ET-Class, an Energy Transfer-based Classification of Space Debris Removal Methods and Missions

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1 Abstract

Space debris is positioned as a fatal problem for current and future space missions. Many effective space debris removal methods have been proposed in the past decade, and several techniques have been either tested on the ground or in parabolic flight experiments. Nevertheless, no uncooperative debris has been removed from any orbit until this moment. Therefore, to expand this research field and progress the development of space debris removal technologies, this paper reviews and compares the existing technologies with past, present, and future methods and missions. Moreover, since one of the critical problems when designing space debris removal solutions is how to transfer the energy between the chaser/de-orbiting kit and target during the first interaction, this paper proposes a novel classification approach, named *ET-Class* (Energy Transfer Class). This classification approach provides an energy-based perspective to the space debris phenomenon by classifying how existing methods dissipate or store energy during first contact.

2 Introduction

As a result of the existence of humankind in space starting from the last century, the Earth orbits have a crucial space debris pollution problem caused by millions of space debris varying at different geometry and mass [1], [2], [3]. Events, such as the collision between Iridium 33 and Cosmos 2251 satellites and Chinese anti-satellite missile test on non-functional meteorological satellite Fengyun FY-1C [4], [5], increased the space debris problem dramatically. This situation constitutes a vital case since operational satellites are in danger of crashing and threatened to be destroyed by space debris [6], [7], [8], [9], [10], [11], [12]. Moreover, newly planned satellite missions may be interrupted by satellites already placed in different orbital trajectories [13]. The Kessler Syndrome states that the number of space debris is exponentially increasing, and eventually, there will not be a chance for a spacecraft to be placed in any orbit in an appropriate manner [14], [15], [16], [17]. To tackle this problem, many space industry companies and organizations work to deal with the existing space debris orbiting Earth [18]. Space debris removal missions are needed to solve the space debris problem [19]. However, the key question is; what type of mechanism is needed to tackle this issue? There is various type of space debris having different geometry, mass, velocity and material. There is no single space debris removal mechanism that can deal with all types of space debris [20], [21]. Therefore, classifying space debris removal systems is crucial to get a meaningful insight into the space debris problem before planning any space debris removal mission.

Many space debris removal technologies and missions are still in concept development stages and have not reached to high Technology Readiness Level (TRL) [22], [23], [24]. The highest TRL level ever reached for space debris removal is TRL-6, which is *Level 6 – System Adequacy Validated in Simulated Environment*. However, this TRL has been reached only for a few methods. The main reasons for this situation are because space debris removal missions are overly expensive [25], some space debris removal techniques require Guidance Navigation and Control (GNC) infrastructure, consisting of both hardware and software components, are extremely advanced [26], [27], [28], [29], [30], [31]. Furthermore, it is also hard to convince sponsors and get funding due to the reasons mentioned above.

To underscore the above-given crucial facts and look for novel solutions, ESA completed a four-day virtual conference for the space debris problem, namely the 8th European Conference on Space Debris, between 20 - 23 Apr 2021. In the conference, several topics were emphasized, such as dramatically increasing AI market, the development of cost-effective and highly advanced computational methods [32], [33], and new material types etc. Space debris is a growing concern for astronauts and satellites as companies launch more missions into space, including mega-constellations [34] like SpaceX's Starlink project, which now numbers more than 1.400 satellites already in orbit [35].

Space debris problem creates prominent danger for the new born space tourism market too. Companies, such as *Blue Origin* owned by *Jeff Bezos* [36], *Virgin Galactic* owned by *Richard Branson* [37], and *SpaceX* owned by *Elon Musk* [38] plan to use reusable rockets to carry space tourists. Apple co-founder *Steve Wozniak* is starting a private space company called *Privateer* [39]. The NSR *Space Tourism and Travel Markets Report* estimates that the space tourism market will generate 7.9 *B USD* by 2030 [40].

Current classification methods existing in the literature approach the space debris removal problem from the structural point of view, such as type of mechanism, or, whether the method is passive or active [41], [42], [43], [44], [45]. However, one of the main problems to face when designing space debris removal strategies is how to transfer the energy between the debris (target) and the chaser during the first interaction [46]. For example, throughout ADR (Active Space Debris Removal) missions, one should consider that it is possible to push away debris floating in space if a mismatch/misalignment problem occurs during the first interaction. Answering the questions, such as how the momentum energy flows between the chaser/deorbiting kit and target satellites, how much energy needs to be dissipated, or how much energy needs to be stored during the first interaction, are critical for the mission's success.

Therefore, existing debris removal methodologies and missions are summarized throughout this paper. Additionally, a novel space debris removal classification approach, named *ET-Class* (*Energy Transfer Class*), is proposed to understand the space debris removal phenomenon in terms of the way the first interaction between the chaser (or de-orbiting kit) and target occurs, which is of great importance to plan new missions. The practical value of ET-Class is that; it allows to understand the trends of the space debris removal research and the lacking areas/parts in terms of the energy transfer occurring at the first interaction between the chaser satellite/de-orbiting kit and target satellite. There will be more solutions in the future than bringing the debris into the atmosphere and burning, or pushing it to a higher orbit, such as collecting all the debris in a specific orbit and using all of them for recycling purposes.

Companies, institutions and organizations that intend to conduct future space debris removal missions must be aware of energy distribution and energy transfer mechanisms between the chaser satellite/de-orbiting kit and target satellite during the first interaction. Mainly because part of the mission objective is not only capturing/de-orbiting the debris but also to do it in such a way that no more debris is created (because of the rigidity of the space debris, a fracture is highly possible during the first interaction) and minimum energy is consumed for the desired trajectory [47].

This paper groups existing debris removal methods under four classes:

- **ET1 Potential energy dissipation:** This class encompasses approaches that focus on the idea of decreasing the potential energy of the debris at the first interaction. The reference point of the potential energy calculation is Earth. While the potential energy of the debris is being dissipated, the debris is getting closer to Earth, which means that it will dive into a more dense atmosphere. As a secondary output, the debris's kinetic energy is also dissipated since it encounters and hits more atmospheric particles. However, this kinetic energy dissipation obtained as a secondary output is caused by the potential energy dissipation of the debris. As mentioned before, the classes defined in ET-Class describe what happens only at the first interaction between the chaser satellite/de-orbiting kit and target satellite in terms of energy transfer. Deorbiting kit on the target satellite, such as tether, solar radiation force-based drag sail, or inflated system, decreases the potential energy of the target satellite while pushing into the atmosphere, and due to the friction, the target satellite coupled with the de-orbiting kit is destroyed. One exception, not working as a de-orbiting kit but as a chaser satellite, is the Ion Beam Shepherd method. Ion Beam projector is integrated on the chaser satellite and applies highly concentrated ions on the target satellite towards Earth direction so that the target satellite's potential energy is dissipated.

- **ET2 Impact energy dissipation:** This class focuses on methods that decrease the impact energy of the debris when the first interaction occurs. Many debris has enormous velocities up to 28.100 km/h. Even the chaser satellites with advanced GNC infrastructure are not capable of perfectly aligning with the velocity of the debris. This velocity difference and friction forces produce an impact during the first mechanical interaction, which should be absorbed by the components used in this technology. After the chaser and the target satellites become a single mass, they can either get into the atmosphere and burn or move to outer space. In addition to harpoon and space net mechanisms, there are different types of robotic capturing mechanisms under this category, such as rigid and flexible robotic.

- **ET3 Neutral energy balance:** This class includes methods that do not require dissipating potential/impact energy during the first interaction between the chaser and the target satellites. There only existing method in this class is the magnetic capturing method. The first interaction between the chaser and target satellites is perfectly isolated in terms of energy transfer until they become a single integrated mass. In the market, cooperative magnetic docking mechanisms are being used to achieve this purpose. There will be no energy transfer in theory during the first interaction, only minimized energy transfer in the application. Since the debris is made of ferromagnetic material and the chaser has electromagnet infrastructure, virtual damping and spring effects that can be manipulated by the controller of the electromagnet play a compliance mechanism role. By adjusting the sequence of the positive/negative balancing forces of the electromagnet at high frequency, the impact energy of debris onto the chaser satellite during the first interaction will be minimized, which is of great advantage and the main reason why future missions in the market will use this type of technology.

- **ET4 Destructive energy absorption:** In this class, the target satellite, as debris, is being destroyed by the chaser satellite using destructive tools, such as peripheral laser devices.

The details of the proposed novel classification are given in the following sections. The paper is organized as follows; in Section-3, ADR challenges are described. Section-4 reviews state-of-the-art space debris removal methods and classifies them according to the *ET-Class*. Section-5 reviews and classifies past and future missions. Finally, Section-6 presents the conclusions and the direction of future work.

3 Active Space Debris Removal Challenges

3.1 The problem

It is estimated by the European Space Agency (ESA) that 130 million objects smaller than 1 cm, 900.000 objects between 1 cm and 10 cm, and 34.000 objects greater than 10 cm are orbiting the World up to the enormous speeds of 28.100 km/h [48], [49]. Even though their masses are relatively small, their impact factor is exceptionally high due to the momentum parameter [50], [51]. By now, only 39% of the satellites sent to space are operational [52]. To solve this bitter situation, the UN General Assembly COPUOS (Committee on the Peaceful Uses of Outer Space) and the International Telecommunications Union (ITU) suggest following some guidelines for future space missions. They suggest to put efforts to shorten the lifetime of debris or that debris removal operation should not create more debris [53], [54], [55], [56]. There are advanced mathematical methods to use the remnant propellant of Jet Propulsion System (JPS) [57], or even more energy-efficient Electric Rocket Propulsion Systems (ERPS) [58], for optimal de-orbiting operation. However, the satellites already placed in orbits were not designed to satisfy the above-given properties. Consequently, many orbits are crowded with several non-functional satellites and their scattered components [59], [60], where many of them are uncooperative.

