state-of-art of laser technologies, a 3 MW ground-based laser generates an energy density of about 250 W/cm² for a satellite with an orbital altitude of 300 km, which can almost directly melt the optical glass on the satellite; US space-based hydrogen fluoride (HF) chemical or harmonic lasers reach 12 MW at an orbital altitude of 1300 km [33]. A high energy combustion driven continuous laser beam can pulverize a small piece of space debris heating it to hundreds of degrees. For example, a cubesat with a mass of 30 kg would be destroyed by a 12 MW space-based laser delivering 50 J/g in 0,125 s. The US Department of Defense (DOD) demonstrated MW chemical laser power for the first time with the Alpha Program between 1992 and 1994 [34]. At the same time, the Zenith Star Program delivered a preliminary design of space vehicles integrating the Alpha laser [35]. Despite both programs were stopped, the US DOD still plans to develop MW class laser weapon capabilities in the 2030s [36].

Figure 2. Alpha laser gain generator: the first MW class chemical laser demonstrated for space applications in the ‘90s [37].

➢ Detonator or Packaged Charge Transfer

A satellite equipped with a detonator or packaged charge approaches debris and transfers the explosive system to it; then, the satellite maneuvers away from the target and remotely initiates the target’s explosion. Only a detonator is transferred when the target’s propulsion system or battery is sufficient to pulverize the entire debris object; in all other cases, it is required to transfer a packaged charge of high-explosive material, like plastic-bonded hexanitrostilbene (HNS) [38] and lead azide of a pure form [39]. An example of active debris removal by deliberate detonation of an explosive device is the fragmentation of Kosmos 2163: with a total mass under 7 t, the satellite exploded at 210 km and its debris re-entered on Earth within weeks [40].

IV. CRITICAL REVIEW OF STATE-OF-ART CONCEPTS AND NEW ADR PARADIGM

Tables I and II report the most relevant parameters, challenges, strengths and weaknesses for each concept and are aimed at providing the design user with guidelines on concept selection and the research user with directions on further studies. All the concepts described in this paper were compared according to the following items:

- Debris Status (Cooperative/Non-Cooperative): it indicates whether the solution is designed for a cooperative or non-cooperative target, or both.
- Debris Size: it refers to the debris diameter, approximating the target shape to a sphere. It is considered “small” under 1 cm, “medium” between 1 cm and 10 cm, and “large” over 10 cm.
- Number of Targets per Mission
- Debris Rotational Status
- Interface (between the concept and the target)
- Knowledge of Debris Characteristics: it reports if debris characteristics must be known prior operations and any critical characteristics’ measurement that the concept can or must perform during operations.
- Demonstration Status
- Power Requirements
- Efficiency
- Collision, Entanglement and Unwanted Deployment Risk
- Scalability
- Debris Control: it refers to debris stability during operations.
- Removal Rate: it refers to the case of multiple targets; in case of single target, it is considered as removal speed.
- Propulsion System: it reports whether it is required or not.
- Technological Challenges
- Regulatory Challenges
- Ethical and Safety Challenges
- Volume
- Weight
- Cost
- Other Benefits: it states the concept’s strengths, in addition to those emerging from the above-mentioned items.
- Other Limitations: it states the concept’s weaknesses, in addition to those emerging from the above-mentioned items.

V. CONCLUSIONS

From a critical review of the state-of-art of space debris mitigation and removal concepts, it does not emerge a single best solution to the threat of the exponential increase with time of collision probability among space debris objects in LEO, also known as Kessler Syndrome. It is instead evident that according to the user drivers and constraints, one or multiple concepts can be selected. This paper presented the new ADR paradigm of pulverization under 1 mm, interpreting the IADC Space Debris Mitigation Guidelines to leverage the opportunity to destroy multiple debris objects at very low orbital altitudes, using either directed energy weapon technology, like MW class lasers, or controlled explosions, via detonator or packaged charge transfer. Referring to both military concepts under development and space qualified technologies, the paper described how to preliminary design an ADR system, whose main advantage is its inherent dual use. Moreover, the new paradigm outperforms other concepts able to generate a “zero debris corridor”, because it uses demonstrated technologies. Further studies are encouraged to preliminary design both technological versions of the new ADR system and simulate the 99% debris pulverization to fragments of 1 mm.

