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MASTER THESIS

Space Debris as an international safety issue. Case studies in active removing techniques.

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ΕΘΝΙΚΟ ΚΑΙ ΚΑΠΟΔΙΣΤΡΙΑΚΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΘΗΝΩΝ

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ΔΙΙΔΡΥΜΑΤΙΚΟ ΠΡΟΓΡΑΜΜΑ ΜΕΤΑΠΤΥΧΙΑΚΩΝ ΣΠΟΥΔΩΝ
"ΔΙΑΣΤΗΜΙΚΕΣ ΤΕΧΝΟΛΟΓΙΕΣ, ΕΦΑΡΜΟΓΕΣ και ΥΠΗΡΕΣΙΕΣ"

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

Τα Διαστημικά Υπολείμματα ως διεθνές ζήτημα ασφάλειας. Μελέτη περιπτώσεων ενεργητικών τεχνικών απομάκρυνσης.

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ABSTRACT

This thesis was conducted under the umbrella of the Department of Informatics & Telecommunication of the National and Kapodistrian University of Athens for the Postgraduate Program “Space Technologies, Applications and Services”. The aim of the thesis was to highlight the significance of taking timely action in an international level, for the space debris issue not to become a major threat against the operational space systems and the humans orbiting earth. Although the issue of space debris has occupied the scientific, technological and political world almost since the beginning of the space era, no substantial solution has yet been found either at a scientific, technological or political level. The following chapters provide an analysis of the space debris problem and present the technological, legal, and financial barriers to an effort to remove space debris. Then, the concept of security in space and the way it is affected by the existence of space debris is developed. At the same time, an analysis of the risk that governs space missions, both at the level of operation of space systems and at the level of human life in relation to the increase in space debris, is conducted. This analysis shows that the increase in space debris due to more space missions, as well as the onset of the era of space tourism, will be a strong risk factor if immediate measures are not taken. Then, at a technical level, the possibilities of locating and tracking space debris are presented, as well as the prospects of these technical systems. In addition, the future requirements for space debris detection and tracking, for space debris removal missions to be effective, are presented. Additionally, the main active space debris removal techniques studied and developed by space agencies and space companies are presented. Finally, a comparative study of space debris removal techniques is conducted by scoring four main criteria and a hypothesis of an optimal space debris removal technology is presented as a result. The analysis of the thesis shows the importance of making immediate decisions and taking the appropriate actions, so that space debris does not constitute a major risk factor for humanity as we know it today.

SUBJECT AREA: Space system engineering, international space safety, active space debris removal techniques, security in space

KEYWORDS: Space debris, active space debris removal, space debris tracking, space safety, space security, space threats

ΠΕΡΙΛΗΨΗ

Η παρούσα διπλωματική εργασία πραγματοποιήθηκε υπό την αιγίδα του Τμήματος Πληροφορικής & Τηλεπικοινωνιών του Εθνικού και Καποδιστριακού Πανεπιστημίου Αθηνών για το Μεταπτυχιακό Πρόγραμμα Σπουδών «Διαστημικές Τεχνολογίες, Εφαρμογές και Υπηρεσίες». Στόχος της διατριβής ήταν να αναδείξει τη σημασία της έγκαιρης ανάληψης δράσης σε διεθνές επίπεδο, ώστε το ζήτημα των διαστημικών υπολειμμάτων να μην γίνει μείζονα απειλή κατά των επιχειρησιακών διαστημικών συστημάτων και των ανθρώπων που βρίσκονται σε τροχιά γύρω από τη γη. Παρόλο που το θέμα των διαστημικών υπολειμμάτων έχει απασχολήσει τον επιστημονικό, τεχνολογικό και πολιτικό κόσμο σχεδόν από την απαρχή της διαστημικής εποχής, δεν έχει ακόμα βρεθεί ουσιαστική λύση ούτε σε επιστημονικό, ούτε σε τεχνολογικό, ούτε σε πολιτικό επίπεδο. Στα παρακάτω κεφάλαια γίνεται μια ανάλυση του προβλήματος των διαστημικών υπολειμμάτων και αναφέρονται τα τεχνολογικά, νομικά και οικονομικά εμπόδια που παρουσιάζονται σε μια προσπάθεια απομάκρυνσης διαστημικών υπολειμμάτων. Στη συνέχεια αναπτύσσεται η έννοια της ασφάλειας στο διάστημα και πώς αυτή επηρεάζεται από την ύπαρξη διαστημικών υπολειμμάτων. Ταυτόχρονα γίνεται μια ανάλυση του ρίσκου που διέπει τις διαστημικές αποστολές, τόσο σε επίπεδο συστημάτων, όσο και σε επίπεδο ανθρώπινης ζωής σε συνάρτηση με την αύξηση των διαστημικών υπολειμμάτων. Από την ανάλυση αυτή δεικνύεται ότι η αύξηση των διαστημικών υπολειμμάτων λόγω περισσότερων διαστημικών αποστολών, καθώς και το ξεκίνημα της εποχής του διαστημικού τουρισμού, θα αποτελέσει έναν ισχυρό παράγοντα κινδύνου εάν δεν παρθούν άμεσα μέτρα. Στη συνέχεια παρουσιάζονται, σε τεχνικό επίπεδο, οι δυνατότητες εντοπισμού και παρατήρησης των διαστημικών υπολειμμάτων, καθώς και οι προοπτικές αυτών των συστημάτων. Επιπλέον, γίνεται αναφορά στο ποιες θα είναι οι μελλοντικές απαιτήσεις εντοπισμού και παρατήρησης των διαστημικών υπολειμμάτων ώστε να είναι αποτελεσματικές οι αποστολές απομάκρυνσης διαστημικών υπολειμμάτων. Συνεχίζοντας, παρουσιάζονται οι κύριες τεχνικές ενεργητικής απομάκρυνσης διαστημικών υπολειμμάτων, όπως αυτές μελετώνται και κατασκευάζονται από διαστημικούς οργανισμούς και διαστημικές εταιρείες. Τέλος, διενεργείται μια συγκριτική μελέτη των τεχνικών απομάκρυνσης διαστημικών υπολειμμάτων μέσω βαθμολόγησης τεσσάρων κύριων κριτηρίων και παρουσιάζεται ως αποτέλεσμα μια υπόθεση βέλτιστης τεχνολογίας απομάκρυνσης διαστημικών υπολειμμάτων. Από τη ανάλυση της Διπλωματικής Εργασίας γίνεται αντιληπτή η σημαντικότητα του να ληφθούν άμεσα αποφάσεις και να γίνουν οι κατάλληλες ενέργειες, ώστε τα διαστημικά υπολείμματα να μην αποτελέσουν κύριο παράγοντα κινδύνου για την ανθρωπότητα όπως τη γνωρίζουμε σήμερα.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ: Σχεδίαση διαστημικών συστημάτων, διεθνής ασφάλεια, ενεργητικές τεχνικές απομάκρυνσης διαστημικών υπολειμμάτων, ασφάλεια στο διάστημα

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: Διαστημικά υπολείμματα, ενεργητική απομάκρυνση διαστημικών υπολειμμάτων, ασφάλεια στο διάστημα, διαστημικές απειλές

To my partner in life, Emina.
To my kids Thanos and Stella.

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They constantly asked me if I had finished studying so that we could play together, my son Thanos and my daughter Stella. They, every single time, were patient until I have finished studying and I thank them for being understanding and mature beyond their age. I hope, that through my paradigm, they will grow up loving knowledge and the process of learning new things every day, as their dad did.

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CONTENTS

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PREFACE

THESIS STRUCTURE

This Thesis is structured in six (6) chapters. The first chapter is an introduction to space debris issue providing insights in space debris itself, space debris and safety issues and space debris active removing techniques.

The second chapter provides a theoretical knowledge on what space debris really is and how it could affect space operations, goes deeper in the subject of safety in space operations, presenting the existing regulations and standards and addresses the obstacles in removing space debris, focusing mostly on technical, legal political and economic barriers.

The third chapter focuses on the risk that space debris poses on space operations and how the increase in space missions in the future will affect it, while the fourth and fifth chapters are providing the background for space debris tracking and space debris capture and removal methods respectively. For space debris tracking, laser ranging, image based, radar and adaptive optics tracking are more thoroughly presented.

For the space debris capturing, stiff connection and flexible connection space debris capturing methods are analyzed. Continuing to removal methods, drag augmentation, electro-dynamic tether, solar radiation force, contactless and contact removal methods are presented.

The sixth chapter constitutes a space debris removal method evaluation system proposal, that scores each Active Debris Removal method’s performance on four main frameworks. These are the political, legal, technical and economic frameworks.

1. INTRODUCTION

1.1 Space Debris

Space has, nowadays, become an exceptionally important exploration field for humanity. Most people acknowledge outer space as an empty space, when contrary, the scientific truth proves that space pulses with millions of artificial debris which impose a possible threat for their still working neighbors, meaning the satellites orbiting the earth and the humans orbiting the earth, either in the International Space Station or in other space missions. Counting from the beginning of the space era, over seven thousand rockets have been sent to space, putting their payloads in orbit. More than half of them are at Low Earth Orbits. The size of these objects is calculated to be between some mm to some meters, with European satellite Envisat being the the bigger [1]. As stated in the Decision of the European Parliament and of the Council for establishing a program to support space surveillance and monitoring, *"... Due to the growing dependence on space services, the ability to protect space infrastructure has become very important in our society. Any interruption of the operation of even a part of the space infrastructure could have a serious impact on the smooth operation of economic activities and the safety of our citizens and would impede the provision of emergency services ..."* [2]. The importance of the effort to protect satellite systems from space debris and find ways to limit them can, thus, be realized.

In order to reduce the risk of collisions, it is necessary to take initiatives to find satellite and space debris monitoring practices, to record their positions, to monitor their orbits, and when there is a risk of a collision, to have an early warning system of management bodies, in order to change their trajectory and avoid the possibility of collision. It is important to note that space debris can be maintained in orbit for quite a long time before being destroyed by entering the lower part of the Earth's atmosphere. More specifically, as reported by Morin and Richard, depending on the height of the orbit, space debris can remain from a few days (altitude ≅200km) to almost eternal in geosynchronous orbits (altitude ≅36000km). The maximum density of space debris in LEO is found at an altitude of about 885km, where they can remain for centuries [3].

It is also necessary to realize that space debris is not only the result of unused satellite systems or launch failures, but also of collisions between space debris and active satellites, which is called "Kessler Syndrome". According to this, when two space systems or a space system with a space debris collide, a chain reaction of collisions is produced, during which space debris are produced at an exponential rate, since after a collision of two space bodies a plethora of fragments is produced, which in turn are responsible for multiple collisions and so on [4].

Some of the most typical cases of collisions between space debris and space systems are the collision of the Space Shuttle Challenger with a fragment in 1983 [5], during which there was a crack in its windshield. It was later found to be a small, 0.2-mm flake of paint, probably from a spent rocket, the collision of a piece of an old Ariane rocket with the still then operational satellite CERISE, which occurred on 24 July 1996 [6], and the destruction of the American satellite Iridium in 2009, after its collision with an out of operation 16-year-old Russian satellite [7].

1.2 Space Debris and Safety Issues

One worrying fact is how the international community addresses the issue. The only legally binding agreements that may be relevant to the problem of space debris are the 1967 Outer Space Treaty (OST), the 1972 Liability Convention (LC) and the 1975 Registration Convention (RC). However, none of the above makes any explicit reference to the term "Space Debris", nor does it delegate responsibility to states for their removal [8].

That means that there does not exist an agreed legal definition of space debris. According to the Inter-Agency Space Debris Coordination Committee (IADC) orbital debris are *"… all man-made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional..."* [9]

Thus, it is not clear whether states launching spacecraft are legally liable for possible consequential damages, which may be caused by the space debris they generate. At this point it is necessary to mention that in Article 3 of the Liability Convention - LC of 1972, it is stated that the state undertaking the launch is responsible for possible damage to a space system or to people in a space vehicle. However, it is not clarified, who is responsible if during a space debris removal mission, more debris are created by mistake [10]. It is now understood that in addition to the scientific coverage of the problem, there is a need for international intervention, creating clear rules through its legal treatment for the problem of space debris.

This thesis will cast some light on the legal issues that are coming with space debris removal missions and will investigate what would be a good option and the necessary legal steps towards a more complete legal environment into which the space fairing nations and the space industry will feel legally free and protected to launch their space debris removal missions.

What is more, it is of great importance to face the real and imminent threats that space debris poses to all operating spacecrafts orbiting earth and more importantly to the humans in orbit. These threats are of safety and security nature. In the following chapters, a distinction between the two is made and the safety issues that are emerging from space debris are researched more thoroughly. Safety is impacted directly by the number of the space debris orbiting the earth. This number is only growing and what is more this growth will be exponential in the upcoming years due to more satellite launches, the launches of formation satellites and the commercialization of space travel. For now, the only measures that can be taken are the end-of-life disposal and the collision avoidance maneuvers. However, these measures will fail to accomplish its protective to the space environment goals in the future and will become inadequate, thus space debris removal techniques seem to be the most promising way of mitigating the risk that space debris poses.

1.3 Space Debris and active removing techniques.

The importance of reducing space debris has been well understood by countries that have or intend to have an active space presence. In addition, services such as the US DARPA (Defense Advanced Research Project Agency) [11] are working on reducing and removing space debris. However, it was not until 2007 that a text of the Space Debris Mitigation Guidelines was signed at the United Nations General Assembly [12], which concerned the conduct of scientific research and discussions on the legal aspects of the issue, both nationally and internationally [1]. Some of the scientific research has yielded results in the construction of active space debris removal systems. These results have not yet brought operational debris removal missions due to the fact that such missions are quite complex and face bargains in the legal, financial and technological field.

These active space debris removal techniques are proposed and developed by governmental organizations, established space companies, governmental organizations and startup companies working in the “new space” environment. There are several techniques and technologies that are proposed and tested, the end result, however, is yet to be proved in the active field of space environment. The removing techniques, that will be thoroughly researched in next chapters, use tentacles, electromagnetic tethers, nets, harpoons and other technologies to catch the space debris and contact or contactless methods to de-orbit it.