This panorama reveals the urgent need for ADR missions to clean the current space debris orbiting the World. The severity of the space debris pollution problem can be seen from ESA's dramatic space debris image given in Fig. 1.

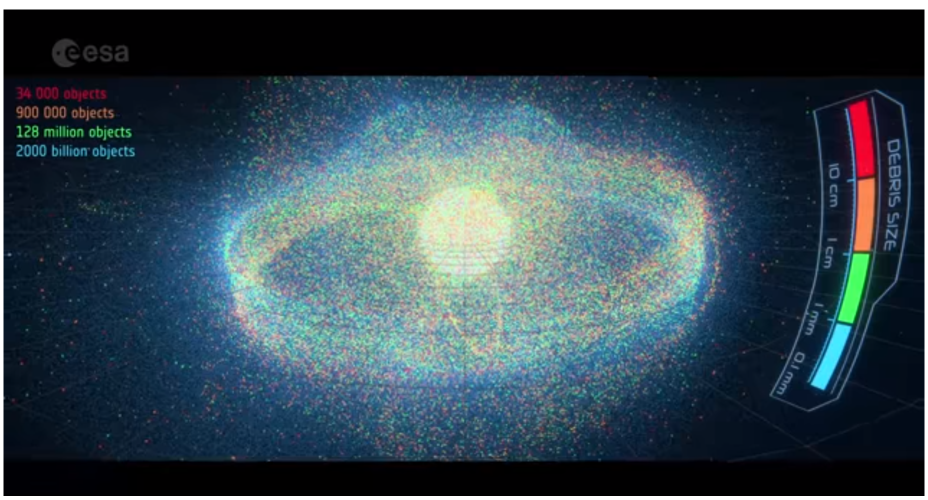


Figure 1: ESA's space debris image showing the varying size of space debris orbiting Earth [52].

One of the recent examples of the seriousness of the space debris problem is the problem experienced by SpaceX's Crew-2 mission on 23 April 2021. The mission was a routine transfer of astronauts to the International Space Station (ISS). However, on their way to the ISS, the astronauts of SpaceX's Crew-2 mission for NASA had a shocking experience when a piece of space debris passed unexpectedly very close to the Dragon capsule [61].

A similar example occurred in September 2020 to the Expedition 63 crew, which had to temporarily relocate to the Russian part in the ISS when a piece of space debris threatened. A piece from Japan's H-2A F40 rocket stage came within 1.39 kilometres of the ISS [62]. On 12 May 2021, a 35 cm diameter hole was found on Canadarm2. ISS, which is about the size of a football field, periodically has to adjust its orbit to avoid pieces of space debris. The latest event that affected the ISS was observed on 15 November 2021. The Russian military shot one of its Soviet-era defunct satellites for a missile test, generating more than 1,500 pieces of space debris. This situation forced ISS astronauts to shelter for two hours in capsules to return them to Earth in the collision event. These examples depict the urgent need for debris-free orbits.

3.2 Challenges

Space has a very different environment from Earth's surface and atmosphere, which is much more severe in terms of radiation, temperature changes, lack of friction, *etc.* [63]. The zero-g condition of space makes hardware behave differently. Although any hardware must go through verification and validation tests before it is launched to space, this is still not sufficient to assure that it will work in space [64]. For many governments and commercial space missions, extensive testing, verification, and validation processes of the hardware and software components are required. [65], [66], [67], [68], [69], [70].

Capturing and de-orbiting a large piece of a defunct space object is not a small challenge from technical, legal, and financial points of view. Considering that many targets need to be removed every year, the arising question is how to make these debris removal operations affordable, and which organizations or governments would pay for the service [71], [72]. ESA's artistic image dramatically shows the severity of the space debris problem, as shown in Fig. 1. This image again raises the question of whether multiple targets could be removed in a single mission or not. Because of this, ADR technologies should not have to rely on specific characteristics of the debris or interfaces on the debris to accomplish the mission but instead should have the capability to appeal to various types of space debris. Docking with an uncooperative target has been already achieved involving human astronauts (such as in the case of the rescue of Intelsat VI) [52], and autonomously with a cooperative target by Astroscale's Elsa-d mission [48]. However, many other challenges remain.

To remove debris from space, the properties of the debris have crucial importance. There are two types of debris, *1- Cooperative* and *2- Uncooperative.* Cooperative debris provides data about their location and mostly has a supporting mechanism for docking or achieving the mechanical interaction between the chaser and target satellites. However, uncooperative debris has neither a supportive mechanism nor provides data to the chaser satellite. This issue constitutes a vital problem for debris removal operations. Moreover, most space debris has various topologies and considerable high angular momentum. One can imagine how hard it is to capture those target satellites when they do not provide data or do not have a supportive mechanism [73], [74], [75], [76]. *Luc Piguet*, founder and CEO of *ClearSpace* comments *"At orbital velocities, even a screw can hit with explosive force, which cannot be shielded against by mission designers. Instead, the threat needs to be managed through the active removal of debris items"* [77].

Currently, two types of approaches are used to mitigate the space debris problem, *active* and *passive*. Active approaches are based on servicing satellites to de-orbit space debris objects. On the other hand, passive approaches are mounted onto the object when its mission starts and activated when it is complete for de-orbiting. Passive approaches will help clean up space in the long run; however, they solely cannot meet the immediate needs for mitigating collision risks [78].

To sum up, the technologies that come to our lives in this era bring enormous opportunities to tackle the challenges mentioned above. The solution to these challenges will positively contribute to the space industry's core and side markets shortly. Mainly for companies and institutions working in the ADR topic, tackling those challenges is not an option but an emergent obligation. Thus, concept studies covering these technologies need to be prepared and pushed to high TRL levels, such as TRL-7, which is *Level 7 – System Adequacy Validated in Space.*

4 Review of State-of-the-Art Methods

Up to now, many methods for space debris removal have been proposed in the literature. According to their characteristics, the methods are divided into several categories, such as harpoon capturing, net capturing, rigid capturing, flexible capturing *etc.*. Some methods do not use the mechanic capturing principle to remove the space debris but use other principles, such as inflated, foaming, and tethering. Advantages and drawbacks exist in any of those options, and there is not a single space debris removal method that can deal with all kinds of space debris. The following sections present the most remarkable space debris removal methods that have been developed so far, categorizing them according to the *ET-Class* proposed in this paper. Fig. 2 presents the distribution of the existing approaches under different *ET-Classes*. The figure provides the highest TRL reached for each method, based on NASA's well-known TRL definition [79].

4.1 Methods ET1: potential energy dissipation

Energy Transfer Class 1 includes methods that focus on decreasing the potential energy of the debris. In the state-of-the-art, four methods fit within this category. 1-Inflated method, which decreases the potential energy of the debris by

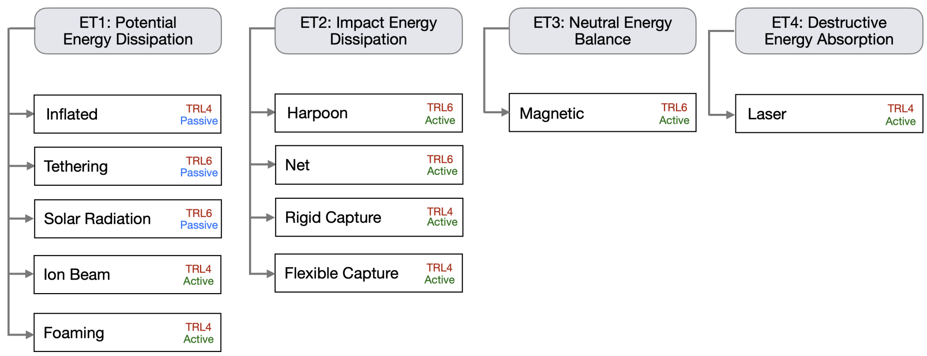


Figure 2: Space debris removal methods classified according to the proposed *ET-Class*.

manipulating the debris' ballistic coefficient. 2-Tethering method, which uses the ionosphere's particles to create drag force, 3-Foaming method, in which the chaser satellite sprays foam onto the target debris via a nozzle, 4-Solar radiation force, which uses the solar radiation to create drag force, and 5-Ion beam shepherd method, which applies ion-beam on the debris and creates drag force. Fig. 3 shows examples of these concepts.

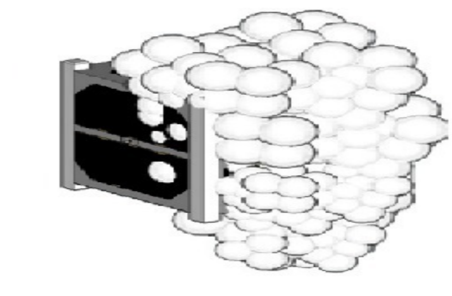
4.1.1 Inflated Method

The idea of the inflated method is to change the ballistic coefficient of the structure so that the gravitational force on the system can easily be manipulated. In the end, the system's potential energy will be decreased while the pulling force towards Earth will be increased. When the debris enters the atmosphere, the friction will handle the dissipation of the kinetic energy. The most well-known study that researched this topic is Gossamer Orbit Lowering Device (GOLD) [80]. The summary of the concept is that; inflated balloon mechanism is integrated into the target satellite before it is launched. When a de-orbiting operation is needed, the envelope is filled with gas. The envelope material is ultra-thin and lightweight. Therefore, even a tiny amount of gas is enough to inflate the balloon. The drawback of this concept is the high risk of the possible damage to the balloon by other space debris having dangerously high momentum [85], or this balloon-like structure can damage other operational satellites in space since it has no advanced positioning control system. The research conducted for this method was kept in concept development and simulation phases. No inflated method based mission has been organized yet, and the highest TRL ever reacted for this method is TRL-4.