TABLE I. CRITICAL REVIEW OF STATE-OF-ART CONCEPTS FOR SPACE DEBRIS REMOVAL AND MITIGATION AND PROPOSED NEW ADR PARADIGM - PART I

Method	**Debris Status (Cooperative/Non-cooperative)**	**Debris Size**	**Number of Targets per Mission**	**Debris Rotational Status**	**Interface**	**Knowledge of Debris Characteristics**	**Demonstration Status**	**Power Requirements**	**Efficiency**	**Collision, Entanglement and Unwanted Deployment Risk**	**Scalability**
Active Debris Removal (ADR)	Both	Depending on the concept	Multiple	Any	Required for most contact-based concepts	Geometry, mass distribution and rotational speed must be assumed or estimated in proximity	No end-to-end in orbit validation (except for Astroscale ELSA-d mission with cooperative client)	High	Depending on the concept	Depending on the concept	High
Contactless ADR	Both	Any	Multiple	Any	Not required	Not required	Depending on the concept	High	Low over distance	Low	High
Ion Beam Shepherd (IBS)	Both	Any	Multiple	Any	Not required	Assumed quasi-circular orbit and linear relative motion (Clohessy–Wiltshire approximation)	Not yet flown	High	Low over distance	Low	High
Lasers	Both	Both smaller than 10 cm and large	Multiple	Any	Not required	Not required prior operations, but precise for re-engagement	Ground tested	High	Low over distance	Low	High
Gravity Tractor	Both	Any	Multiple	Any	Not required	Minimal sensitivity to debris characteristics	Conceptual stage	Low	Low over distance, directly proportional to S/C mass	Low	High
Tungsten Dust Clouds	Non-cooperative	Smaller than 10 cm	Multiple areas	Any	Not required	Effective with untrackable debris	Conceptual stage	Low	High	Low	High
Gaseous Clouds	Both	Any	Multiple areas	Any	Not required	Required prior knowledge of debris ballistic coefficient	Conceptual stage	Low	High	Low	Low
Contact-Based ADR	Both	Any	Small populations of fragments	Depending on the concept	Depending on the concept	Depending on the concept	Depending on the concept	Depending on the concept	Depending on the concept	High	Depending on the concept
Magnetic Docking	Cooperative	Small	Multiple	Any	Magnetic plates or docking interface	Required prior knowledge of debris characteristics	Demonstrated in orbit	Low	High	Low	High
Electro-Mechanical Docking	Non-cooperative	Large	Multiple	Any	No specific structural grasping interface required with soft docking (electrostatic adhesion); specific grasping interface required with hard docking (e.g. corkscrew).	Required prior knowledge of debris characteristics	Conceptual stage	Low	High	High	High
Orbital Debris Sweeper	Non-cooperative	Small and medium	Multiple	Any	Not required	Debris size can be estimated	Conceptual stage	High	High	High	High
Slingshot Method	Non-cooperative	Medium and large	Multiple	Any	Not required	Debris mass must be known in advance	Conceptual stage	High	High	High	High
Tentacles	Non-cooperative	Small	Single	Any	Not required	Required prior knowledge of debris characteristics; orbital parameters can be predicted.	Easy to test and high TRL	High	Low	High	Low
Robotic Soft Nets	Non-cooperative	Large	Single	Not tumbling	Not required	Required prior knowledge of debris characteristics	Simulation stage	Low	High with respect to contactless methods	High	Low
Robotic Arms	Cooperative	Any	Multiple	Not highly rotating	Custom-designed with markers	Debris shape and size must be known prior operations	Conceptual or simulation stage	Low	High in multi-arm configuration	High	High
Continuum Space Manipulators (CSMs)	Both	Large	Multiple	Any	Not required	Required prior knowledge of debris characteristics	Required extensive testing and validation	Low	High over time	High	High
Adhesive Method	Both	Various	Single	Any	Not required	Required prior knowledge of target's surface characteristics	Conceptual stage	Low	High	Low	High
Foam-Based Method	Non-cooperative	Large	Multiple	High-rotating	Not required	Required prior knowledge of debris characteristics	Not yet tested in microgravity, max TRL achieved: 4.	Low	High	Low	High
Fiber-Based Method	Non-cooperative	Any	Multiple debris at the same time	Any	Not required	Not required	Theoretical	Low	High	High	High
Electrodynamic Tethers (EDTs)	Both	Large	Multiple	Any	Safe distance during de-orbiting	Not required prior knowledge of the debris' center of mass	Unproven at full scale	Low for single mission, high to be reusable	High over distance, low over time	High	High
Passive Debris Mitigation	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Depending on the concept	Depending on the concept	High	Depending on the concept	Depending on the concept
Deployable or Inflatable Drag Sails	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Demonstrated	Low	High	High	High
Terminator Tape	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Demonstrated	Low	Low	Low with respect to sails, otherwise high	High
EOL Passivation	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Demonstrated	Low	High	Low	High
Design-for-Demise (e.g. Wooden Structure)	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Demonstrated	Low	High	Low	High
Self-Eating Satellite (Autophage Propulsion System)	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Ground tested rocket engine prototypes, theoretical satellite (PDR phase).	Low	High	Low	High
Just-in-Time Collision Avoidance (JCA)	Non-cooperative	Large	Not applicable	Any	Not required	Required	Demonstrated	Low	Low	Low	Not applicable
On-Orbit Servicing (OOS)	Cooperative	Any	Multiple	Not highly rotating	Required	Required	Demonstrated	Low	High	Low	High
New ADR Paradygm: Pulverization under 1 mm	Depending on the concept	Depending on the concept	Multiple	Depending on the concept	Depending on the concept	Required	Limited satellite break-up tests on real models	Depending on the concept	Depending on the concept	Depending on the concept	Depending on the concept
Megawatt Class (MW) Space-Based Lasers	Both	Small	Multiple	Any	Not required	Required prior knowledge of debris characteristics	Demonstrated MW power on ground testing facility	High	High per object removed, low over time	Low	Low
Detonator or Packaged Charge Transfer	Cooperative	Any	Multiple	Not highly rotating	Required	Required prior knowledge of debris characteristics	Demonstrated satellite self-destruction by remote detonation of explosive device	Low	Low with respect to MW laser	High	High