To successfully remove space debris, it is firstly needed to find and track it. For now this is mostly done by United States radar and telescope systems, which, however, are becoming inadequate not only due to their inability to track small pieces of space debris (<10cm), but also due to the accuracy that is needed for an active space debris removal mission, which these systems do not have for now. This means that either the existing systems need to be improved, or new ones need to be produced.

After the space debris tracking and removal methods are developed there will be a need for international agreements on how these technologies will work in real life, with the legal and geostrategic issues having been solved in the first place. What is more to be discussed, is the way that space fairing nations will ensure that these technologies will not be used as hostile acts from a nation to another. All of the above are addressed with details in the next chapters.

2. LITERATURE REVIEW

2.1 Space debris

2.1.1 Origin of Space debris

The largest sources of space debris in orbit are natural and man-made. Natural ones refer to meteorites and dust. Anthropogenic refers to inactive space systems, mission remnants, launchers, explosive/ defective fragments, collisions between space systems, and even deliberate explosions for anti-satellite weapons (ASAT) [1]

More specifically, micrometeorites are very small pieces of rock, which move at extremely high speeds in space and are remnants of larger rock formations and dust, created at the beginning of the solar system. They usually weigh less than one gram and are found in orbit around planets or between planetary orbits. The launching of satellites or other loads is done by rockets, which in order to place them in low earth orbit or higher, use at least two stages of propulsion. The first stage can be reusable, so that it returns to earth, or non-reusable, thus it burns in the atmosphere. The second and / or third stage are fired into space and remain there after their use as space debris.

According to "Kessler Syndrome", their possible collisions with other space debris create multiple remnants. In addition, satellites that have come to their operational life end due to the expiration of their operational time or due to malfunction, may contain fuel. Sunlight or possible collisions with micrometeorites weaken the protective covers, resulting in fuel leakage and subsequent explosion, which in turn causes additional space debris. Table 1 shows the recorded catastrophic satellite losses, the causes of the disasters, and the number of observable space debris due to them. Finally, the United States, Russia, China, and most recently India, have conducted anti-satellite missile tests. These tests have been instrumental in generating potentially hazardous space debris [1].

Table 1. Failures of satellites and other objects that led to large production of space debris [1]

Common Name	*Catalogued Debris*	*Debris in Orbit*	*Year of break-up*	*Break-up Altitude*	*Cause of Break-up*
Fengyun - 1C	3216	2987	2007	850 km	Collision
Cosmos 2251	1559	1371	2009	790 km	Collision with Iridium 33

STEP 2 Rocket Body	710	58	1998	625 km	Accidental Explosion
Iridium 33	567	487	2009	790 km	Collision with Cosmos 2251
Cosmos 2421	509	0	2008	410 km	Unknown
SPOT 1 Rocket Body	492	32	1986	805 km	Accidental Explosion
OV 2-1/LCS 2 Rocket Body	473	35	1965	740 km	Accidental Explosion
Nimbus Rocket Body	375	245	1970	1075 km	Accidental Explosion
TES Rocket Body	370	111	2001	670 km	Accidental Explosion
CBERS 1 Rocket Body	343	178	2000	740 km	Accidental Explosion

2.1.2 Size of Space Debris

Due to the extremely high speed and consequently high momentum of space debris, even very small pieces can be a danger in case they collide with a space system. Figuratively speaking, an object of mass 80gr that performs an orbit at an altitude of about 300km (LEO), has kinetic energy corresponding to the energy produced during the explosion of 1kg TNT [1]. As mentioned above, the population of space debris orbiting the Earth is capable of causing significant damage to operating satellite systems. Space debris, according to their size, is divided into three main categories, as shown below [13]:

Category 1. Size greater than 10 cm, which can be detected by the US Air Force Space Surveillance Network (SSN).

Category 2. Size from 1cm to 10cm, which cannot be detected.

Category 3. Size from 1mm to 1 cm.

It can be easily understood that damage to satellite systems can be avoided if the location of the space debris is known. Category 1 debris is the most hazardous due to its size. The US Space Surveillance Network (SSN), uses optical and radar technology supporting the Joint Space Operations Center's (JSpOC) mission which is the detection, tracking, identification, and cataloging all objects coming from earth and now orbiting it [14]. It is capable of detecting space debris larger than 10cm in LEO and bigger than 30cm in GEO. It is shown that with current technology, only a portion of space debris can be detected and observed to prevent major disasters. In addition, it is necessary to realize that fragments smaller than 10 cm, which cannot be detected by modern means of observation, can create very serious or catastrophic problems in satellite systems [13]. Table 2 shows the number of estimated and observable quantities of space debris per size, while Table 3 shows the risk of damage depending on the size of space debris.

Table 2. Quantity of Space Debris per size [1].

Size	***Quantity of Space Debris***
<1cm	128,000,000
1-10cm	900,00
>10cm	34,000

Table 3. Risk of damage depending on the size of space debris [7].

Category	***Size***	***Potential risk to satellites***
Trackable	>10cm	complete destruction
Potentially Trackable	>1cm	complete to partial destruction
Untrackable	<1cm	Degradation, loss of certain sensors or subsystems

2.1.3 Space Debris Orbits

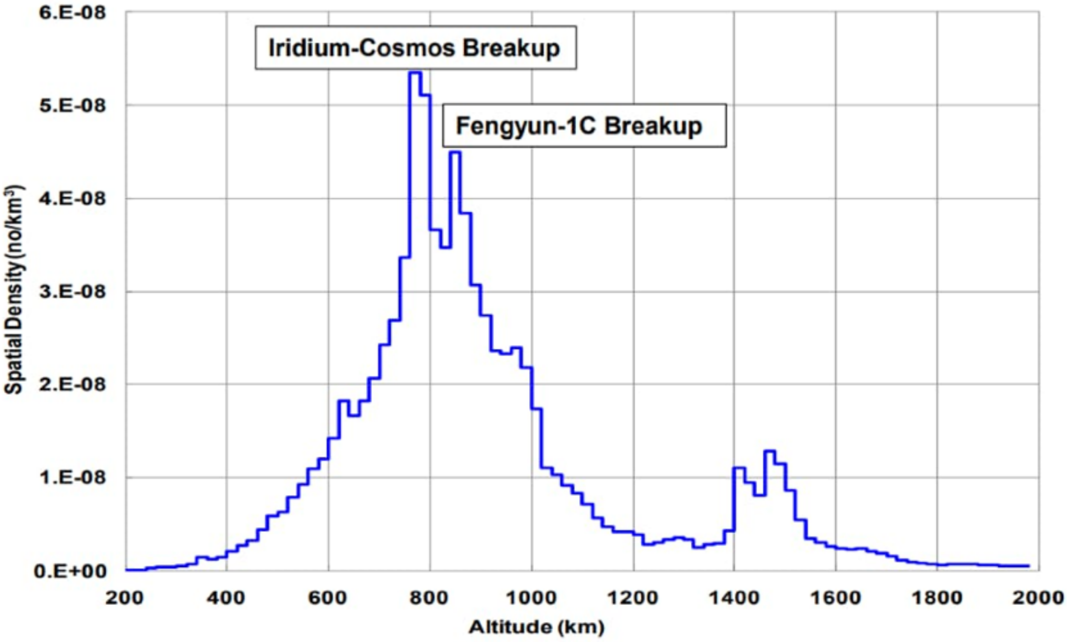
According to Mullic et al., 2019 [1], the orbits in which space debris moves, could be divided into two main categories. The low earth orbit (LEO) on its own and in aggregate, the geostatic or geosynchronous, interplanetary transport orbits and geostatic transport orbits.

More specifically, the majority of space debris is observed in LEO. Therefore, the risk of collisions is higher than on other orbits. Before 2007, most space debris were junk from space missions. The collision of the Iridium 33 with the Cosmos 2251 in 2009 [15], as well as China's anti-satellite missile tests in 2007 added a significant amount of debris to these heights. At these heights, however, the friction created by the atmosphere helps to reduce the velocity of the residues and their re-entry and incineration in the denser parts of the atmosphere, resulting in a kind of "self-cleaning process" of the LEO and for this reason, the ISS has been placed on a 408km high orbit.

For the orbits of the second category it is pointed out that the same phenomenon of natural self-cleaning is not created, due to the very small effect of atmospheric friction at these altitudes. Even at these altitudes, however, atmospheric disturbances, radiation pressure, and solar winds can potentially reduce the amount of space debris that enters and gets destroyed at the densest parts of the atmosphere, which can take even hundreds or thousands of years, as shown in Table 4. Many telecommunications satellites in geostationary orbits have intersecting orbits, which poses a potential risk of collision. The speed of the collision, however, and the corresponding negative results are reduced, since the speed of rotation at these altitudes is of the order of 1.6km / s. As a precautionary measure, the International Telecommunication Union (ITU), which is the main controlling authority, requires that it be possible to exit orbit or enter a “graveyard” orbit after the operational life of the satellites. The "graveyard" orbit is a trajectory a few hundred kilometers above the geostationary orbits used, so the chances of a collision with active satellites are very small. This solution is chosen when the change in velocity needed to transport a decommissioned satellite out of orbit and burn up in the atmosphere is greater than that required to move to a “graveyard” orbit [1]. Graph 1 shows the distribution of space debris in orbit, depending on the orbital altitude.

Table 4. Life time of objects in LEO at four distinct altitudes [7].

Orbital altitude	*Life time of objects*
200 km	1 to 4 days
600 km	25 to 30 years
1000 km	~ 2000 years
2000 km	~ 20000 years



Graph 1. Spatial density of space debris in reference to the orbital altitude [1]

2.2 Safety in Space Operations

In space operations, human life protection and critical infrastructures' integrity are of utmost importance. In order to achieve this, the spacefaring nations worldwide shall try their best to guarantee safety in every space mission, whether it is exploratory, commercial, manned, scientific, unmanned or military. Space safety could be defined as: *"... the effective mitigation or complete freedom of human or natural conditions that could cause harm to a human in space, or a critical and/ or high value space system..."* [16]

The terms space safety and space security need to be distinguished from the early beginning, due to the fact that in some languages, i.e. Greek, the same term is used for both, something that many times lead to confusion. There are various definitions.

According to Bowen, 2014 [17] *"...Space safety is a concept similar to space security, but the focus is placed on the measures to accomplish safer conduct in space activities by various methods..."* According to Pelton, Sgobba and Trujillo, 2020 [16], the term safety refers to threats imposed by errors in the design process, errors caused by humans, technical malfunctions, natural hazards, that are nonvoluntary in nature, while security refers to threats that are aggressive and voluntary in nature, meaning ASAT weapons. As much as twenty-three astronauts and cosmonauts have died in duty since the beginning of the space era. The risk being around 1 fatality in 100 space flights is enormous comparing to civil aviation where the associated risk is approximately 1 in 10 million flights in the U.S [16]. However, space safety does not only concern astronaut safety but also for the systems in orbit and the area that they orbit and also the Earth in general.

Although it seems that there is no profound connection between the two, other than the destruction of all kinds of military satellites, by space debris, space security issues in conjunction with space debris should not be underestimated. Space security can be defined as a two-dimensional issue; security from space and security in space [18]. Security from space is identified as the support to military and law enforcement forces from satellites in, strategic, operational and tactical level, while security in space can be defined as the protection of a space fairing countries' assets (satellites etc.) from all kinds of natural or human-imposed threats [19].

The past few years, quite few attempts have been made but more have been designed on manufacturing satellites that could deorbit non factional satellites in orbit, or space debris generally. "Remove Debris" program led by the Surrey Space Center and Astroscale's "End of Life Services-demonstration (ELSA-d) are such programs and pose the question, if a satellite or a space system could deorbit another satellite when the last comes to the end of its operational lifetime, could it not also deorbit any other satellite, even working ones [20]? And there arises the security issue. What if a hostile de-orbiter satellite, that would be launched, supposedly, for space debris removing purposes, tries to deorbit another nation's functional military satellite [21]? China's SJ-17 satellite, has shown a non-typical orbital behavior coming in close proximity with other geosynchronous satellites and it is said to also have de-orbital capabilities [22]

[23]. It becomes clear that in the name of removing space debris, potential hostilities could occur in space, although there are many technical, economic, political and ethical problems to intervene for such a thing to happen. For the purposes of this thesis space security issues will not be analyzed more, while space safety issues due to space debris will be addressed thoroughly.

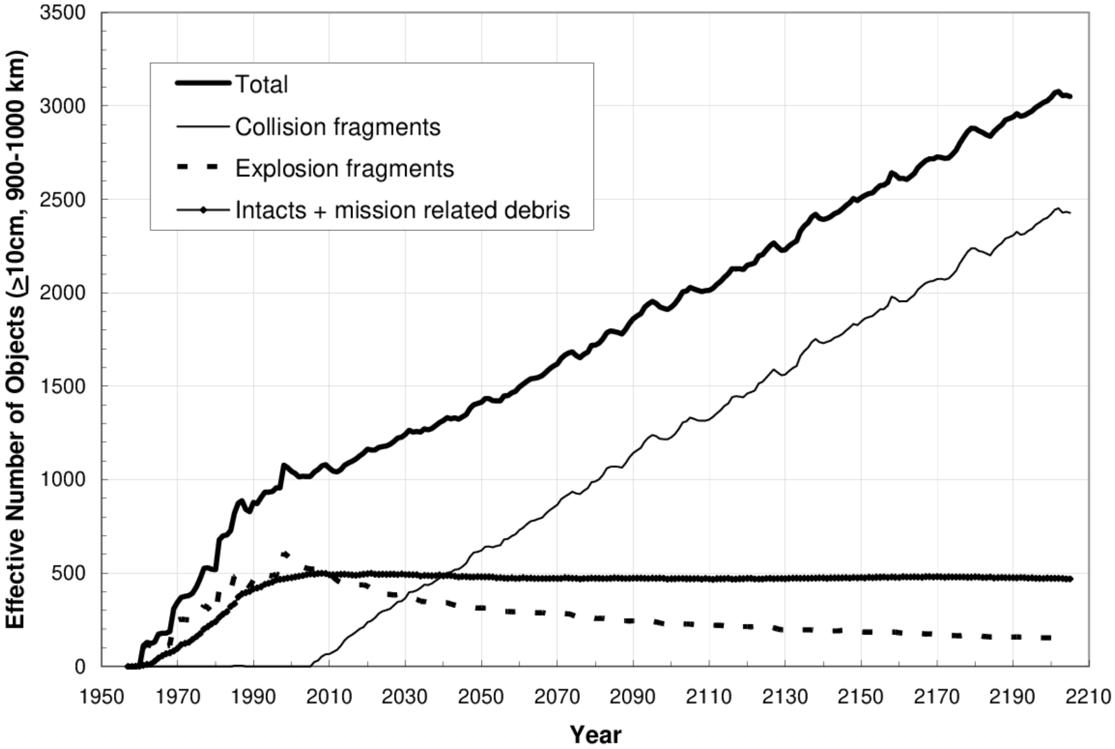
Space safety concerns many fields, is of national, international and even global interest, while the risk mitigation processes lie upon design procedures, operations or both. It is commonly acceptable that there is not such a condition as zero risk in any human activity. For a system, a device or an operation to be granted as absolutely safe, there should not exist a possibility or the potential to cause any accident [16].