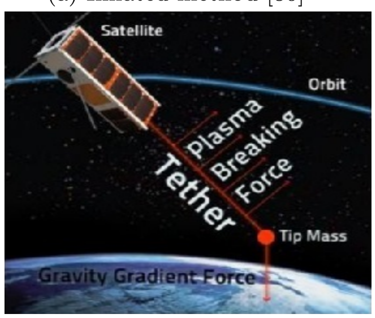
4.1.2 Tethering Method

Space tethers are essentially used for propulsion purposes in space. These tethers are made of electrical conductor materials that can create a voltage difference

(a) Inflated method [80]

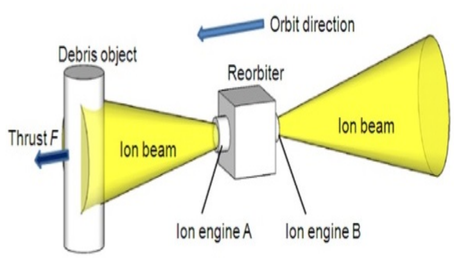


(b) Foam method [81]



(c) Tether method [82]

(d) Solar radiation method [83]



(e) Ion beam shepherd method [84]

Figure 3: Examples of existing ET1 methods: Potential Energy Dissipation. Energy Transfer Class 1 methods focus on decreasing the potential energy of the debris.

between the edges of the tether. There are two common tethering methods in the literature, 1- Electrostatic tethering, 2- Electrodynamic tethering, the detailed descriptions of these methods are given in the following subsections. When the tether physically interacts with the charged particles of the ionosphere in LEO, drag force is generated on the tether. Therefore, this principle is used to de-orbit any space object [86]. The space tethers can be integrated on a spacecraft even before it is launched as an onboard system or attached by a different spacecraft in space. When the tether is spooled out, the debris's potential energy decreases while the pulling force towards Earth is increased. This pulling force turns the potential energy of the debris into kinetic energy. Space tether systems are varying in terms of many different aspects, such as open-loop or closed-loop control [87], [88], rigid or elastic [89], [90], [91], [92], [93].

Space tethers are very famous and have a wide range of application areas. When firstly proposed, the actual purpose of the electrodynamic tether method was to change the orbit of satellites. NASA's Gemini-11 mission demonstrated passive attitude stabilization of the two spacecraft connected by a tether and generated artificial gravity by spinning the integrated spacecraft. In ASI (Italian Space Agency) TSS-1, ASI TSS-1R missions, it was aimed to generate electrical energy based on the Faraday effect. ESA's YES2 mission was focused on testing the usage of tethers as de-orbiting propulsion system [94]. The tethering applications conducted so far use a de-orbiting kit integrated on the target satellite before it is launched. The tethering process is triggered when the life of the satellite ends. Therefore, the de-orbiting kit and the target satellite start to have interaction. The disadvantage of this approach is that it is not valid for already existing uncooperative targets.

- **Electrostatic tether method:** The idea behind this tethering method is the creation of electrical potential between the edges of the tether so that its interaction with the charged particles of the ionosphere [95] generates a drag force that pulls the space debris towards Earth. An integrated battery produces the electrical potential, and unlike the electrodynamic tether method, this battery is not charged by the particles of the ionosphere. One of the most advanced works conducted so far is *Finnish Meteorological Institute's Electrostatic Tether Plasma Brake* [82] in which verification and validation were done with Aalto-1 satellite (3-U CubeSat). The advantage of electrostatic tether over electrodynamic tether is that the open-loop control of electrostatic tether brings a severe amount of simplicity. Electrodynamic tether is frequently charged by the ionosphere's particles so that this charge needs to be integrated into the closed-loop structure of the control algorithm. On the contrary, there is no charging requirement for electrostatic tethers. The electrostatic tether is controlled via DC voltage of an integrated battery [96]. Electrostatic tether systems can be used not only for removing space debris but also for many different purposes, such as planetary exploration [97] and space elevators [98] The highest TRL ever reached for this technology is TRL-6.

- **Electrodynamic tether method:** The advantage of the electrodynamic tether method is that; the battery of the electrodynamic tether can be charged several times using the ions located in the ionosphere [99], [100]. So that, the battery's energy can repetitively be used via sophisticated control methodologies, such as sliding mode control or adaptive control approaches [101], to generate extra drag force along the tether. The charging property of the ions cannot be used for electrostatic tethers, the particles are used to create only the drag force. Compared with electrostatic tethers, electrodynamic tethers can bring the non-functional satellite to the Earth faster since the ionosphere charges its battery. The first disadvantage of this method is that it cannot work outside of LEO since the non-existence of charged particles, i.e. insufficient magnetic intensity [102]. Numerical simulation is one of the most important aspects when a tether system is designed [103]. However, simulation results cannot solely prove the reliability of proposed methods. Validation and verification steps in the space environment are needed to show the effectiveness of any approach. In [104], tethering method is compared with other alternative methods, advantages and disadvantages are emphasized. The second disadvantage is that the magnitude of the Lorentz force is not always enough to take the debris into the atmosphere in a short period. The third disadvantage is the complexity of deploying a long tether; there is always a chance that the tether may fold. The longer the tether is, the bigger the Lorentz force generated. However, this long tether can collide easily with any object flying close by, like the ISS orbiting in LEO. The highest TRL ever reached for this technology is TRL-6. To sum up, different approaches in the literature for electrodynamic tether method vary by material type, tether length, tether spooling mechanism *etc.*, yet the fundamental principle of electrodynamic tether stays unchanged for different studies.

4.1.3 Foaming Method

The foaming method is based on spraying foam onto the target debris and manipulating its ballistic coefficient. The most important advantage of this method is that there is no need for a docking mechanism or de-tumbling the target so that this method is applicable for non-cooperative targets having high angular velocities. While the chaser satellite has proximity rendezvous with space debris, the foaming process is started as follows: the foam is sprayed towards the target satellite [81], the foam ball that is created at the end increases the surface area of the target, the target slows down since its surface area interacts with the atmospheric particles more intensively, the rising area-to-mass ratio of the foam-covered debris generates an atmospheric drag force, the target's potential energy is initially dissipated because of the enhancement of the friction and pressure of the atmospheric particles that hit towards the increased surface, after the target is fully covered by the foam and become a foam ball, it starts getting into the atmosphere and burn. The contradictory point is that; the foam should be stiff enough so that the foam ball will not be destroyed by small pieces of other space debris existing in the same orbit, and new space debris will not be created [105]. If the foam ball is overly soft, it will not endure long. In conclusion, the chemical composition of the foam needs to have a balance between stiffness and softness spectrum. This issue constitutes the disadvantage of using this method: determining these coefficients for varying space debris types and topology? The foam technology has also different usage areas in space, such as space debris shielding [106]. No foam-based mission has been organized yet, and the concept has low TRL [107]. The highest TRL ever reached is TRL-4.

4.1.4 Solar Radiation Force Method

The idea behind the solar radiation force method is based on using the solar radiation pressure to create drag force and decrease the altitude, potential energy in other words, of the satellite, as long as the orientation of the surface of the solar sail wings is well aligned, as orthogonal, with the solar array.

Some of the advantages of this method are that; solar sails are scalable, which means that it can be applied to varying range of weight and geometry. Moreover, because of the topology of the principle, the method is easy to model [108], [109] [110], easy to deploy [111], [112], and passive [113], [114], [115].

Solar radiation pressure applied onto the wings of the solar sail, which have orthogonality with the solar array, generates a drag force that pushes the satellite towards Earth. Active control of the solar wings is crucially needed to ensure orthogonality throughout the process. While the potential energy of the debris is being dissipated using the solar sail wings, the distance of the debris to the Earth is decreasing, which means that the debris will get into a more dense atmosphere. As a secondary output, the debris' kinetic energy is dissipated too since it encounters atmospheric particles more frequently. The more potential energy of the debris is dissipated, the more kinetic energy is dissipated; this causality creates an infinite loop between the potential and kinetic energy dissipations. Another type of drag force is the atmospheric drag. The atmospheric drag is strictly dependent on the atmosphere's density, which changes considerably throughout the orbit. Moreover, the atmospheric drag force is also dependent on the geomagnetic effect of the solar activity, which changes along the year.

A solar sail can generate both. However, a solar sail is generally used in higher orbits where there is no or neglectable atmospheric drag, and the atmospheric drag occurs closer to the Earth, such as in LEO. The drawback of this method is that it highly depends on the sun's orientation. The method is not applicable for the altitude below 750 km because the atmosphere absorbs radiation. One of the most known examples of the solar radiation force method is the RemoveDEBRIS-Drag Sail mission. The method is promising and conducted advanced research since it satisfies many debris removal aspects, such as minimal energy consumption via passive solar sails, compactness and scalability for different satellite models planned to be launched in future. For space debris removal applications, the highest TRL ever reached with this method is TRL-6, achieved via RemoveDEBRIS mission. The details of this mission are given in

Section-5.