TABLE II. CRITICAL REVIEW OF STATE-OF-ART CONCEPTS FOR SPACE DEBRIS REMOVAL AND MITIGATION AND PROPOSED NEW ADR PARADIGM - PART II

Method	Debris Control	Removal Rate	Propulsion System	Technological Challenges	Regulatory Challenges	Ethical and Safety Challenges	Volume	Weight	Cost	Other Benefits	Other Limitations
Active Debris Removal (ADR)	High	Inversely proportional to debris size	Required	Depending on the concept	Depending on the concept	Depending on the concept	Depending on the concept	Depending on the concept	Depending on the concept	Depending on the concept	Depending on the concept
Contactless ADR	Low with respect to contact-based ADR	Inversely proportional to debris size	Required	Large-scale deployment, stability and precision	Large-scale deployment	Unknown effects with space environment	Depending on the concept	Depending on the concept	Low	Depending on the concept	Depending on the concept
Ion Beam Shepherd (IBS)	Low	Inversely proportional to debris size	Required	Thrusters' coordination	Risk to people and property	Unknown effects with space environment	Low	Low	Low	None	Required ion engines' upgrade to increase efficiency, which in turn increases volume, weight and cost.
Lasers	Low	Inversely proportional to debris size	Required	Precise targeting	Geopolitical risk	Not identified	Directly proportional to laser power	Directly proportional to laser power	Low-per-object, high for launch	Additional uses: preventing collisions, increasing accuracy of debris ephemerides and controlling large debris impact location.	Difficult in-orbit repairing
Gravity Tractor	Low	Low	Required	Not identified	Geopolitical risk	Not identified	Low	Directly proportional to debris mass	Low	In-orbit adjustability, high precision, simplicity, feasibility.	Conceived for asteroids' deflection
Tungsten Dust Clouds	Low	High	Required	Not identified	Not identified	Dust dispersion in space environment	Low	Low	Low	None	More effective right after satellite fragmentation due to the small volume occupied by debris.
Gaseous Clouds	Low	Inversely proportional to debris size	Required	Not identified	Not identified	Not identified	High	High	High	None	Applicable to debris having a relatively low ballistic coefficient.
Contact-Based ADR	High	Depending on the concept	Required	Depending on the concept	Depending on the concept	Depending on the concept	Depending on the concept	Depending on the concept	Expensive maneuvering	None	None
Magnetic Docking	High and easy	Low	Required	Complexity of client search, rendezvous and magnetic capture mechanism.	Not identified	Not identified	Low	Low	Low	Low mechanical complexity with respect to robots and tethers	None
Electro-Mechanical Docking	High	High	Required	Structural challenges during Hybrid Propulsion Module (HPM) thrust phase	Not identified	Not identified	Low	Low	Low	None	None
Orbital Debris Sweeper	Low	Controlled frequency of removal depending on debris size	Required	Not identified	Not identified	Not identified	Requires large operational areas	Low	Low	None	None
Slingshot Method	Low	High	Required	Structural challenges with vibration and impact loads	Not identified	Not identified	Requires large operational areas	Low	Low with respect to traditional successive rendezvous methods	Reduced fuel requirements with respect to successive rendezvous methods; after capture debris mass can be estimated through changes in angular velocity to optimize ejection speed.	None
Tentacles	High	Low	Required	Non-demisable materials (e.g. tanks and solar-array driver mechanisms); GNC and capture systems' high level of confidence and interaction.	Required ability to perform Collision Avoidance Manoeuvre (CAM)	Uncontrolled re-entry casualty risk	Low	Low	Expensive concept, cost-effective launch	None	None
Robotic Soft Nets	High	Low	Required	High dependency of controller's parameters on target and mechanical model of the net	Not identified	Not identified	High	Low	Low with respect to contactless methods	High compliance	None
Robotic Arms	High in dual-arm configuration	Low	Required	Dynamic coupling between the manipulators and the base, computational complexity and the need for precise control.	Not identified	Not identified	High	Directly proportional to the required number of arms	Expensive shielding	None	Restricted degrees of freedom (DOF) and difficulties in executing complex tasks.