Thus, in reality, there is no absolute safety, rather an acceptable or mitigated risk level. Defining the acceptable safety level is not simple, especially when international commerce is concerned. The acceptable safety level is based on technical, financial, political and cultural considerations. For the above reasons, generally the safety acceptability level is regulated by national regulations. However, when it comes to operations that evolve international parties, such as civil aviation or space operations, the national rules have to be harmonized under the international umbrella. As far as the space sector is concerned, currently there are no international regulations that mitigate the risk bonded to space operations [16]. For the purpose of this thesis only the on- orbit safety issues will be addressed.

As addressed in previous sections, space debris orbits earth in continuously ascending numbers due to the fact that no countermeasures are taken yet. The population of space debris in the future will depend on whether the removal or creation rates will dominate. Until now, the only actively working mechanism for the removal of space debris is the natural one, meaning the orbital decay of space debris due to atmospheric drag and/or solar radiation. This mechanism, however, is very slow in its process, thus the orbital debris does not enter the atmosphere to burn in rates that could diminish the problem.

The problem is, that the survival time of orbital debris, without human intervention, is very big and can vary from some hundreds of years for debris at about 1000km orbits, to millions of years for debris in geosynchronous orbits. What had been extracted from several studies is that the creation of space debris outpaces the removal rate having as a result, an average growth of space debris population of about 5% per year [16]. With the prognosed future launch rates, the space debris fragments number at some Low Earth Orbit altitudes have the potential to become unstable, while the dominant debris creation mechanism will be collisions instead of catastrophic failures or explosions. Due to the Kessler Syndrome that had been addressed in previous section these collisions will generate space debris that will induce more and more collisions. Even now, the region between 900 and 1000km is considered particularly unstable in terms of space debris population [24].

In space safety there are two fundamentals concepts concerning the Space Traffic Management (STM) and Space Situational Awareness (SSA). STM's definition comes from the International Academy of Astronautics (IAA) and is described as *"... the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and return from outer* *space to Earth free from physical or radio-frequency interference..."* [25] On the other hand, SSA, involves actions and technologies for monitoring and tracking near earth objects and monitoring and forecasting space weather [26]. STM and SSA are close-related since STM needs data produced by the SSA to provide alerts and consequently perform the necessary avoidance maneuvers, which are stated as (CAM- collision avoidance maneuvers), if needed [27]. As it will be shown in chapter 3, both STM and SSA are critical components for the risk assessment of space debris problem.



Graph 2. Effective number of objects>10cm [14].

2.2.1 Existing Regulations and Standards

As described above, the issues emerging from increased space debris are of national and international interest. When it comes to launch and reentry operations, the spacefaring nations follow their own national regulations, however, no international regulations have been established worldwide. The increasing pollution of the space environment with space debris, has now brought the world and especially the most advanced nations before their responsibilities. After quite a few years of debate, some international space debris mitigation guidelines have been agreed by the Inter-Agency Space Debris Coordination Committee (IADC), but only have been incorporated as voluntary standards under the umbrella of the United Nations Committee on the Peaceful Uses of Outer Space. UN COPUOS was established by the General

Assembly in 1959 to govern the exploration and use of space for the benefit of all humanity: for peace, security and development [28]. Furthermore, ISO 24113), standard on space debris mitigation has been published by the International Organization for Standardization (ISO) according to which the design and production of future space systems should implement these standardized design and operational practices to minimize the generation of space debris [16]. However, even though some sort of international agreement on the future manufacturing and design processes of a space system in accordance with space debris mitigation has been worked out, there is no frame for remediation activities of the already existing problem.

It would be interesting to explore, whether in a more and more commercialized sector, as the space sector is, safety could be treated as a business case. Self-regulations could be an alternative to government regulations. These self-regulations are promoting a high level of safety as a business case. Thus, to take all the needed precautions in order their system to operate safely and in a safe environment. There are quite a few paradigms where, in absence of adequate central governmental regulations, the business itself regulated the standards for a safer operational environment (i.e. Formula 1).

Nowadays, entrance of a new system in operation comes after the evaluation from "safety case" techniques that are sophisticated and are dedicated to the above purpose [16]. These techniques shall respect the fact that the system developer implements the most appropriate design solutions, technical requirements, and verification methods for the safety criteria, that are imposed by the regulatory authority, to be fulfilled. According to Pelton et al.,2020, a safety case differentiates from the prescriptive requirements as the latter is *"...an explicitly required design solution for an implicit safety goal..."*. A Safety Case Report that follows the safety case is consisted of the following:

- The summary description of the system and relevant environment and operations.
- Identified hazards and risks, their level of seriousness and applicable regulatory criteria/ requirements.
- Identified causes of hazards and risks.
- Description of how hazards and risks are mitigated
- Description of relevant verification plans, procedures and methods [16].

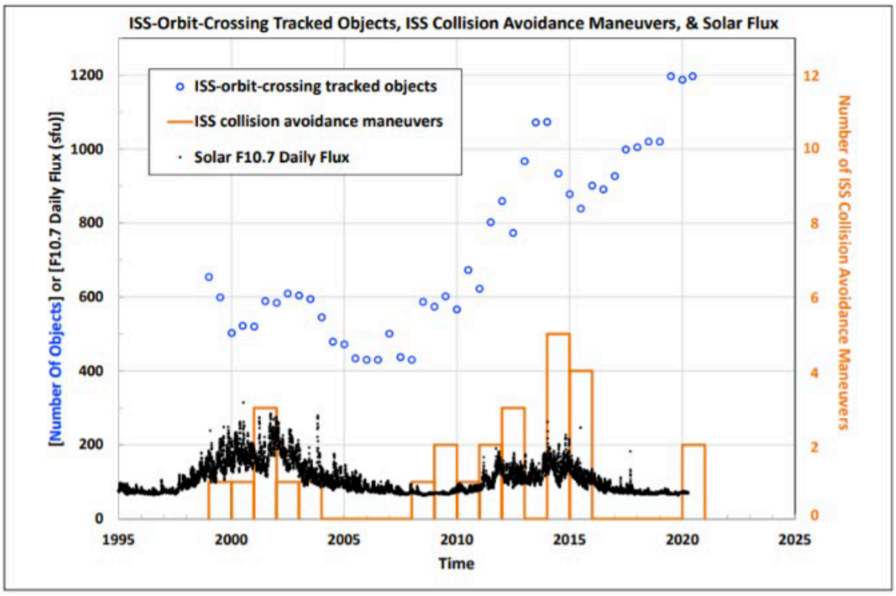
Giving an example, the ISS safety program follows the safety case technique, as the generic safety requirements are been given to system developers, who in turn prepare incremental safety case reports. [29].

2.3 Obstacles in removing Space Debris

The problem of space debris has been recognized not only by the scientific and technological fields but also by international political entities, as evidenced by the European Commission Communication (February 2021) to the European Parliament, the Council, the European Economic and Social Organization. Social Committee and the Committee of the Regions, proposing the launch of 3 flagship projects, one of which concerns the "EU Strategy for the Management of Space Traffic". More specifically, it states: "... This flagship project will develop space traffic management standards and rules, which are necessary to avoid collisions that may arise from the multiplication of satellites and space debris and could lead to in catastrophic events for the fixed assets of the EU in space ... " [30]. Despite the mobilization, there is a relatively passive approach to implementing plans and policies, the causes of which are analyzed below.

2.3.1 Technical barriers

The technical barriers to the active removal of space debris start with the fact that they can be tiny. The example of ISS and space debris avoidance efforts in recent years illustrates the problem of dealing with small fragments of space debris. The ISS has a system for locating potentially dangerous space debris and by 2020 has performed 27 collision avoidance maneuvers, as shown in Graph 2. Objects larger than 10cm are easier to detect and therefore the biggest problem is created by objects of size 1-10cm [10].



Graph 3. Evolution of objects that cross the ISS orbit in relationship to ISS escape maneuvers [5]

Due to the fact that the sizes of space debris can range from 300m to 0.1mm, the problem that arises is how to design active space debris removal techniques that will be able to deal with both extremes in relation to the above sizes. Large space debris would require an equally large system, which is not practical with current technology. Respectively, for small-sized debris, the problem of locating it and its large quantities arises, as mentioned above. Even ground-based system designs, that solves the problem of large size, such as ground-based laser systems, presents technical difficulties in terms of energy requirements, reduced ability to track small space debris, and accurate targeting [31].

Events such as the Chinese ASAT test (2007) and the collision between Cosmos 2251 and Iridium 33 show profoundly the need for actively and timely moving towards space debris removal operations. The political conscience seems to have been awaken. In turn, the technical community has begun a race to implement the most realistic and economical ADR (active debris removal) systems, that systems, which need to be brought into action in a reasonable though unspecified timeframe. The term economical used previously sets another barrier, as an ADR project that that does not provide short to medium- range financial advantages is not attractive to private funding, thus it is abandoned [32].

Other constricting parameters to be set to the engineers could be imposed by the defense agencies. It is easily understood that a giant laser built to deorbit space debris by heat, could also disable an operational satellite if misused. After all the above issues would be solved, the technical community will have to prioritize the removal of small fragments of space debris over bigger ones or the opposite due to the fact that the ADR resources are projected to be limited. To answer the above problematic, the space environment situational awareness shall be enhanced.

To date, only the U.S. Strategic Command (USSTRATCOM) through its Combined Space Operations Center (CSpOC) located at Vandenberg Space Force Base monitors space debris generating the question, if the US are obliged to warn another nation or a company for an impending collision [32]. Furthermore, this tracking technology is quite outdated. Space Fence is the latest project that Lockheed Martin implements in a contract of nearly one billion dollars, awarded by the US Government. It is calculated that with the Space Fence program, the tracked space debris will increase from nearly 20,000 to 200,000. Yet, until this technology is brought in life, CSpOC should be enhanced with software-based predictive models that will give it a better ability to track space debris. The enhancement of situational awareness will alleviate in great degree the technical issues plaguing the debate on liability as it will be addressed later.

Space being a hostile environment with high radiation levels, no atmosphere, extreme temperatures and the ADR missions being remotely controlled makes these operations technically extremely complex. What is more, high costs, the uncertainty of the outcome, non-real-life tested technologies and the ambiguity in prioritization, leaves it to the mercy of political whim.

2.3.2 Legal and political barriers

Currently, five treaties constitute the legal framework governing space-related activities. These are chronological: the "Outer Space Treaty" (1967), the "Rescue Agreement" (1968), the "Liability Convention" (1972), the "Registration Agreement" (Registration Convention) (1976) and the Moon Agreement (1984) Although their purpose is to encourage international cooperation and to discourage "non-appropriation of space", these conditions are now obsolete because they did not keep in pace with the growth of aerospace technology, resulting in the accumulation of space debris, without any international reaction [33]. A thorough analysis of the Liability Convention (1972) shows that according to it, no obligation could be imposed to space faring states as there is no legal provision to state it, thus they do not take action to prevent space debris creation or undertake any mitigation actions. That is, because, the L.C. (1972) states that if any damage is not on the surface of the earth, but elsewhere (space), a launching state is not liable if the damage is not due to its fault or the fault of persons for whom the state is responsible.

That means, that in case of a mishap or accident, being difficult to consolidate fault legally, no one is to blame and thus, there is no obligation for the removal of any space debris created. What is more, when a liability onto a space fairing state is consolidated, it is a common practice for the liable state to go into international negotiations to avoid full liability and proceed with only compensation payments [34]. Although, article III of L.C. (1972) and article VII of OST (1967) pose liability for any State Party that launches or procures the launch of an object in outer space, is internationally liable for any damage in another State Party of the Treaty, there is no provision for what happens in case of space debris, since each space debris fragment should be identified and that is not easy or practical to be accomplished.

The number of space debris is such, that even if some international agreement was made on the above direction, it would take years to recognize even a fraction of the space debris in orbit. Moreover, some space debris targets could serve secret purposes or operate under the US International Traffic in Arms Regulations (ITARs), which clearly states that without the approval of the US State Department no spacecrafts in relations with ITARs can be transferred to nay foreign state, company or person. The problem here is, that the number of space objects under this category are quite many. Furthermore, if during an Active Debris Removal (ADR) mission any damage is caused to a third party, due to the congestion in space environment, the launching state from which the company that carried out the ADR mission had launched, will have to pay a compensation to the claimant. Even the new Space Debris Mitigation Guidelines fail to provide a legal framework, which would force the space fairing states to undertake responsibility for creation of space debris.