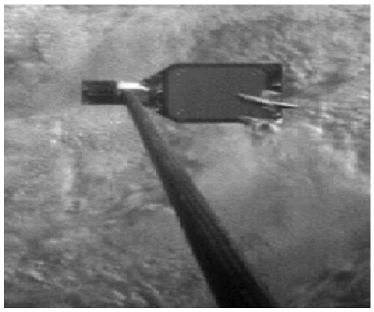
4.1.5 Ion Beam Shepherd Method

This method is based on applying a plasma ion beam onto the space debris and lowering its altitude (lower potential energy, in other words) over time. The electromechanical model of this method relies on the dynamics of ion actuation [116]. Outputs of this method with different ion actuation models are given in [117], [118]. Fundamentally, the ion beam acts as a physical link between the chaser and target satellites, and when properly controlled, it works as a stable, spring-like mechanism to transfer the necessary forces on the debris for de-orbiting purposes. During the ion-beam actuation, the relative position stability between the chaser satellite and the debris can be ensured using $\mathcal{H}_\infty$ optimal control framework [119].

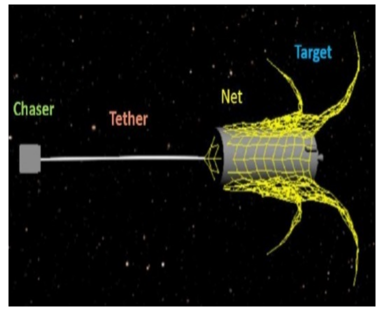
This concept can be applied to non-cooperative and cooperative targets on both LEO and GEO orbits [84], [120]. Cooperative targets can provide their location to be de-orbited by the chaser satellite, yet this method was developed to find a solution primarily for uncooperative targets. The velocity of ions is exceptionally high, around 38 km/s for xenon ions at 1-kV beam, and a higher power energy source can increase this value. The method is highly space debris topology-dependent, and energy consumption requirement is hard to overcome. No ion-beam shepherd mission has been organized yet, and the concept has low TRL. The highest TRL ever riched for this method is TRL-4.

4.2 Methods ET2: impact energy dissipation

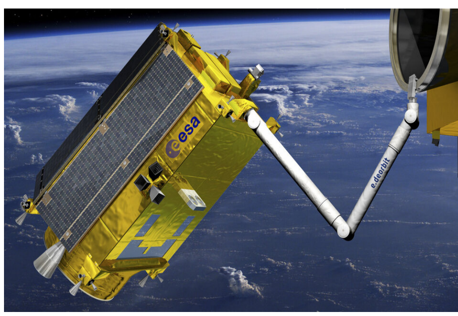
Energy Transfer Class 2 includes methods that should decrease the impact energy of the debris when the first contact occurs between the chaser satellite and debris. To reduce this impact energy, GNC infrastructure or compliance mechanisms of the chaser satellite can be used. Five methods fit within this category. 1-Harpoon capturing method creates impact energy on the chaser with a harpoon shot. When the harpoon pierces the debris, mechanical contact that secures the chaser and target satellites creates impact energy on the chaser satellite. 2-Net capturing method. When the net catches the debris, the mechanical connection is secured between the chaser and target satellites so that some amount of the momentum of the debris is accumulated by the chaser satellite, or even be manipulated by the chaser satellite's propulsion system, 3-Rigid capturing method should have a compliance mechanism that decreases impact energy of the debris during the capturing phase. The rigid capturing method can be supported with tentacle design architecture and 4-Flexible capturing method, which softly complies with the debris during the capturing phase and decreases debris' impact energy with flexible links.



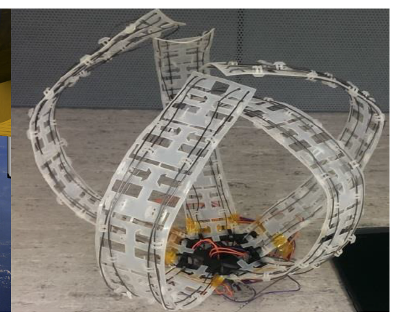
(a) Harpoon capturing method [83]



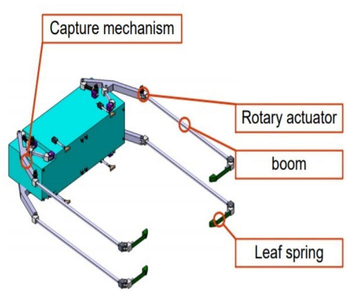
(b) Net capturing method [121]



(c) Rigid capturing method [122]



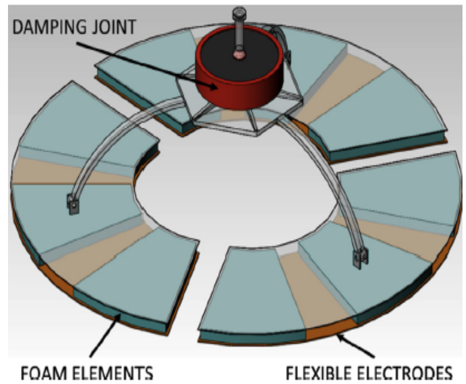
(d) Flexible capturing method [123]



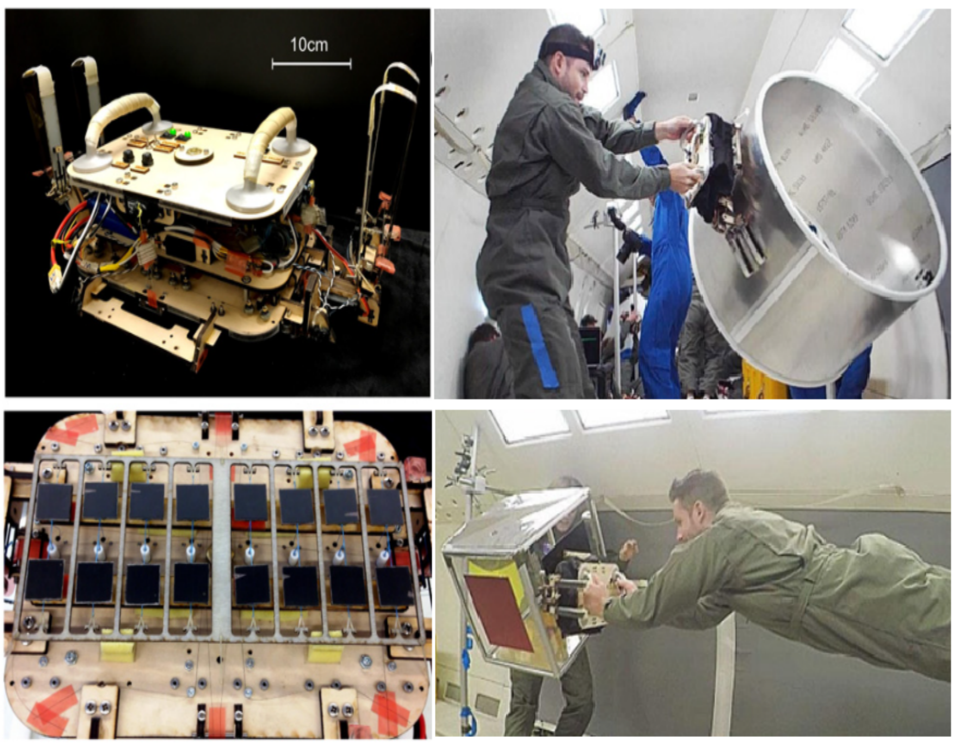
(e) Tentacle design architecture [124]

Figure 4: Examples of existing ET2 methods: Impact Energy Dissipation.

(a) Adhesive pads integrated with robotic gripper - 1 [125]



(b) Voltage-induced electro-static adhesion. [126]



(c) Adhesive pads integrated with robotic gripper -2 [127]

Figure 5: Examples of adhesive technology.

4.2.1 Harpoon Capturing Method

In this method, the chaser satellite deploys a harpoon mechanism to penetrate space debris [128] (see Fig 4a). After the successful shot, the chaser satellite, harpoon and target become integrated, satellite and target are connected via elastic tether, and the chaser satellite will pull the debris to re-enter the atmosphere and burn together or fly to a graveyard orbit. One disadvantage of this method is that it is tough to shoot an object tumbling at a high angular velocity in space. To achieve this, the chaser satellite needs to be supported by an advanced GNC infrastructure to get aligned and close proximity rendezvous with the debris. Harpoon method is among the promising debris capturing methods so that there are ongoing researches for this topic, both in simulation and experiment levels. An uncertain part of the simulation studies conducted for this method is the difficulty of proving the results since the simulation results may not be fully compatible with the experimental results. Furthermore, verification and validation processes of the product in space are needed [129]. Some simulation studies conducted in this field include harpoon modelling [130], piercing geometry modelling [131], pulling mechanism modelling, GNC infrastructure support for harpoon systems [132]. The disadvantage of this method is that; an unsuccessful shot may create more space debris depending on the debris material and targeted point, and there is only one chance to shoot [133]. The concept missions using harpoon technology are given in *Review Technologies and Missions* section.

4.2.2 Net Capturing Method

The net capturing method is based on shooting a flexible net onto the target debris. The net is shot from a chaser satellite by releasing corner masses outward in the target debris' orientation. Therefore the net wraps the debris. This method has several advantages; for instance, the net-capturing method enables shooting from a relatively long distance between chaser satellite and target debris such that close rendezvous and docking operations with the debris are not obligatory, and there is not necessary to de-tumble the target satellite before capturing [121]. In other words, this method does not require a chaser satellite that has to achieve proximity rendezvous with precision. Moreover, the method is independent of the debris' geometry, which means that the net can catch space debris in different scales [134], [135]. The most common materials used for net design are Kevlar, Dyneema, Vectran and Zylon [136], [137], [138]. The disadvantages of this method are; how to determine the elasticity of the net's material and geometry of the net's topology since these parameters will dramatically affect the first interaction dynamics [139], [140], [141]. Another disadvantage of this method is that the net can be shot only once.