Continuum Space Manipulators (CSMs)	High	High	Required	Mechanical complexity (kinematiks and dynamics) and challenges with non-cooperative debris.	Not identified	Not identified	Effective in confined spaces	Lower than robotic arms	Lower than robotic arms	Intrinsic flexibility and exceptional dexterity, full-arm operation capabilities, effective for irregularly shaped targets, capable of whole-arm grasping, envisioned multisensory capabilities.	None
Adhesive Method	High	Not applicable	Required	Technical challenges with arms' bending stiffness and adhesive material's surface energy density.	Not identified	Not identified	Low	Low	Low	None	None
Foam-Based Method	Low	High	Required	Choice of foam material and design of optimal de-orbiting period.	Not identified	Not identified	High	High	Expensive in uncontrolled configuration	None	None
Fiber-Based Method	High	High	Required	In-orbit fiber production	Not identified	Not identified	Impractical length during de-orbiting phase	Low	High	It can bring back the debris to the Earth surface.	None
Electrodynamic Tethers (EDTs)	High	High	Required	Advanced mechanisms, sophisticated flight control techniques.	Not identified	Safety challenges due to complex controlled re-entry.	Low volume, but impractical lenght during de-orbiting.	Low	Low	Low attitude control requirements, no thrust vector control, compatibility with different target shapes, usability as passive debris mitigation solution.	None
Passive Debris Mitigation	Not applicable	Not applicable	Not required	Depending on the concept	Depending on the concept	Material ablation and deposition in the atmosphere, risk of ground impact.	Depending on the concept	Depending on the concept	Low	None	None
Deployable or Inflatable Drag Sails	Not applicable	Not applicable	Required for deployment and AOCS	Not identified	Not identified	Not identified	Impractical width during de-orbiting phase	High	Low	None	None
Terminator Tape	Not applicable	Not applicable	Not required	Not identified	Not identified	Not identified	Impractical length during de-orbiting phase	Low	Low	None	None
EOL Passivation	Not applicable	Not applicable	Not required	Full propulsion system's passivation must be designed at early stage, inaccurate sensing of remaining fuel at EOL.	In case of less than complete passivation	Not identified	Low	Low	Low	None	Risk of creating single mission points of failure, requires minimization of highly survivable materials.
Design-for-Demise (e.g. Wooden Structure)	Not applicable	Not applicable	Not required	Not identified	Not identified	Unknown reactions with electric particles in space	Low	Low	Low	Reduced metal vapour in Earth atmosphere, radio signals unperturbed, high vibrations' absorption.	Protective coat needed in vacuum
Self-Eating Satellite (Autophage Propulsion System)	Not applicable	Not applicable	Required	Complex systems of autonomous self-deconstruction.	Not identified	Long-term safety impact	Low	Low	Low	None	None
Just-in-Time Collision Avoidance (JCA)	Not applicable	Not applicable	Required	Requires higher level of accuracy on debris characteristics than currently available.	Not identified	Not identified	Low	Low	Low	None	None
On-Orbit Servicing (OOS)	Not applicable	Not applicable	Required	Fluid connectors' mating during refuelling, cryogenic replenishment, autonomous operations, integration of mature technologies.	Not identified	Not identified	Depending on the technological solution	Depending on the technological solution	High	Envisioned supply by lunar in-situ resources	Required supply from Earth
New ADR Paradygm: Pulverization under 1 mm	Depending on the concept	Depending on the concept	Required	Pulverized debris containment	Generation of further debris	Uncontrolled debris dispersion in higher orbits	Depending on the concept	Depending on the concept	Depending on the concept	Accelerated natural decay by ballistic coefficient's reduction	Space objects orbiting in the generated debris-free corridor require shielding.
Megawatt Class (MW) Space-Based Lasers	Low	High	Required	Beam quality and control; size, weight, power and cooling requirements.	Geopolitical risk	Uncontrolled debris dispersion in higher orbits	High	High	High	Near-continuous operations	None
Detonator or Packaged Charge Transfer	High	Low with respect to MW laser	Required	Spontaneous explosion	ASAT regulations	Uncontrolled debris dispersion in higher orbits	Low	Low	Low with respect to MW laser	None	None

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