Even if, besides the bargains shown above, states genuinely agree to undertake the issue and try to find the best solutions, only very few nations are capable of removing space debris from LEO, MEO and GEO and these are mostly the United States, Russia and maybe EU through ESA. As mentioned above, according both the OST and the Registration Agreement, there is no salvage rights in orbital debris and spacecrafts in general. This means, that everything put in orbit remains the property of the entity that launched it. This is true even if the spacecraft in question explodes in thousands of pieces. Therefore, for any space debris removal mission to take place, the permission of the state to which the space debris entity belongs shall be given. Thus, article VIII of the OST that embodies the above rule, would deter the efforts of, US or Russia to remove the hypothetical space debris.

Legal and political embankments that prevent the rapid development of space debris observation and removal systems can be summarized as follows:

i. The absence of an internationally defined and legally audited definition of the concept of space debris.
ii. Non-binding precedents for the restoration of the space environment from space debris.
iii. The strict ownership of space systems.
iv. Ambiguities in the commission of guilt and the proof of negligence [35].

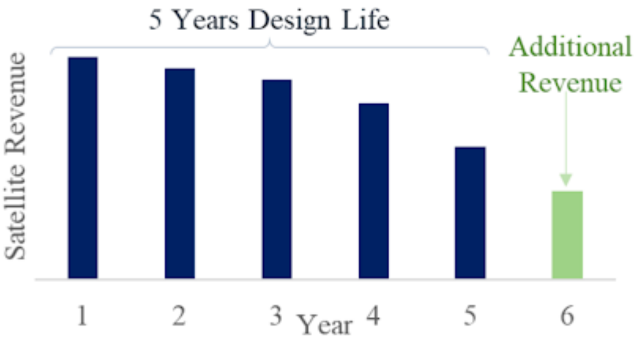
The actions, that should be taken internationally, to legally embrace the space debris removal issue should be, at least, the below summarized ones [34]:

i. To agree on a commonly acceptable Space Debris definition to give the path to space farers to proceed with what needed for ADR missions
ii. To define a pro-active legal regime for the responsibility sharing between private and public partnerships.
iii. To develop better monitoring and tracking capabilities in order to classify space debris.
iv. An international organization should be established for storing data on orbital space debris.

2.3.3 Financial barriers

The space industry, like any kind of non-state industry, is driven by profit. It is these profit-increasing practices that pose obstacles to the removal or reduction of space debris. It is common practice for companies operating satellite systems to extend their lifespan, well beyond what was originally designed, to cover the difference in cost overruns at the development and launch stages of satellite systems, which usually deviate from the original budget, due to the peculiarities of the development of satellite systems. However, the more a satellite system operates beyond its planned operational life, the greater the risk of damage and consequent conversion to out-of-control space debris [36].

ESA's Envisat satellite is a prime example. ESA extended its operations for five years beyond what was originally planned, until it suddenly stopped operating. The 8,000kg satellite is currently one of the biggest hazards in low Earth orbit. It is therefore crucial in the effort to reduce space waste that companies do not pursue the extra profit from extending the life of satellite systems for such purposes. Graph 4 shows an example of an increase in profit from extending the operational life of a satellite system.



Graph 4. Increase in profitability by extending the operating life of satellite systems [25].

There are numerous commercial and economic considerations to space debris removal. To put it on a more simplistic way, the one part of the economics of space debris removal has to do with the actual cost of an Active space Debris Removal (ADR) operation, while the other aspect is the value that an ADR mission could provide to the operator.

To make the process of removing space debris attractive, the cost of the process needs to be significantly lower than the launch costs per kilogram of cargo [37]. To achieve this, space debris removal systems need to remove a lot of debris per shipment. The problem that arises here is that in order to achieve the above goal, the duration of operational life of the space debris removal systems should reach ten years and have the necessary fuel for continuous changes of trajectory, which is extremely costly. In addition, most space debris removal technologies have not been demonstrated operationally. The development and testing costs would lead the companies developing the above technologies to consume funds much more than the mission budget could afford. The only solution is state financial assistance, which could be sustainable for the geosynchronous orbit, where there are the largest space debris, but not for the LEO orbit, where there are too many unrecorded and small fragments.

A method that is proposed to decrease the collision risk, between satellites and space debris and thus the creation of even more debris fragments is to remove the satellites from their operational orbits at the end of their operational lifetime. According to the UN guidelines and the ISO Standard (ISO 24113) this can be achieved either by lowering the orbit for the space system to decay and re-enter the denser, lower parts of atmosphere and eventually burn in the process, or by placing the space system to an orbit away from the regions that need to be protected, the so called «Graveyard Orbit» [38]. The recommendations, also, imply that a space system should remain in operation for a maximum of 25 years. For a system that operates above 2000 km altitude, it is not economically viable to force re-entry earlier or at 25 years. For any of the two disposal maneuvers to be performed, propellants need to be reserved something that creates penalties to the mission in terms of reduced performance and operational lifetime reduction. For geosynchronous satellites this lifetime reduction is estimated between 6 to 24 months and that, for a typical commercial communications satellite would cost an average loss of approximately a year’s profit in terms of how much the satellite would stay in operation if it wasn’t needed to be transferred in a graveyard orbit [16].

What has been proposed as a mitigation to the cost of an ADR mission lies in an international policy approach. It could be an international tax or license fee on every launch operation. In this approach, the taxing authority, that is to have international validity, would then purchase the ADR services by the proceeds. As an alternative to the above taxing method, the operator of space debris that needs to be removed would directly pay a fee so that it could be removed. A problem arises when there is no identification of the space debris to be removed, owner. Then, the operators in an identified hazardous area would pay a tax for using that area, in order to be freed of space debris [34].

Defining who has to pay is of the greatest importance. Defining the amount, they have to pay is also very important, though. A cost and value assessment must be made. If the cost of an ADR operation is smaller than the value proposition and at the same time lower than the alternatives (collision avoidance maneuvers), the operation would be procured, possibly using the above methods. For the value of removing space debris to be derived, the risk that space debris poses to nearby assets has to be determined first. This risk is to be examined on both a catastrophic risk and mission-limiting risk basis and their economical results for the operators. As in every aspect of a space operation, time is a crucial component in the economics of ADR missions too. On that basis, the time-discounted value of the space asset at risk shall be calculated. What is more, the case of reducing the risk at various time frames, such as early on, while the space debris is still in one piece, or following a collision or space debris catastrophic break-up has to be considered. The above described risk assessment may well then be applied to every space asset, irrelevant of being at immediate risk or not.

Having not yet demonstrated a fully operational ADR mission poses a problem on the estimation of the cost of such an operation in real life. Therefore, for the stakeholders to be convinced on financing such a mission, a built-it-first approach should be considered. Private or governmental funds could finance a demonstrator mission that could solve many technical issues of an ADR mission and thus would set the baseline mission cost on a more realistic basis. National space agencies have previously followed this approach in various space related fields, such as launches, satellite missions and for the International Space Station. Having public sector engaged in ADR missions would have as a result longer projection time in assessing the time frame for risk assessment, thus giving more time to proact in a better way, before that risk is realized. Summarizing the above, the primary objectives, on a financial stage, for ADR missions could be addressed as follows [34]:

- Clear identification of the value proposition for the stakeholders
- Assessment and modeling of the risk to multiple space assets over a discounted time frame
- Identification of the alternatives and trade study of those options.

2.4 Policy perspectives.

It is understood that developing standardized rules for governing and regulating space debris matter would be highly beneficial; thus they would resolve the unsolved issues present in space operations regarding to space debris. For this to happen, drawing on a similar context could be helpful. That context could be drawn on international organizations and maritime law. Such organizations could be the International Telecommunication Union (ITU). On this basis, the problem of abandoned spacecrafts could be facilitated by the law on salvage on the high seas. This law was developed by the International Maritime Organization. At the same time, ITU, as an internationally recognized organization could become a reference when trying to develop biding space debris mitigation rules.

That is not something new. From the beginning of the space era jurists have looked into maritime law to find similarities that could be used as role models to the development of rules regarding outer space activities. Many provisions have profound similarities, so in phrasing as in context, with the necessary adaptation to the different contexts [39]. Despite the technological advancements, the ambitious governmental and commercial plans for exploration and exploitation of space resources, brings upfront the necessity of a legal standardization on national and international level. The “Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies” (Outer Space Treaty 1967), implies that governmental organizations should aim to assure that all countries would benefit, regardless of their scientific, technological and economic status [40]. This provision is similar, when compared to the Law of Sea, especially when it comes to the sustainability and protection of natural resources.

What is needed here, is a conjuncting international legal instrument and due to the treaties taking too long to formed, soft law and rules could be the road to an international solution to the non-existence of regulations on the space debris issue. Maritime law can be used as a reference when used to establish a regime as that of the international law of salvage in high seas, outlined in the International Convention on Salvage, IMO 1989, for the abandoned sea vessels, projected to space for abandoned spacecrafts [41]. In similar regard, the ITU could play a significant role in setting regulations for the Active Debris Removal Missions. ITU, besides other, is the organization that assigns satellite orbits and coordinates the definition of technical standards, thus, it might be suitable to be the referral organization that would issue binding international space debris mitigation rules.

Trying to draw analogies between maritime and outer space operations [42], in order to pursue regulation context on space debris, it is profound that both impose challenges when it comes to the international level. The most significant challenge is raised by individual nations on whether the try for a supranational law frame, would be an effort to control and limit freedom, but as shown by the year after year application Law of the Seas, this is not the case.

More specifically, as far as the issue of salvage operations is concerned, the International Maritime Organization (IMO) Convention calls the below:

- The state parties shall be very careful when carrying out the salvage operation (article 8)
- Following a maritime casualty the state parties shall take measure to protect any maritime related interest, such as coastline, from pollution or threat of pollution (article 9)
- A reward should be given to encourage salvage operation (article 12) [43]

Regarding returning objects launched in space, the only binding policy provisions are contained in the Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of objects launched in outer space of 1968 (Rescue Agreement) [44]. Article 5 addresses the importance of reaction when a space object or its components become a threat or potentially harmful. Moreover, unlike the Convention on the IMO, there is no reference to a possible reward for the launching authority for paying the costs incurred to recover and return the in-question space object as implied by article 6 [39].

Another similar approach to maritime and space international law is the usage of sustainable materials in order to protect the space and maritime environment respectively. As for maritime zones protection with the Convention concerning Cooperation in Preventing Pollution from Ships and, in Cases of Emergency, Combating Pollution of the Mediterranean Sea (January 2002), there is an approach on building new satellites to incorporate sustainable materials, called “eco-design” in a way that the impact of space debris is minimized [45]. This could happen by using a specific percentage of compostable materials on manufacturing process of the new satellites so that most part of them would disintegrate when at the end of their operational lifetime, thus posing minimum threat to other space systems and/or space environment in general [39]. However, the above are not yet legislated by an internationally accepted authority.

The absence of an internationally accepted authority for the regulation of the crucial issue of space debris eventually results in the inability to reach any common agreement at the international level. The question that emerges is, should the above-mentioned authority be a brand new one, or an already existing one? Could ITU play the role of this international authority? When it comes to space debris and de-orbiting issues, ITU has only proposed some recommendations such as the one concerning the «Environmental protection of the geostationary- satellite orbit (ITU-R S.1003-2). By definition, though, a recommendation, even from an international organization such as the ITU has no legal binding.

But how can ITU practically engage in the space debris removal issue? The satellite orbits assignation is already part of ITU’s statory activities. Thus, it would be natural for ITU to expand its sphere of action to the space debris problem, rather than waiting a totally new regulatory body to be decreed. What is more, ITU is the only United Nations agency to incorporate both public and private stakeholders with 193 Member States, about 700 tech companies and leading academic institutions [48]. Governments and private entities would benefit by the efficiency and immediacy of the dialogue under the umbrella of an organization as ITU.

Going back to maritime law, it would be interesting to investigate whether a similar approach, as the one that already exists for the routes of the vessels, could be implemented for the orbits of the spacecrafts. There are provisions in the maritime law that state that any vessel that crosses and disturbs the passage of another vessel shall allow sufficient sea room for the safe passage of the other vessel by taking appropriate and timely action (Rule 9) [49]. Upon the above provision and with the help of ITU, an obligation for the launching states could be shaped so that they would take all the necessary actions not to obstruct the safe routing of another orbiting spacecraft. Moreover, this could expand to an obligation for the states or the space companies to plan in advance and take appropriate measures for deorbiting their spacecrafts timely, to clear the path as stated by the hypothetical rule.

3. SPACE DEBRIS' INCREASE IS ASSOCIATED WITH A GREATER RISK FOR SPACE OPERATIONS

As already mentioned, the “Kessler Syndrome” is of particular concern to the space community as an extremely dangerous possibility. Until 2019, the only satellite with sufficient mass to create this sequence of events on low Earth orbit was the European Space Agency's Envisat [50]. With a mass of 8,200kg it moves in an area where the density of space debris is significantly high with two recorded objects approaching at a distance of less than 200 meters each year. From 2019 onwards, about 5,400 launches have taken place, a number that will grow exponentially in the coming years, as more and more space debris will accumulate from previous missions. If a 10cm space debris fragment collides with a 1,200kg spacecraft, over 1 million fragments sizing from 1mm and greater could be produced. In the event that an event as described by Kessler Syndrome actually occurs, it will not make the area of the event completely inaccessible, but it will be unprofitable in cost and time to bypass it [1].

The probability of a working spacecraft colliding with a space debris is increased as much from the increase in space debris, as from the increase in active satellite formations. The growing demand for global internet coverage, better geospatial and navigation technologies is rapidly increasing the number of satellites being launched into orbit. The World Economic Forum estimates that there are approximately 6,000 satellites in orbit by 2020, of which only 40% are operational. In 2020 alone, 955 new satellites were launched, accounting for 35% of existing satellites. The approximately 3,300 inactive satellites in orbit are considered space debris and are a potential hazard. Another factor that will increase the risk of space conflicts is the participation of private companies in programs such as space tourism. Whether the private missions involve LEO, MEO or GEO orbits, or simply transport orbits for short-Earth or long-distance missions, increased traffic will result in increased space debris. Therefore, these new spacecrafts need to have increased protection against collisions with space debris [51].