In conclusion, net-based capturing methods in the literature are very similar since the main principle is to use a net to capture space debris. The only difference in the proposed studies is the nets' geometric and material properties. Several concept missions have been developed for net capturing methods, the research for the applicability of this method is kept active by different institutions. More detailed information about this method and related research are given in *Review of Technologies and Missions* section. The highest TRL ever reached for this method is TRL-6.

4.2.3 Rigid Capturing Method

The rigid capturing method can be evaluated under *impact energy dissipation category* since as soon as the mechanical interaction is ensured between the chaser and target satellites, impact energy occurs on the chaser satellite. This operation is needed to achieve robust capturing because both objects are rigid, and any misalignment of the contact between the chaser and debris can push the debris far away from the chaser's rigid capturing mechanism, especially in case of the object is tumbling at high angular velocity [142]. Therefore, the rigid capturing method is more applicable for cooperative targets that have a docking port/mechanism [143]. After completing the capturing phase, the chaser satellite can carry the target satellite anywhere in space, to the atmosphere or an outer orbit. Several studies vary from simulation to experiment level, conducted to research the applicability of rigid robotic capturing systems for space debris mitigation problems. Any rigid capturing mechanism needs to be lightweight, easy to control, and compatible with the varying topology of space debris [144]. In the literature, there are several rigid robotic system designs from single-arm to multiple arms [145], in which the control strategy of multiple arms to catch the debris are collaborative. Multiple arms are controlled by more sophisticated control system approaches, such as sliding mode control, and adaptive control [146], compared with control system approaches for single-arm robotic capture. For single arm rigid capturing methods, mostly well-known PID control approach is enough to achieve position and velocity control of the end-effector [147]. In some cases of multiple rigid robotic arms usage, one of the arms is used to catch the debris, whereas the other arm is used for manoeuvring purposes and create rotational and translational movements in space [148]. On another point, there is ongoing research for autonomy and teleoperation of rigid capturing mechanisms in space [149]. However, most of these works cannot go beyond the theoretical level since it is tough to realize sophisticated rigid capturing scenarios in frictionless space conditions.

A tentacle-like structure was proposed by ROGER project of ESA [150]. One of the scopes of ROGER project was to design a rigid capturing system with a tentacle design to get the first interaction with uncooperative space debris in the geostationary orbit. ROGER aimed to create a basic research infrastructure for this capture mechanism. The geostationary orbit is critical, since many commercial and military telecommunication satellites exist in GEO. The goal was to carry the debris to outer orbit after a successful catch. However, high TRL never reached the project since it was concept research. TRL-4 is achieved at the end of the project.

One problem of rigid capturing methods is to get a robust mechanical interaction with a fully rigid structure in space since rigidness creates a lack of appropriate impact energy dissipation in a friction-free environment. In other words, it is tough to catch a rigid object with a rigid structure in an environment that has no friction [151], [152].

4.2.4 Flexible Capturing Method

The flexible capturing method can be evaluated under *impact energy dissipation category* since the capturing mechanisms of this method decrease the impact energy of the debris at the first contact. Several flexible capturing mechanisms fit with the scope of this method, such as shape memory alloy capturing mechanisms or pneumatic capturing mechanisms [153]. Verification and validation processes of pneumatic capturing mechanisms have given satisfying results for on-ground conditions, yet the performance is still questionable for the zero-gravity condition of space. Moreover, the air consumption in space is critical and needs to be limited due to the necessary air consumption of the propulsion system. Therefore, the industry is inclined to use shape-memory-alloy-based capturing mechanisms as a flexible method in space. The actuation of this flexible capturing system is realized by the electrical voltage difference applied to the shape memory alloy material. The capturing mechanism made of shape memory alloy material fully complies with the debris during the capturing phase and reduces its impact energy. During this coherence, the chaser satellite absorbs the impact energy of the debris. After the full capture is ensured, the debris can be moved into the atmosphere or outer space. The recent advancement of shape memory alloys is becoming a hot topic in the material science discipline. The actuation of the mechanical structures made of this kind of material does not require a considerable high-power consumption. In other words, energy consumption is a critical matter for every space application, so that these materials are excellent candidates for space debris capturing mechanisms since the structures that are made of shape memory alloys can easily be re-shaped by temperature or electrical potential gradient [154]. The most advanced study conducted for this topic is MEDUSA. MEDUSA has arms that can grasp any object with flexible structures actuated by an electrical signal. When a simple electrical signal triggers the circuits consisting of nitinol wires of MEDUSA, the arms of MEDUSA start to change their topology and grasp the space debris [123]. Several experiments were conducted in ground conditions for MEDUSA, and the results were satisfying in terms of robustness of the mechanical interaction. Another advantage of using shape memory alloy material for space applications is that since it can be controlled either open-loop or closed-loop very effectively, the computational complexity of the control system is manageable [155], [156]. No flexible capturing method based mission has been organized yet, and the concept has low TRL, which is TRL-4. However, the method is promising since there is much ongoing research for the flexible capturing method, as given in the above references.

4.2.5 Other technologies

In addition to the previously mentioned concepts, some technologies are being used as part of the concepts classified as ET2, such as adhesive material technology or tentacle design architecture. For example, gecko-inspired adhesive pads or voltage induced electro-static adhesion props can be assembled on the end-effector of both rigid and flexible capturing mechanisms [126]. The tentacle-like design may consist of multiple joint-link couples with rigid robotic arms or flexible robotic arms. Fig. 5 shows examples of robotic grippers with adhesive technology.

One of the most troublesome tasks in space is to achieve a robust mechanical interaction between the chaser and target satellites. Grasping tasks using robotic arms/grippers are not easy, and the infrastructure needs to be supported by dedicated GNC hardware and software components. In this sense, adhesive materials have been proposed to hit and stick on the surface of the debris and slow down its velocity [157], [158]. The first adhesive technology for ADR was proposed by Astroscale with the idea of using the technology to reduce the complexity of the mechanical interaction or to de-tumble the debris before the capturing processes are initiated [48].

The JPL of NASA proposed another use of the adhesive technology. They developed a gecko-like adhesive material for uncooperative space debris [159], [125]. The tests of this product were conducted in parabolic flights and gave satisfactory results. However, despite the promising results, no mission that uses adhesive material has been organized yet. The technology has low TRL (TRL-4). Nevertheless, the horizon for this technology is very promising since the research of this type of material is ongoing for many different space applications. Moreover, any adhesive material type can be combined and integrated with different space-related material and structure types to synthesize hybrid concepts with higher TRL. For instance, an adhesive material can support shape memory alloys or tentacle-like structures.

4.3 Methods ET3: neutral energy balance

Energy Transfer Class 3 includes methods where the first interaction between the chaser and target satellites is perfectly isolated in terms of energy transfer until they become a single integrated mass. During the first interaction, there is no need on dissipating impact or potential energy.

The only example that has been developed under this category is the magnetic capturing method. In magnetic capture, the first interaction between the capturing system and the debris occurs without changing the potential energy and without an impact energy transfer. Instead, the kinetic energy of both the chaser and the target satellites is balanced to minimize the impact energy, i.e. the electromagnetic coils play a perfect compliance mechanism role, even though it is not a physical compliance mechanism.

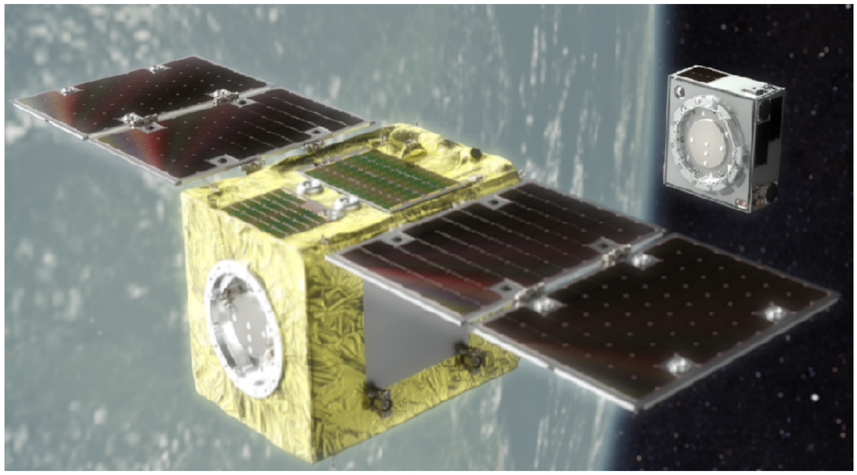


Figure 6: Example of existing ET3 Methods: Neutral Energy Balance. Magnetic capturing method [48].

4.3.1 Magnetic Capturing Method

When the magnetic coupling is generated between a ferromagnetic object and an electromagnetic coil, virtual spring and damping elements occur between two objects. By controlling the electromagnet using specific control algorithms, the coefficients of the damping and spring elements can be manipulated iteratively, which means that the transferred impact energy can be controlled iteratively [160], [161], [162] since the damping is the dissipative energy element. In contrast, the spring is the energy storage element in control theory. The chaser can both push and pull the target, which means that; by adjusting the sequence of the push/pull forces at high frequency, the impact of debris onto the chaser satellite will be minimized. One can say that; if the chaser pushes the target, the target pushes the chaser as well due to Newton's well-known 3rd law (when two bodies interact, they apply forces to one another that are equal in magnitude and opposite in direction). However, this opposite reaction force can be compensated by the propulsion system of the chaser satellite. As the name of the category refers to neutral energy balance, the kinetic energy of both chaser and target satellites is balanced to minimize the impact energy. In other words, the electromagnetic coils play a perfect compliance mechanism role, even though it is not a physical compliance mechanism

The magnetic force is only used for soft-capture/soft-docking of the debris when the close-proximity operation is achieved. The advantage of this method is the low possibility of crash and fracture since the virtual damping and spring elements generated by the magnetic field create a virtual cushion between two objects. However, the disadvantage of this method is that; either debris needs to be cooperative with a ferromagnetic docking port or uncooperative with a ferromagnetic body.

In recent years, magnetic systems have been extensively used in many applications, from clean-room design to robotic capturing. The magnetic system of ELSA-d mission, given in Fig. 6, uses the magnetic capturing method since the chaser satellite uses a unique magnetic coil to soft-capture/soft-docking the debris. ELSA-d consists of two satellites stacked together, a chaser designed to safely remove debris from orbit and a target satellite that serves as a piece of mock-up debris, was launched by GK Launch Services into a 550 km orbit on a Soyuz rocket from the Baikonur Cosmodrome in Kazakhstan on Monday, 22 March 2021, at 6:07 am (UTC) [48].

The chaser is equipped with proximity rendezvous technologies and a magnetic docking mechanism while the target, mimicking a defunct satellite, has a magnetic plate that allows docking. The chaser will repeatedly release and dock with the target in a series of technical demonstrations, proving the capability to find and dock with debris. Demonstrations include target search, target inspection, target rendezvous and both non-tumbling and tumbling docking. The highest TRL ever reached is TRL-6.

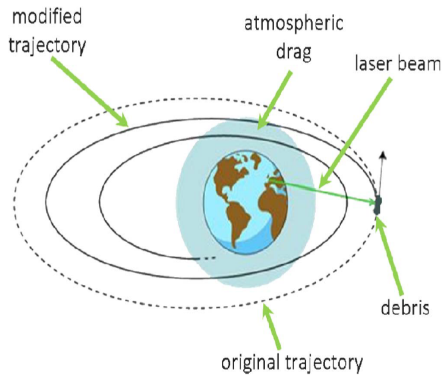
4.4 Methods ET4: destructive energy absorption

Energy Transfer Class 4 includes methods that aim at destroying the debris.

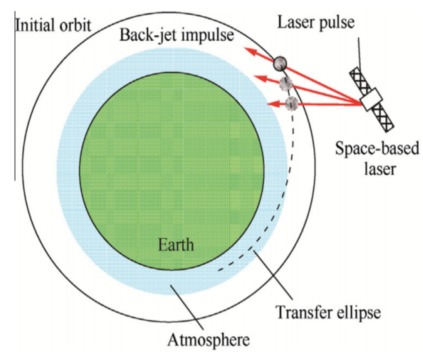
4.4.1 Laser Method

This method aims at destroying small debris targets in case of the laser beam has enough energy [163]. Examples of this method are given in Fig 7. For chaser satellites, one of the main problems in space is how to carry a battery that can produce enough energy to create a laser beam since the weight is a severe constraint for any space application. If the laser beam does not contain enough energy, or the battery is not capable of doing so, then to thoroughly burn the debris, the chaser satellite will change the debris' kinetic or potential energy depending on the orientation of the laser beam. Therefore the residual mass will keep on existing in orbit. However, the industry is inclined to thoroughly burn the debris in space using a laser system for future applications. State Key Laboratory of Laser Propulsion from China has been developing a space-based laser system, as assembled on a chaser satellite, that is capable of targeting debris whose diameter is up to 20 cm, and consisting of mostly aluminium, carbon, and iron-based materials [164]. They claim that for an aluminium debris particle with a 10-cm diameter, the required laser pulse energy to destroy the debris is 1 kJ.

On the other hand, the current de-orbiting applications of laser focus on changing the orbiting trajectory of the debris by sending a laser beam from an earth-based station. An example of this concept is the Project ORION (Orbital Debris Removal Using Ground-Based Sensors and Lasers)[165], [166]. In ORION, a ground-based system to shoot the debris is proposed. According to the team, a laser destruction system combined with a space debris detection system can work for a varying distance of space debris, between 1cm to 500 km.



(a) Ground-based laser system method [163]



(b) Space-based laser system method [164]

Figure 7: Examples of existing ET4 Methods: Destructive Energy Absorption. These methods aim at destroying the debris.

Ground-based laser methods contain many negative aspects, such as the possible interference of other objects between the laser beam and debris. Additionally, the laser's energy is not enough to melt the debris if the target is too big. In this case, the debris may be divided into several pieces or change its trajectory in an uncontrolled way. The Australian space company Electro Optic Systems is developing a pair of ground-based lasers to tackle small debris orbiting Earth [167]. Generally speaking, there are several difficulties to overcome for this method, such as debris topology and material dependency, high-energy consumption, or a possible collision/interfere risk with some other object in space. All these are crucial parameters for the chaser satellites orbiting in space. Currently, the technology has low TRL, which is TRL-4 and no laser system method-based mission has been organized yet [168], [169].

5 Review of Technologies and Missions

No uncooperative debris has been removed from any orbit yet. However, there are a few missions that push to achieve this goal. The most successful ones of these missions are summarized throughout this section and categorized according to our proposed *ET-class* (see Fig. 8). Most of the missions organized so far focus mainly on the potential and impact energy dissipation classes [170], [171], [172].

5.1 Missions ET1: potential energy dissipation

Within this section, we present the missions that correspond to ET1. Examples of the concepts are given in Fig. 9.

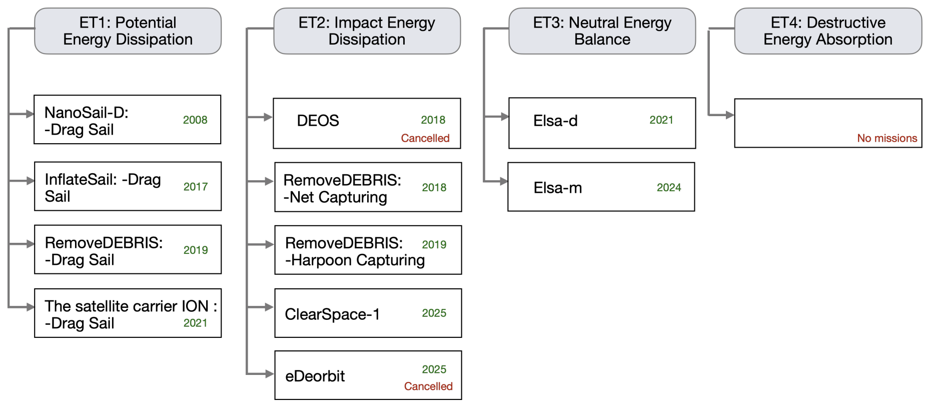


Figure 8: Space debris removal past and future missions classified according to the proposed *ET-class*.

5.1.1 RemoveDEBRIS - Drag Sail

RemoveDEBRIS was a satellite research and development project to demonstrate different ADR technologies, such as the net, the harpoon, and the drag sail concepts [173], [83]. The Surrey Space Centre led the mission, and the satellite was manufactured by Surrey Satellite Technology Ltd (SSTL). The platform was equipped with a net, a harpoon, a laser ranging instrument, a drag sail, and two CubeSats. Unique mechanisms were adapted to the platform to validate different ADR technologies. For example, to test the harpoon ADR concept, a target was assembled to the chaser satellite with a link; thus, it did not have a tumbling state, and no close-proximity operation was needed.

After end-to-end testing, the spacecraft was placed in an ISS cargo transfer bag and assembled with the CRS-14 SpaceX Dragon Spacecraft. The Dragon resupply mission with RemoveDEBRIS onboard was launched on April 2, 2018, arriving at the ISS on April 4 2018. The deployment of the satellite took place on June 20 2018. The satellite deployed a large sail, and the drag sail brought RemoveDEBRIS from the low orbital altitude of the space station into Earth's atmosphere to burn.

5.1.2 The satellite carrier ION - Drag Sail

In June 2021, an ADEO-N solar sail was mounted on the 220-kilogram 'ION Platform' from D-Orbit [174], which was launched on a Falcon9 by SpaceX. ION Platform is a space vehicle that can transport many satellites in orbit and release them into distinct orbital points, reducing the time from launch. After six months of the launch, the ADEO-N will open its 3.5-square-metre drag sail, and the spacecraft will start to de-orbit. An in-orbit verification and validation of a bigger ADEO-L drag sail is planned for a future EU mission.

5.1.3 NanoSail-D - Drag Sail

The NanoSail-D mission was launched onboard a Falcon 1 rocket in August 2008. The overall system contained a sail subsystem integrated into a CubeSat-2U for a main CubeSat 1U body. Due to budget limitations, no onboard camera or sensory infrastructure was installed to image the deployed sail or measure the attitude dynamics. Unfortunately, Falcon-1 rocket malfunctioned during the launch, and the NanoSail-D could not be deployed [175]. NanoSail-D was not dedicated to showing debris removal properties. Instead, it was planned to test the navigation capabilities of the sail.