An example of an increase in the probability of encountering space debris is the example of the ISS. From 1999 to 2018 the ISS had to maneuver 25 times to avoid dangerous situations involving space debris. For 2020, only it had to maneuver 3 times. This increase is worrying, compared to a frequency of 1/year in previous years. Recently, there was a collision of space debris with the Canadian robotic arm of the ISS (Canadarm2), which although did not cause any problems, was extremely worrying for the safety of those in space [52].

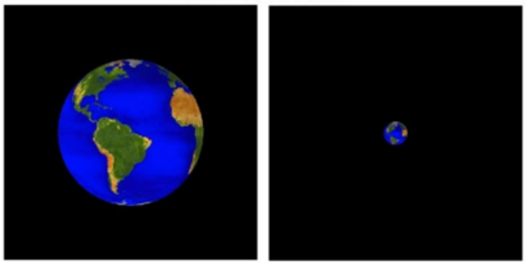
As mentioned above (see Chapter 2b), the Space Surveillance Network of the U.S. Airforce can detect space debris larger than 10cm. The problem was that this system concerns military applications and has no jurisdiction over civil space systems, although it has often provided, for security reasons, location information for non-military space debris. U.S. Airforce’s new surveillance system “Space Fence” will have ten times better detection capabilities and it is believed that users of civilian satellite systems will be able to obtain information to avoid collisions with space debris. [53].

The relative speed of orbital debris to operational satellites is very high. In LEO the average relative impact velocity lies in the magnitude of 10km/sec or about 36,000 km/h. It becomes obvious, that in these hyper velocities, space debris has a gigantic amount of kinetic energy. Debris fragments from 1mm to 1cm have the potential of penetrating a spacecraft (depending on the material of the debris and whether the spacecraft is shielded or not). Debris fragments between 1cm and 10cm have the potential to penetrate any and damage most spacecraft [16].

Orbital debris collision poses a topped risk for human spaceflight. Nowadays, orbital debris collision is the primary risk for the safety of ISS and everybody onboard. ISS is shielded to minimize the risk for the crew's health. An impact of space debris the size of 1cm can be withstand by critical components such as habitable compartments or high-pressure tank.

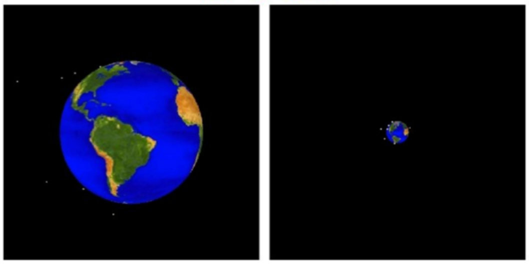
Below is a series of images showing the increase in space debris over the years.

Before 1957 = 0 objects



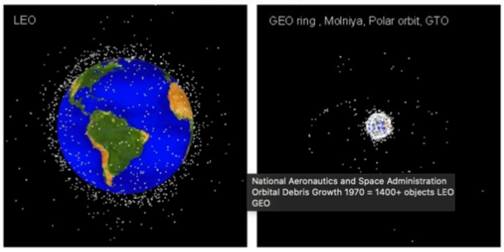
Cataloged objects (>10 cm diameter) represented by white dots *(not to scale)*

1960 = 10+ objects



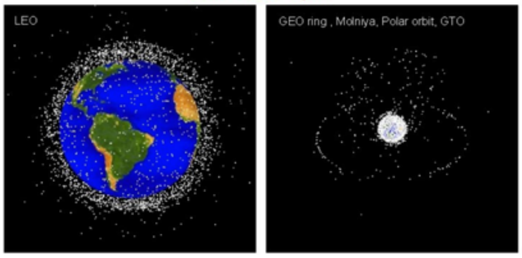
Cataloged objects >10 cm diameter

1970 = 1400+ objects



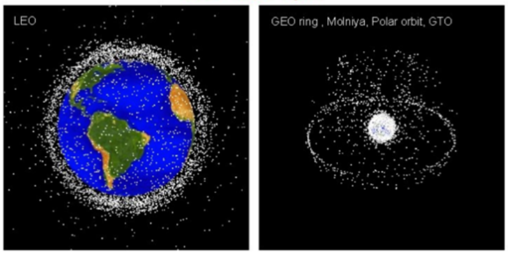
Cataloged objects >10 cm diameter

1980 = 3700+ objects



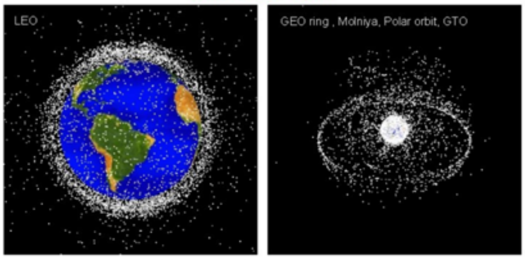
Cataloged objects >10 cm diameter

1990 = 6000+ objects



Cataloged objects >10 cm diameter

2000 = 8900+ objects



Cataloged objects >10 cm diameter

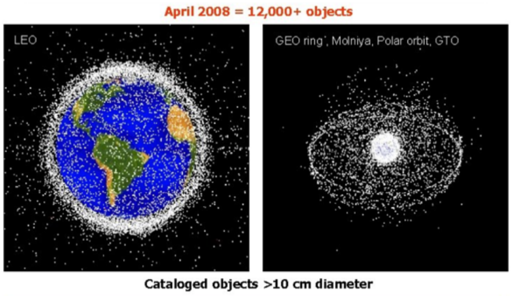


Figure 1. Recorded space debris larger than 10cm per year. (Retrieved from: https://slidetodoc.com/national-aeronautics-and-space-administration-orbital-debris-past/)

To control the orbital debris risk, a number of design and operational measures can be taken, taking into account that there are no active space debris removing techniques in operation. Such measures could be end-of-life disposal, collision avoidance and passivation. Passivation is the act taken to eliminate the risk of explosion by removing the stored energy, such as propellant or batteries at the end of a spacecrafts useful life. This can be achieved by either venting or burning propellant to depletion. Another way to mitigate the risk of space debris is the spacecrafts to perform avoidance maneuvers. ISS has maneuvered in several occasions avoiding potentially dangerous debris. Lastly, collision risks could be reduced by moving satellites and upper stages at the end of their operational lifetime from orbits used by missions to higher orbits, that are protected. These orbits are called graveyard orbits.

To mitigate the risk that space debris poses to spacecrafts and astronauts it is imperative to be proactive. Humans have a limited capability of interpreting data without the help of computers. The situation emerging by the space debris threat needs to be addressed by a machine that is able to perform faster and make decisions based on a wider range of parameters than humans; that could most probably be artificial intelligence [27]. As new, more advanced space debris detecting infrastructures are expected to operate in the next few years, the population of space debris objects that will be catalogued will increase significantly. That will not only be due to the increase of the number of satellites and spacecrafts that are planned to be launched the next years, but mostly due to the fact that the new detecting systems will be able to detect space debris fragments that is undetectable by the current systems, as shown at Figure 2 [54].

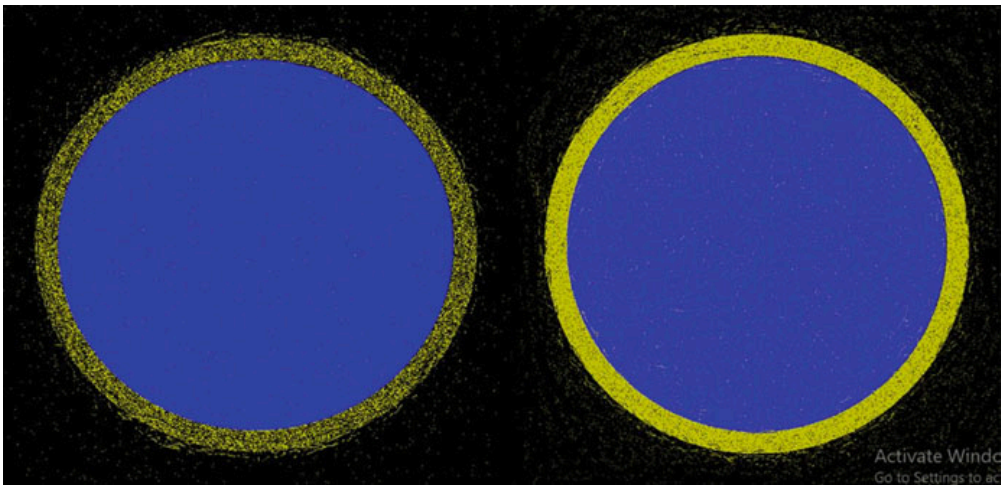


Figure 2. Space Fence's operation leads to increase of catalogued LEO space debris objects [40]

The increase on catalogued space debris could cause the collapse of the STM (Space Traffic Management) system, since a significant increase in conjunction alerts can be expected (Figure 3). Although, most of the above alerts will not mean significant threat of collision or activation of CAM (collision avoidance maneuvers) it will require vast amounts of time and effort to assess the risk link to them. What is more, the metric that is currently used to decide whether an event is of low or high risk is to reevaluated and with the implementation of Artificial Intelligence will be more reliable [55]. As an example of the current situation, the event of the collision between Iridium-33 and the Russian Cosmos-2251 was not classified as a high risk before it happened (Figure 4).

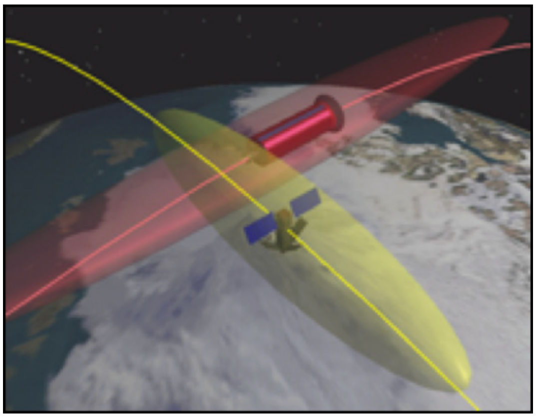


Figure 3. Possibility of Conjunction between two objects [55]

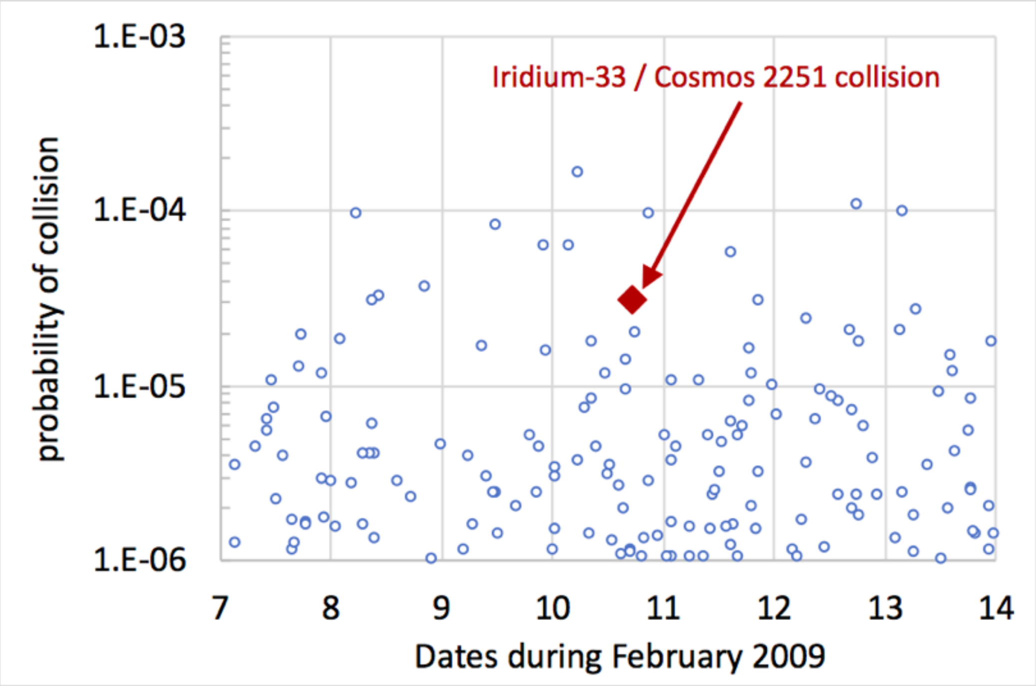


Figure 4. Iridium-33 and Cosmos 2251 did not stand out from other conjunctions as being noticeably dangerous under those tracking accuracies [55]

The now ongoing tactic is as follows. All trackable space objects, including space debris, around earth, are monitored by SSA (Space Situational Awareness) service providers, with USSTRATCOM being the leading player. When a potential of collision between two space objects, with at least one of them being operational, emerges, a Conjunction Data Message (CDM) is created and sent to those in charge for the involved space systems. When all the available CDM's associated with a specific event are gathered, the operators of the space system execute the so-called CARA (Conjunction Assessment Risk Analysis).

By using this analysis, they estimate whether there is a high or low probability of collision associated with the event. If the risk analysis shows high probability, it is then time to start the more complex process between the operators to take actions against the probability of collision. This is a complex and time-consuming process that starts with manual communication between the operators to come to an agreement of a common strategy. After that, the procedure, agreed by the operators, is analyzed by the flight dynamics, payload and ground stations teams so that they come up with a possible collision avoidance maneuver procedure.

Once the strategy is agreed, it is reevaluated in terms of future possible collision risks (secondary collisions, tertiary collisions). When, eventually, the whole strategy is decided and approved, the development of the event is monitored and one or two days before the TCA (Time of Closest Approach), if the risk remains high, the agreed Collision Avoidance Maneuver is performed. It can be seen that just for a single CAM, associated with a single event, there are many critical points to be assessed. The most critical component in the process is time, as the operators have, at most, 7 days from the first indication to perform the maneuver. But time is not the only issue here. When evaluating the collision avoidance strategy the, coordination between several teams such as flight dynamics, the flight control, ground station and overall mission requirements have to be considered [27]. It can be understood, that if two operational space systems are involved, the coordination problem becomes even more profound, as the common strategy to be followed, must be agreed by the teams of both missions. If the lack of protocols and specific regulations is also considered, the problem becomes bigger [56]. Taking in mind, that with the existing number of CAMs the teams struggle to cope, the increase of space traffic and the larger numbers of debris detection in the future, will make the current system unable to be effective. Unless, an automated system, driven by AI, is used to support and replace most of the operator’s tasks is used, the future situation will only worsen [57].