5.1.4 LightSail - Drag Sail

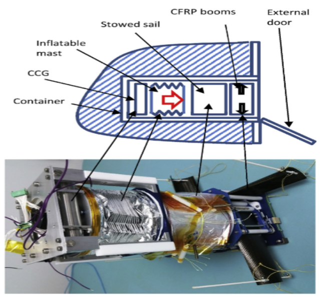
The LightSail programme organized by The Planetary Society includes two missions, LightSail-1 and LightSail-2. LightSail-1 was launched on 20 May 2015, and the mission objectives were to test preliminary and straightforward CubeSat functionalities about the solar sail deployment process. The avionics part was assembled into a 1U volume, whereas the solar sail part was integrated into a 2U volume. After the success of LightSail-1 mission, LightSail-2 mission was planned to be organized to test more advanced scenarios, such as active control of the solar sail. The active control was achieved using a single-axis momentum wheel and magnetic torque tools. Compared with the Nano-Sail-D mission, LightSail missions have sophisticated sensory and actuation infrastructures, such as onboard cameras, momentum and magnetic actuation parts. The Planetary Society announced that LightSail-2 mission success on 31 July 2019 [176]. LightSail-2 was not dedicated to showing debris removal properties. Instead, it was planned to test the navigation capabilities of the sail.

5.1.5 InflateSail - Drag Sail

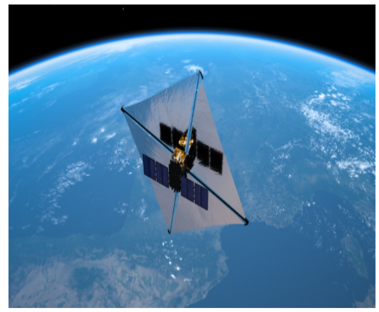
InflateSail mission was a preliminary part of RemoveDEBRIS - Drag Sail mission. InflateSail mission was organized by Surrey Space Centre and the Von Karman Institute. The total weight of the 3U CubeSat was 3.2 kg and equipped with a 1m long inflatable mast and a $10m^2$ drag sail. InflateSail successfully demonstrated the de-orbiting process of a CubeSat in LEO for the first time using European drag-sail technologies [177]. It was launched at 505 km altitude on 23 June 2017 and de-orbited 72 days after the deployment of the drag-sail.

5.2 Missions ET2: impact energy dissipation

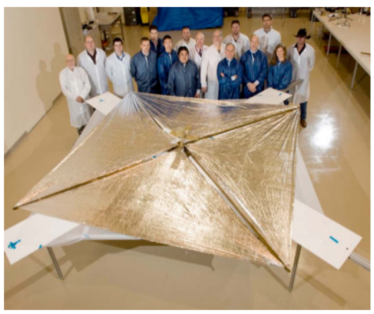
The missions classified in the impact energy dissipation category are given in this section. Examples of the concepts explored in the missions are given in Fig. 10.



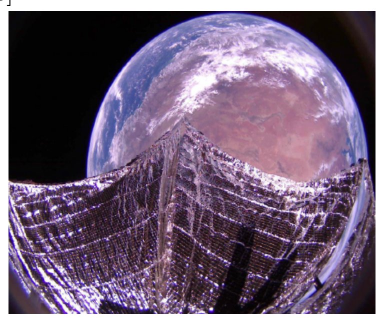
(a) RemoveDEBRIS - Drag Sail [173]



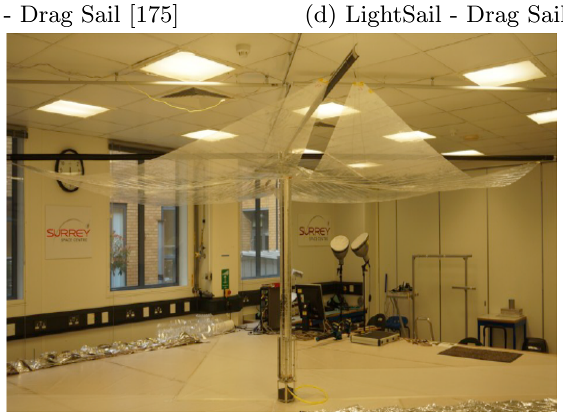
(b) The satellite carrier ION - Drag Sail [178]



(c) NanoSail-D - Drag Sail [175]

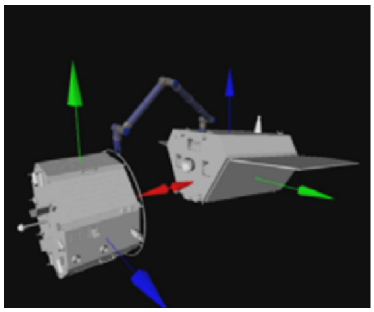


(d) LightSail - Drag Sail [176]

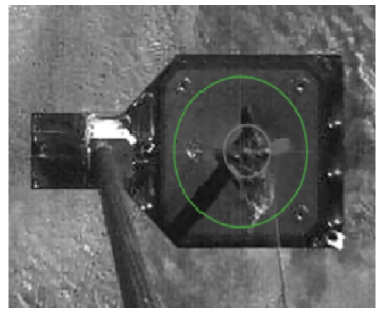


(e) InflateSail - Drag Sail [177]

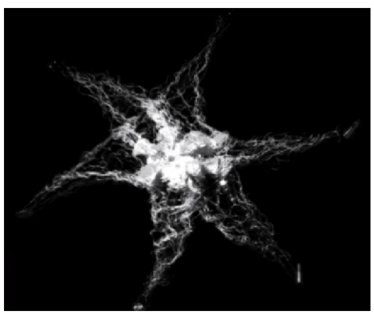
Figure 9: Examples of ET1 Missions: Potential Energy Dissipation.



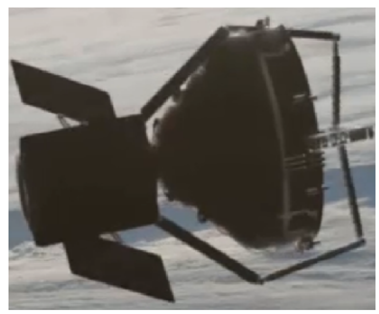
(a) DEOS [179]



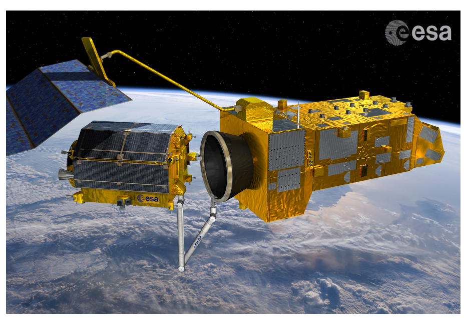
(b) RemoveDEBRIS - Harpoon capturing [173], [83]



(c) RemoveDEBRIS - Net capturing [173], [83]



(d) ClearSpace-1 [180]



(e) e.Deorbit [181], [182], [183], [178]

Figure 10: Examples of ET2 Missions: Impact Energy Dissipation.

5.2.1 DEOS

DEOS (Deutsche Orbitale Servicing Mission) mission can be evaluated under *impact energy dissipation category* since the idea was to use a rigid robotic arm to get interaction with the target satellite and manipulate it in the orbit [184]. This operation requires intensive impact energy dissipation at the first contact. DEOS was organized by DLR (German Space Agency). It was a mission to practice conducting tasks, such as maintenance or debris removal. DEOS consisted of two satellites, *a client* and *a servicer*. The client acts as the satellite requiring maintenance or removal. The servicer carries out the duty on the client and uses a robotic manipulator controlled remotely [179]. The two satellites were to be launched together and brought into orbit at 550 kilometres height. DLR started the DEOS mission in 2012, and three phases were completed. Phase 0 - Concept phase, exploring different systems and mission concepts. Phase A - Feasibility phase, where the technical aspects and uncertainty risks were researched, and Phase B - Preliminary Design Definition phase, where technical requirements of the system were defined. DEOS was expected to be launched in 2018, but the project was cancelled after Phase - B because of technical difficulties.

5.2.2 RemoveDEBRIS - Net and Harpoon Capturing

RemoveDEBRIS was deployed in June 2018 and focused on demonstrating different ADR technologies.

The Net demonstration: A CubeSat named DebrisSat 1 deployed a balloon meant to simulate a piece of space debris [173]. From a short distance, approximately 7 m, the RemoveDEBRIS satellite attempted to capture the debris with a net and then move this package to enter Earth's atmosphere and burn up. Airbus produced the net. On 16 September 2018, it demonstrated the net ability to capture a deployed simulated object. The outputs of this demonstration proved that the net-capturing method could effectively catch space debris from a short distance.

The Harpoon demonstration: On February 8th 2019, SSTL demonstrated the RemoveDEBRIS harpoon mission, fired at 20 meters per second speed, penetrating the target extended from the satellite on a 1.5 m rigid boom. The experiment gave satisfactory results in terms of successful space debris piercing [83]. However, it is important to mention that the target was connected to the satellite with a rigid link in the experiment, which means that it was cooperative in terms of position stability. On the other hand, the target consisted of metallic alloys, which opens the question of whether the harpoon method can pierce different materials, such as composite materials. Because of this, more demonstrations are required to analyze the system's viability to capture targets made of different materials or having different geometries or angular velocities.

5.2.3 e.Deorbit

In 2012, ESA launched the Clean Space Initiative to tackle the environmental impact of the space debris problem [181], [182]. Since the beginning, a central focus of Clean Space has been decreasing space debris through “design for destroying”. As time goes by, the ESA Clean Space Initiative has focused on both in-orbit servicing and ADR topics and started to work on e.Deorbit mission. In e.Deorbit mission, 1,600-kilogram spacecraft was to be launched into orbit at an altitude of 800–1,000 kilometres (LEO). Once in orbit, the spacecraft would rendezvous with the defunct satellite Envisat which is in an unknown condition, uncooperative, and probably tumbling at high angular velocity.

Within the preparation phase of the e.Deorbit mission, several concepts were analyzed and studied, 1) a robotic arm-based solution that catches the target, 2) a flexible link-based solution (capturing the target using a net or a harpoon). From this point of view, e.Deorbit mission can be evaluated under *impact energy dissipation category* since all methods include impact energy dissipation requirement at first interaction. The launch was planned for 2025 onboard a Vega launch vehicle. However, the funding of the mission stopped in 2018. Instead, ESA member states now focus on the ClearSpace-1 mission, which is now under the development phase.

5.2.4 ClearSpace-1

In 2019, the ClearSpace start-up was selected by ESA to lead the first ADR mission by 2025 [180]. In 2025, ClearSpace will launch the first ADR mission called ClearSpace-1. It will rendezvous, capture, and de-orbit to burn up in the atmosphere the upper part of a Vespa (Vega Secondary Payload Adapter), which was left in a ‘gradual disposal’ orbit (altitude 801 km by 664 km). There will be no de-tumbling or separate docking mechanism. The rigid robotic capturing mechanism will include tentacles for the first mechanical interaction with the space debris. The tentacles will encircle the debris and align with it before dragging it into the lower levels of the atmosphere.

ClearSpace-1’s Vespa target is 112 kg (classified as a small satellite). Its compact shape and homogeneous geometry make it an appropriate first step before progressing to larger, more advanced captures by the subsequent missions. The future goal of ClearSpace-1 mission is to achieve multiple capturing operations in a single mission. The ClearSpace-1 mission will be launched into a 500 km LEO for initial feature tests before moving to the target orbit for rendezvous and capture. In the end, the chaser combined with the Vespa target will de-orbit and burn in the atmosphere.

5.3 Missions ET3: neutral energy balance

This section presents Elsa-d and Elsa-m missions classified in the neutral energy balance category. Examples of the concepts explored in the missions are shown in Fig. 11.

5.3.1 Elsa-d

The mission will validate an innovative soft-capture/soft-docking mechanism, as well as the CONOPS (Concept of Operations) for capturing and removing non-tumbling and tumbling targets from orbit. The target satellite has a DP (docking plate) that can be used to interact with the magnetic coil of the chaser satellite. Moreover, the chaser satellite has an autonomy mode, which means that the chaser satellite is able to operate either by itself or receiving commands from the ground. If needed, different algorithms can be uploaded from the ground station to the chaser satellite during the operation phase. The chaser minisatellite's weight is 180 kg, the target microsatellite's weight is 20 kg.

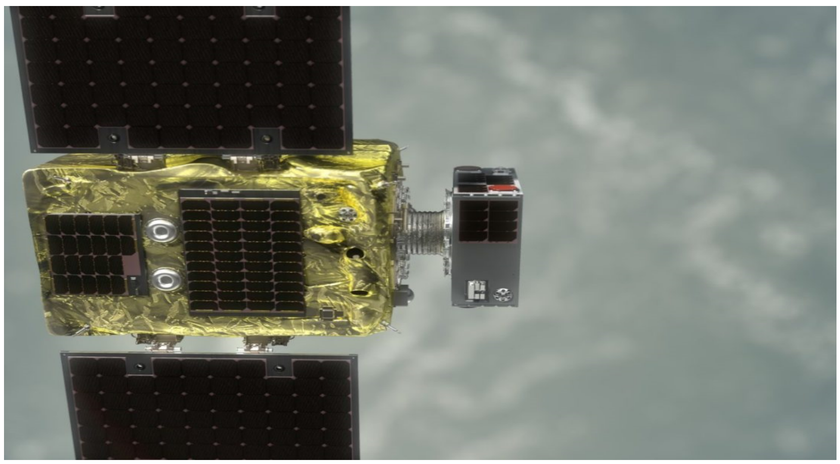
The target satellite incorporates S-band communications, GPS positioning, a 3-axis control system and a laser retro-reflector. The constellation platform is designed for 5-100 kg range operational missions. It also carries an HD camera and lighting to record the capture sequences during the eclipse in the absence of light. ELSA-d mission was launched by GK Launch Services into a 550 km orbit on a Soyuz rocket from Kazakhstan on 22 March 2021, at 6:07 am (UTC), and still is in operation phase. The data flow, such as odometry, energy consumption, trajectory data flows, is being realized between the satellite and ground station. Nevertheless, the data recorded by the embedded devices will be investigated during the post-operation phase after the mission ends. The outputs of the mission have not been shared with the public yet.

5.3.2 Elsa-m

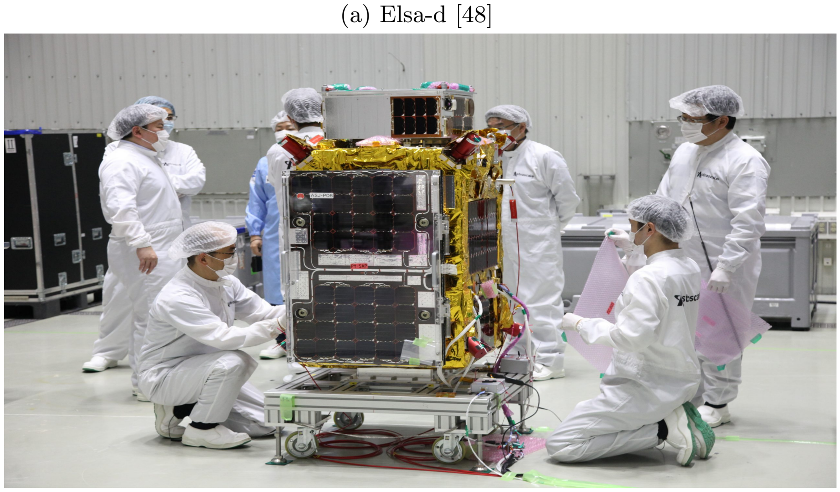
In May 2021, Astroscale signed £2.5 M agreement for research and development of space debris removal technology innovations with OneWeb [48]. The communication infrastructure of Elsa-m mission will be supported by OneWeb and will be based on 5G technology. Within ELSA-m, the technology to tackle multiple retired satellites in a single mission will be verified and validated, and it is claimed that the technology will be ready to use by 2024. This multi-client strategy will reduce launch and operation costs. Each constellation satellite will carry a passive magnetic docking port (DP) consisting of permanent physical magnets. DP will be used to create a weak magnetic attraction force for the re-assembly of the chaser and target satellites, while the chaser satellite's magnetic coil system generates a magnetic field. Sophisticated control algorithms can drive the magnetic coil of the chaser satellite to create the appropriate magnetic field patterns. These control algorithms can be uploaded to the chaser satellite from the ground station even when the operation is on. In this way, the chaser satellite will catch multiple satellites in the constellation.

5.4 Missions ET4: destructive energy absorption

In this category, no mission has been organized yet. The concepts presented in Section-4.4 are still in low TRL.



(a) Elsa-d [48]



(b) Elsa-m [48]

Figure 11: Examples of ET3 Missions: Neutral Energy Balance.

6 Conclusion

The existing taxonomies approach the space debris removal problem from the point of view of the mechanism's structure, or whether the method is passive or active. However, many existing concepts depend on effective first interaction between the chaser and target satellites. Finding a way to dissipate and/or store the debris's potential energy and impact energy is vital to remove debris successfully. The study assists in understanding the SOTA in terms of existing debris removal technologies, their current state (TRL and missions), and on generating awareness on the importance of the first interaction between the chaser satellite and the debris, pointing out how different concepts handle this first interaction.

This paper presented a novel energy-based classification approach for space debris removal concepts and missions, named *ET-class*. It classifies the existing methods into four categories, according to how the energy between the chaser and target satellites is dissipated at first contact: ET1 Potential energy dissipation, ET2 impact energy dissipation, ET3 neutral energy balance ET4 destructive energy absorption. The industry is inclined to research and develop different approaches using several technologies, as pointed out throughout the study. The missions classified in *neutral energy balance* and *impact energy dissipation* categories are the most recent and promising ones, as explained in the paper. However, varying technologies related to the space industry are under research and development phases, requiring intensive, multidisciplinary perspectives and massive research funds. Moreover, the cost/efficiency curve complicates the situation in finding concrete research direction and appropriate funds to investigate several technology fields. Companies, institutions, and organizations have difficulties having the budget to flourish their research on new technologies. Thus, the future landscape of space debris removal is still not very clear.

The authors believe that the proposed energy-based *ET-class* will give insights to companies, institutions, and organizations for future missions and help to understand what are the critical points for successful space debris removal operations. ET-Class will allow understanding the space debris removal research trends and the missing points in terms of the energy transfer at the first interaction between the chaser/de-orbiting kit and target satellites.

Author Contributions

Conceptualization: B.C.Y., C.M., M.H.D., G.R., J.Z. and M.A.O.M.; Methodology: B.C.Y., C.M., M.H.D., G.R., J.Z. and M.A.O.M.; Formal Analysis: B.C.Y., C.M.; Investigation, B.C.Y., C.M., M.H.D.; Writing Original Draft Preparation, B.C.Y.; Writing Review and Editing, B.C.Y., C.M.; Funding Acquisition, G.R., J.Z. and M.A.O.M.; All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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