By providing an Artificial Intelligence system with more and more reliable data, it will be able to learn directly from them (machine learning) and predict more accurate results than any physical model that is used nowadays. With time being a critical resource, AI systems using the surrogate model [58], will contribute to the automation of STM (Space Traffic Management) system. There is not a lot of AI examples implemented to space systems, however, AI has been used successfully for decision support and event prediction in other engineering fields, such as Air Traffic Management and space generally [27].

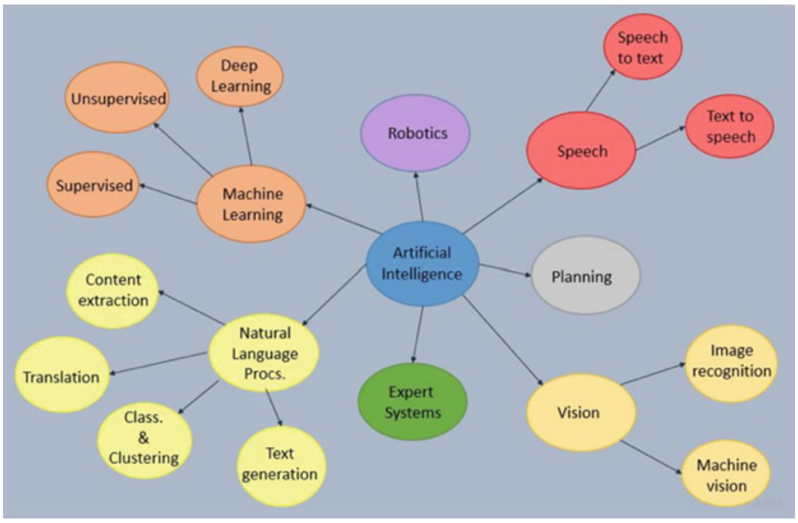


Figure 5. Artificial Intelligence areas of application [17].

Air Traffic and Unmanned Air Traffic systems (ATM/UTM) are two examples with similar to space operations that have incorporated automation and AI when it deemed necessary by the increase in traffic population. Automation and AI, in ATM and UTM operations, are playing a key role especially when it comes to decision making in highly congested air regions, thus they can rapidly consider a wide set of parameters and rank the best options to be implemented under a conflicting state. This automatizes tasks previously done mostly manually by human operators and therefore speeds up the process altogether. [59] [60]. The European Space Agency has acknowledged three fields that AI would be beneficial in terms of risk assessment in space missions, due to the population increment on the orbital environment. These are first, the reduction of the operator's workload (automation), secondly, the shrinking of the decision-making time on risk assessment over conjunction and avoidance planning and lastly, the downscaling of false alerts [61] [62].

Although there hasn't been much research on how AI would be implemented in STM and SSA systems, there are some pioneer works on the subject. More specifically, Peng and Bai, (2018a/ 2018b), have proposed, initially, support vector machine to reduce the positional error for satellites after orbit determination and orbit propagation processes, continuing by on the same field by switching from support vector machine to artificial neural networks (ANN). Their work demonstrated the possibility of using Machine Learning to reduce orbit determination errors (Figure 6) [63] [64].

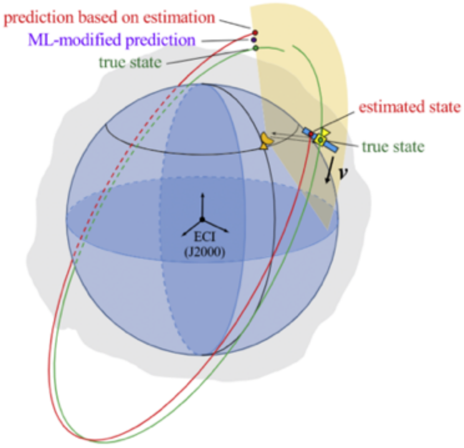


Figure 6. Modified prediction through Machine Learning correction [50]

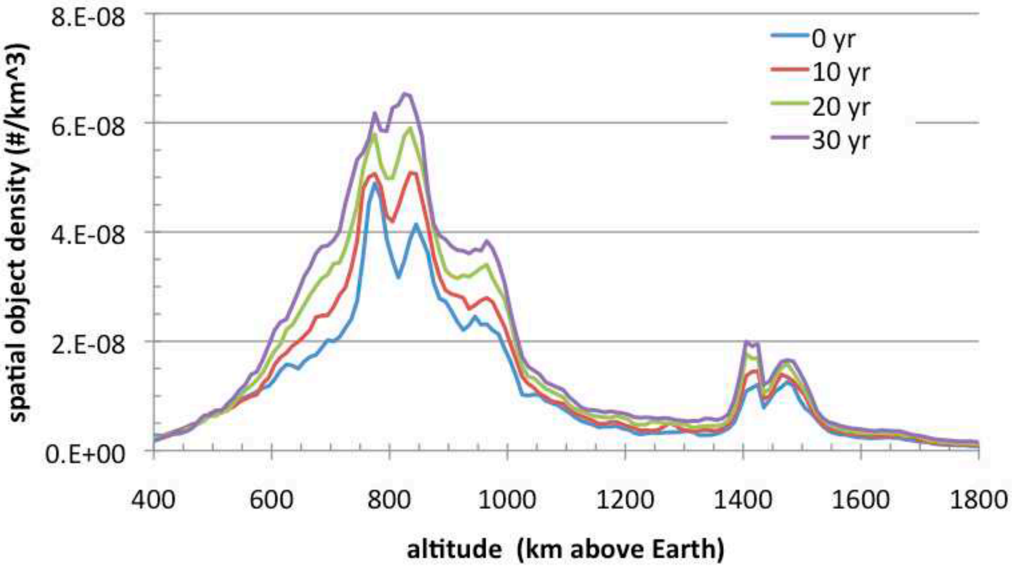
Sanchez et al., 2020, have proposed another approach for applying AI in Space Traffic Management (STM). The new approach has to do with using Machine Learning algorithms to assess the risk by overcoming some of the limitation present in a common risk assessment metric. This is achieved by using the belief and plausibility concepts coming from the evidence theory, thus limiting the epistemic uncertainty on a classic approach collision risk assessment [27].

The AI approach in STM and SSA is gaining more and more attention continuously among the researchers as seen in recent works. Mashiku et al., (2019), propose a supervised and unsupervised Machine Learning algorithms and fuzzy logic to predict close approaches using not only the classical approach, but also other parameters [65]. What is more, Machine Learning algorithms have been used in predicting when a maneuver should be executed in the future to improve Space Situational Awareness (SSA) capabilities [66].In conclusion, Artificial Intelligence being an area with several fields, can be used, focusing mostly in Machine Learning area for now, in assessing the risk probability of a future collision. To obtain maximum benefits, each AI branch should be studied for matching the best problem related to Space Safety.

4. SPACE DEBRIS TRACKING

The importance of tracking space debris is self-explanatory, as someone can easily understand that to facilitate the space debris problem, space debris objects must initially be tracked. There are quite a few efforts and research done in this field, mostly concerning optic physics and radar technology. If perfect and complete information about space debris were available, it would be easier not only to perform collision avoidance maneuvers, but also to reach and remove space debris objects.

However, for now, the capabilities of tracking systems are imperfect, thus the prediction of a satellite or space debris exact position in the future (days) can only represented as a three-dimensional probability density function. A point location of the previous statement cannot be accurately estimated [67]. Up until today only predictions based on observations can be made. These observations show, that, especially in the LEO region, and more specifically at about 850 km altitude, the density of the objects increase by an estimated 50% over the next 30 years, starting from 2009, as shown in Graph 5.



Graph 5. Spatial density for tracked (>10cm) objects (year 0=2009) [53]

Another observation that had been made when trying to predict by observations and mathematical estimations is that conjunction events are more probable in Low Earth Orbits and in particular over the North and South poles. This is expected because most objects are in sun-synchronous orbits having high inclinations and similar orbital heights making these regions quite dense as shown at Figure 7 below. It is shown that even a small improvement in space debris tracking capability would substantially contribute to reducing the number of predicted conjunctions [67].

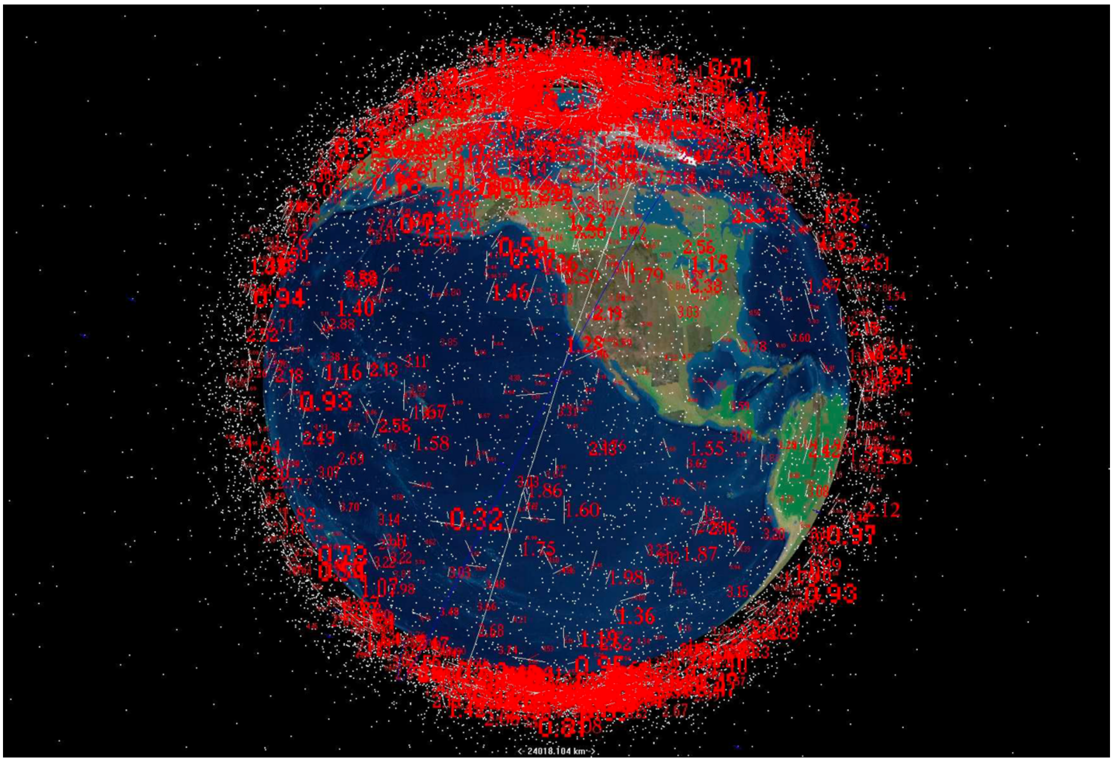


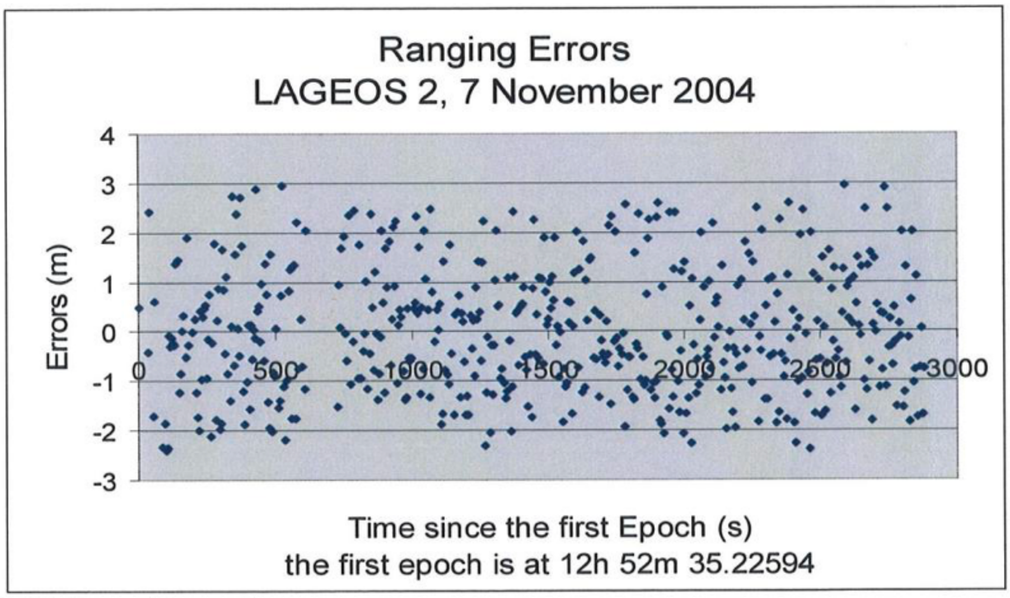
Figure 7. Screen capture from the SEAS simulation of a month time frame probability of conjunctions in year 2039 for 44 LEO satellites vs. 17,029 (over 10cm) debris objects prediction [53]

For the time of successful ADR missions are conducted is quite far away, it is of imperative need to know the exact position of space debris, so that collision avoidance maneuvers can be performed. Furthermore, ADR missions will need the most accurate position determination to operate properly, as it will be shown in the next chapter. The techniques for space debris and satellite tracking that have been researched more, are Laser Ranging, image-based tracking, radio telescopes and adaptive optics.

4.1 Laser Ranging and Tracking

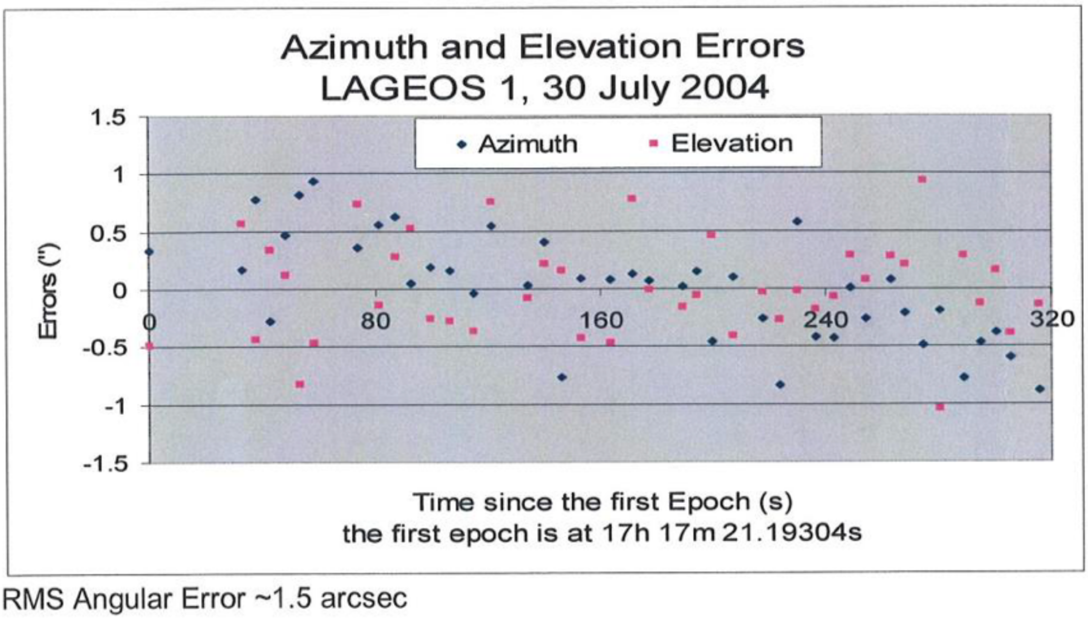
The need for precise satellite orbit determination, even since the 1950's, gave birth to the International Laser Ranging Service (ILRS), which nowadays coordinates over 20 Satellite Laser Ranging (SLR) sites around the globe. Space faring countries that present this capability are, USA, China and Europe through Germany's DLR [68]. Satellite Laser Ranging technology typically uses short in time pulses -in the magnitude of picoseconds (ps)- to track satellites, with a precision of 5-10mm for Geodetic satellites. This leads to an accuracy in the knowledge of satellite orbits with a precision within centimeters [70].

The drawback of SLR technology is that it needs retro-reflectors installed on the satellites, making it not useful for tracking space debris. EOS Space Systems extended SLR capabilities to no retro-reflectors needing, thus making it possible to track space debris with an accuracy in the magnitude of meters. This is achievable by using nano-second class pulses. Due to the fact that orbits of satellites and space debris themselves have large uncertainties, a golden standard, derived from the well-known by the ILRS system Lageos1 and 2 orbits is used for determination of the accuracy of the DLR system. As shown in the next two graphs, the DLR accuracy when compared to the LAGEOS 1 and LAGEOS 2 satellite known orbits lies between +/- 3 meters. A number of sensitivity tests made to the DLR system showed that it can track most objects in LEO region (below-1500km).



RMS Range Error ~1m

Graph 6. Ranging errors on Lageos 2 for the DLR system [54].



Graph 7. DLR system azimuth and elevation results (~1.5 arcseconds rms- 3.6m) [54].

As shown in the two Figures above, DLR system has a significant tracking ability when it comes to Low Earth Orbits, while the ranging errors in the magnitude of meters are insignificant to Active Debris Removal missions, as the ADR spacecraft itself will have the necessary ranging capabilities for the final stage of the rendezvous.

4.2 Image-based tracking

It is a common practice, when it is needed to track something in the sky or in space, to do so from earth's ground. This is due to the fact that this practice is easier and more tested. There is, however, nowadays research done in tracking space debris not from ground, but from other spacecrafts. This becomes a reality through image-based tracking. This strategy uses a carrier satellite with an onboard camera specially designed for space debris tracking. The spacecraft orients itself in such a way that the camera points to a predetermined area in space. Afterwards, when space debris passes through this area (camera's field of view), the spacecraft change its attitude so that it follows the space debris' motion [71].

Onboard sensors such as those described previously offer quite a few advantages. They present weather independency, they are not affected by turbulences and diffractions in the atmosphere and what is more, better accuracy. The sensors that could be used, are CCD (Charge-Coupled Device), CMOS (complementary metal oxide semiconductor) and photon counting sensors, all three being reliable and cost-effective. Taking the above into account, a mission for space debris tracking that uses a formation of small satellites equipped with the suitable sensors to detect and track space debris has been proposed [72].

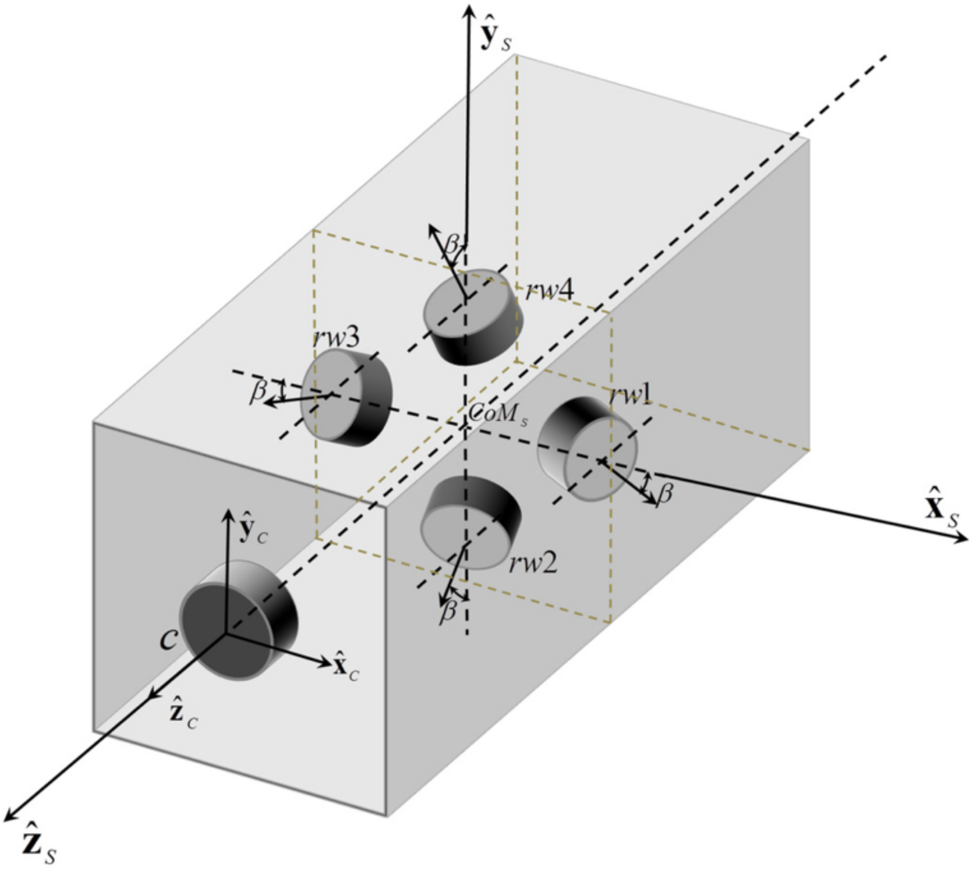
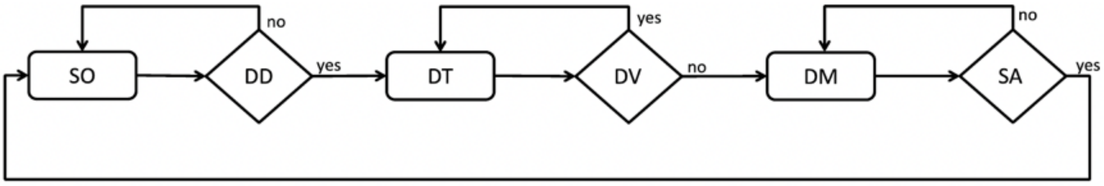


Figure 8. Carrier satellite platform with an onboard camera specially designed for space debris tracking [55]

The algorithm that is proposed for image-based tracking technologies is shown simplified on Graph 8 below.

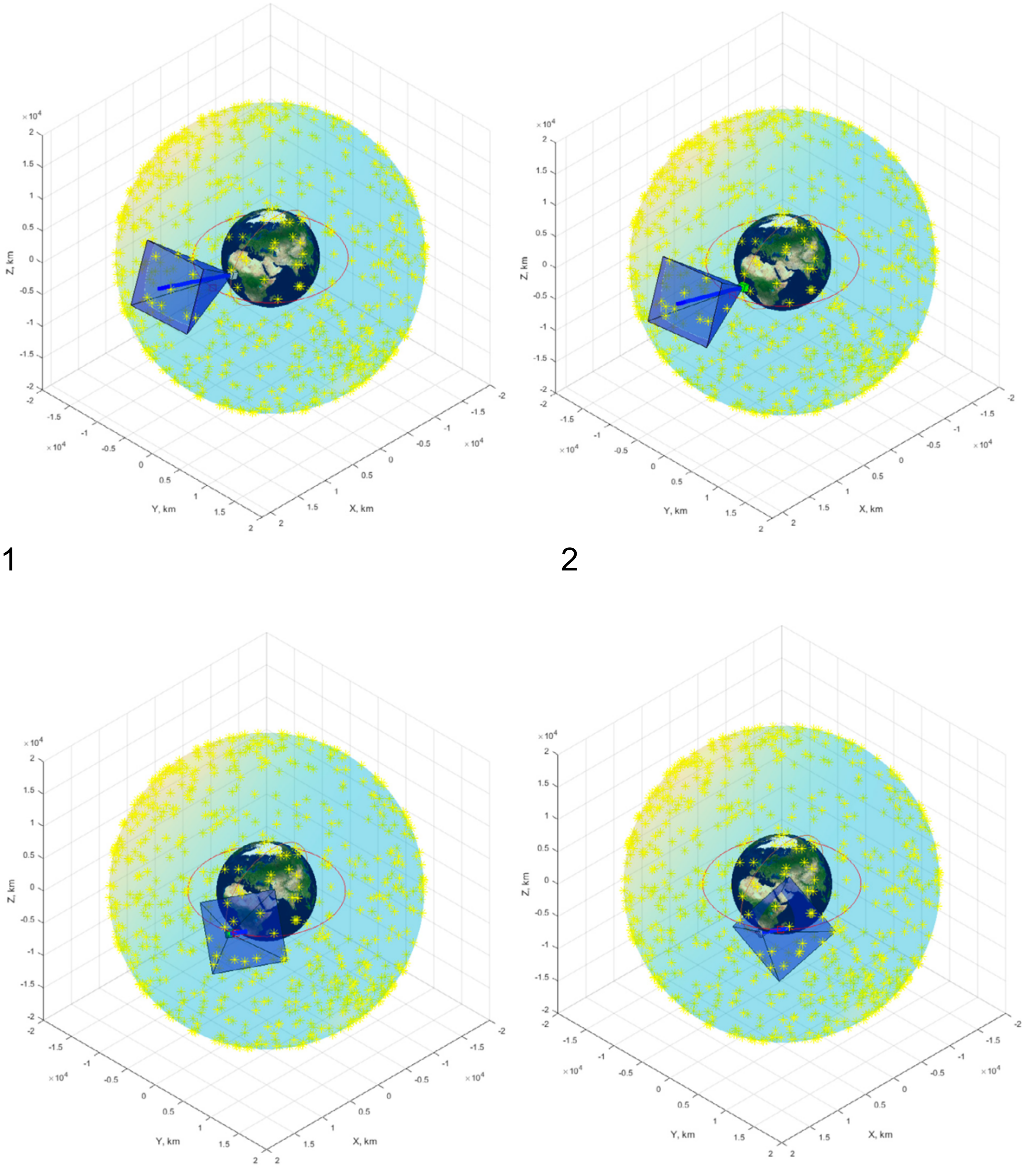


Graph 8. Flowchart of image-based space debris tracking [55]

The rectangular shapes show the modes that the attitude control system must accomplish, while the rhombus ones the conditions to be met for proper system operation. More specifically:

- The Stars Observation mode (SO) is using a sensor to correct the attitude of the satellite. The camera points to a fixed direction and the images of the background stars are compared to a reference for the deviations to be derived and the satellite to correct its attitude.
- The Debris Detection condition (DD) activates when a streak occurs in the images used as a reference by the SO sensor. This streak means that an object closer than the reference stars and with a greater velocity is moving in the field of view of the camera. At that time the control algorithm shall switch from the SO mode to the DT mode.
- The Debris Tracking mode (DT) makes the satellite to correct its attitude when space debris is identified, in order to keep it in the field of view of the camera.
- The Debris Visibility condition (DV) depends on whether the camera retains or loses the ability to keep tracking the space debris. If this condition is lost the algorithm switches from DT mode to DM mode.
- The Disengagement Maneuver mode (DM) is used to restore the satellite's attitude when the camera loses the space debris visibility conditions.
- The Stationary Attitude (SA) condition is activated whenever the satellite angular rate drops below a certain threshold, at which point the control algorithm switches from DM to SO mode.

The four mission phases are depicted on Figure 9 below:



1

2

3

4

Figure 9. Mission phases:1) Stars Observation, 2) Debris Detection, 3) Debris Tracking, 4) Disengagement Maneuver

4.3 Radar tracking

The ESA and the German tracking and Imaging Radar (FGAN/TIRA) team collaborated to for the radar to be, also, used as searching and tracking system for space objects. The main subsystems of the radar are a 34-meter antenna, a narrow band mono-pulse antenna and a high-resolution Ku-band imaging radar [73]. TIRA radar, mainly, searches and tracks space objects, determining their orbit, helps to characterize the space debris environment and helps validate the space debris models.

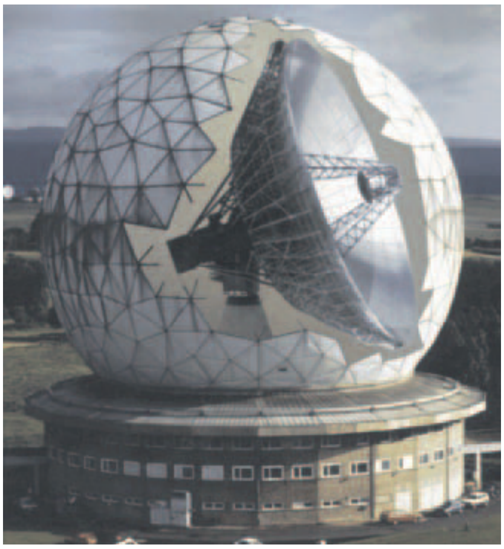


Figure 10. The TIRA facility [57]

For the space debris tracking and searching the radar beam is pointed to a pre-determined area in space and observes whether there is any space debris present. To isolate space debris from other objects an a priori information concerning the cross section of the object or a group of sizes of objects and some orbital elements are provided. To characterize the space debris environment, the radar beam is maintained to a predetermined fixed position in reference to earth, thus scanning a 360-degree section during a day. During that period the objects that pass through the beam are registered, while from the backscattering of the radar signal some orbital elements of these objects can be determined. The radar's capability can detect 2cm sized objects at a height of 1000km [73].

4.4 Adaptive optics

Adaptive optics are used by astronomers to make space images, taken from earth, almost as sharp as if they were taken in space. Deformable mirrors controlled by sophisticated computers can correct images taken, for the distortion induced by the turbulence caused by earth's atmosphere. European Southern Observatory (ESO) has moved beyond that and led the way in developing adaptive optics in combination with laser guide star technologies [74]. For the purpose of tracking space debris, a partnership between the Research School of Astronomy and Astrophysics (RSAA/ Australia) and ESO has as a result the Adaptive Optics Demonstrator (AOD) at the Observatory of Mount Stromlo.

The goal of the Adaptive Optics Demonstrator project is to research whether there can be any improvement in tracking capability of a ground based optical tracking system with Adaptive Optics. The project combines the Adaptive Optics and instrumentation expertise at RSAA with the tracking facilities of EOS. The basic components of the system are a 1064nm/ 200W ns pulsed laser and a telescope 1,8m in diameter with laser guide star AO system. EOS has the ability to track and determine the orbit of a space object with an accuracy of 200 meters after 24 hours. It is not a system with the best accuracy, but it is better than radar tracking or passive optical systems tracking.

Adaptive optics come to enhance these capabilities by decreasing the effect of the drawbacks of ground laser telescopes. Ground laser telescopes present limitations when it comes to track space debris with high flux, thus objects below 15cm or beyond 1500 km. The three most influential causes are, the telescope size, the laser power and low Strehl ratio. The first two are being solved by the increase of the power of the lasers that can nowadays reach kilowatt power levels, while the telescopes are being constantly developed to the better. An Adaptive Optics system can be used to improve the Strehl ratio, thus to achieve higher photon return and better tracking ability [75].

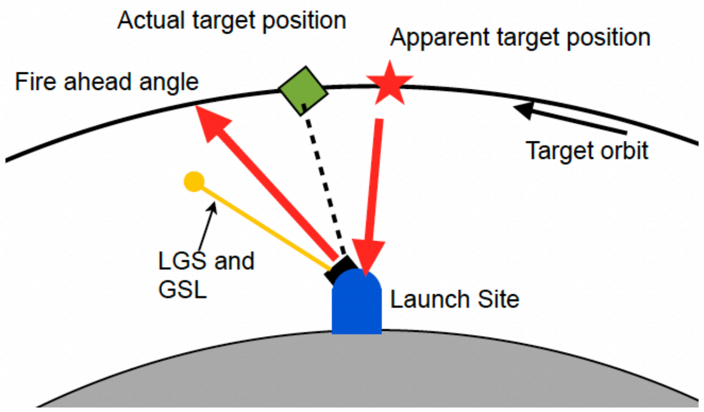


Figure 11. Laser ground tracking system with target passing overhead [75].

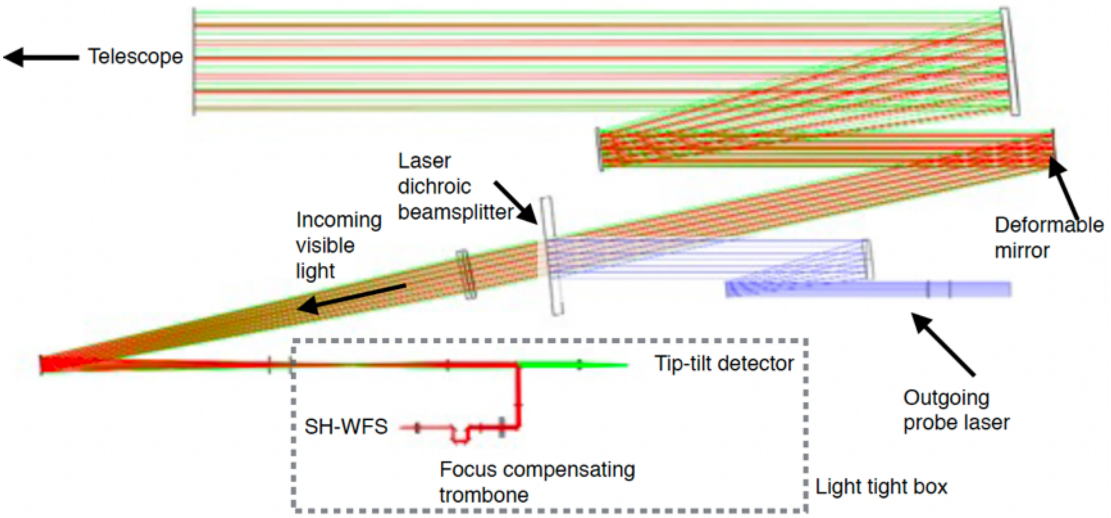


Figure 12. Wave front sensing subsystem. [75]

5. SPACE DEBRIS CAPTURE AND REMOVAL TECHNIQUES

The importance of reducing space debris has been understood by countries that have or intend to have an active space presence. In addition, services such as the US DARPA (Defense Advanced Research Project Agency) are working on reducing and removing space debris. However, it was not until 2007 that a text of the Space Debris Mitigation Guidelines was signed at the UN General Assembly (UNGA), conducting scientific research and discussions on the legal aspects of the issue, both at national and at international level. Some of the scientific research has yielded results in the construction of active space debris removal systems, a small number of which are sampled below [76].

The Japanese Aerospace Exploration Agency (JAXA) tested the idea of an electrodynamic tether that would remove space debris. The experiment, called the KITE (Kounotori Integrated Tether Experiment), was placed as payload in an International Space Station supply capsule. "After its removal from the ISS, it was supposed to extend the 700-meter electrodynamic tether, but it failed, so it returned to earth 7 days later, without any result [77].

The Laser Orbital Debris Removal (LODR) is a system proposed by NASA but never put into operation. According to this, space debris would be heated by a laser beam either from the ground or from space, thus changing its kinetic state and either changing its orbit so that they fell to earth, or changing its orbit, to avoid a collision with a space system. According to NASA, the velocity of the space debris would change by about 0.1 mm/s each time the object received the laser beam. Aiming at the object for a few hours would be enough to change its trajectory by 200 meters [78].

In 2012, the Swiss Federal Institute of Technology in Lausanne (EPFL) announced the CleanSpace One program, according to which a satellite would be launched to collect space debris through a net and would then be brought back to Earth [79].

In February 2019, Airbus, in partnership with the University of Surrey-Surrey Satellite Technology Ltd., conducted the first space debris collection operational test. The plan was to launch a harpoon cartridge, which would be attached to the space debris and then brought to the mother satellite. The test was successful and a titanium cartridge the size of a pen was launched from the mother satellite at an aluminum target, which it was then successfully brought back to the mother ship [80]. Figure 2 below shows the test result as well as the cartridge used.

In 2010, Russia's Energia space program announced the study of an active space debris removal system through a net that would orbit and collect more than 600 pieces of space debris. The proposal suggested that the mother satellite to be nuclear-powered with a lifespan of about 15 years [81].

It is understood that Universities or other scientific bodies have designed many space debris removal programs. The difficulty in getting them into operation lies in the actual development and testing procedures, and this difficulty has economic, technological and political roots, as will be examined in the next chapter.

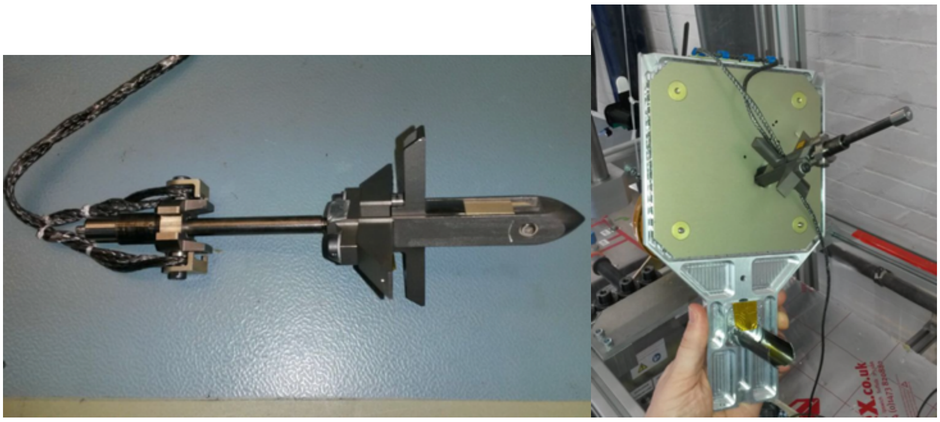
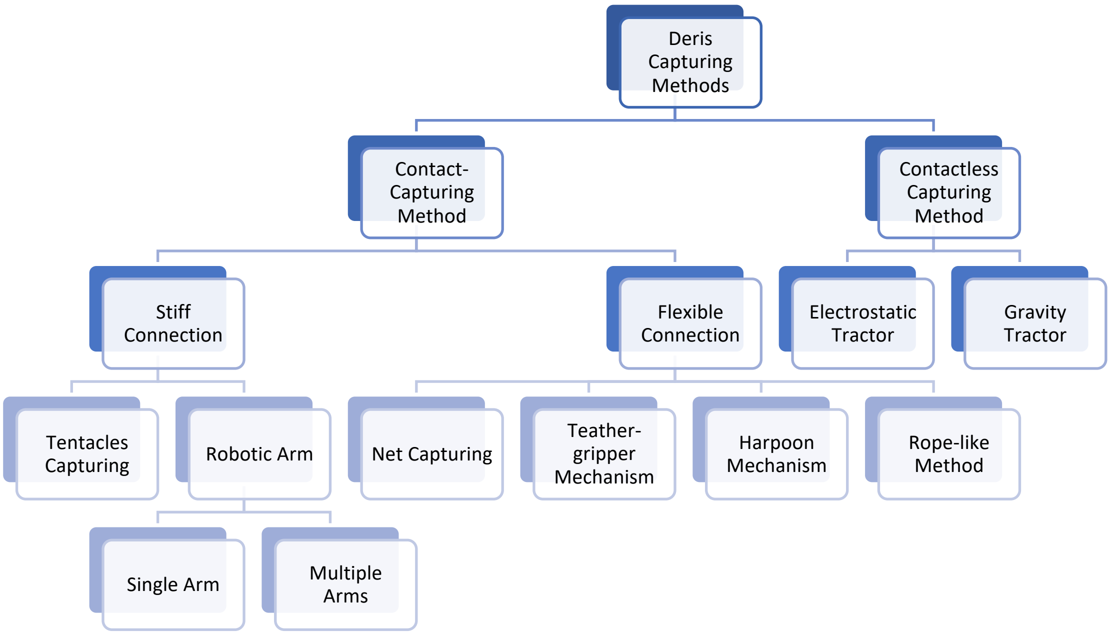


Figure 13. The cartridge used and the test result in cooperation of Airbus- Surrey Satellite Technology Ltd. (Retrieved from https://www.space.com/space-junk-harpoon-removedebris-satellite-video.html ,2022

5.1 Space Debris capturing methods

As shown previously, space debris is a significant threat for operational satellites and humans in space. Since the suggested 25-year safety standard is not followed yet, five to ten space debris objects will be needed to be removed every year for the near to earth space environment to be stabilized according to NASA [82]. In this subchapter, case studies concerning the active debris removal will be discussed.

There are five phases in a space mission for active space debris removal. Launch and Early orbit Phase (LEOP), far-range rendezvous phase, close-range rendezvous phase, capturing phase and removal phase. The methods discussed below are further divided into two main categories: contact and contactless [83]. A classification diagram is shown in Graph 9 showing the investigated space debris capturing methods. There are advantages and disadvantages in all of the as for now proposed methods which are listed at Table 5, below. There, the most relevant and researched methods are listed.



Graph 9. Concept Diagram of capturing methods [66]

Table 5. Overview of space debris capturing techniques [66]

Capturing Methods	**Advantages**	**Disadvantages**	**Existing Research**	**Institute**	**Reference**
Tentacles	• Stiff composite • Easy to test on ground • Higher Technology Readiness Level (TRL)	• Complicated Rendezvous phase • Possibility for bouncing • Accurate relative positioning and velocity needed	e. Deorbit CADET TAKO	ESA Aviospace Japan	[84] [85] [86]
Single robotic arm	• Stiff composite • Easy to test on ground • Higher (TRL)	• Higher probability of collision • Grappling point required • Rendezvous and docking needed	OctArm DEOS EPOS FREND	USA DLR DLR DARPA	[87] [88] [89] [90]
Multiple Arms	• Stiff composite • Easy to test on ground • Flexible capturing	• Complex control system • Higher mass and cost • Rendezvous needed	ATLAS	UK	[91]
Net Capturing	• Allows a large capturing distance • Reduced requirements on precision • Compatible for different size of debris	• Hard to control • Risk of critical oscillations • Hard to test on ground	ROGER e.Deorbit D-CoNe REDCROC	ESA ESA Italy Colorado	[92] [84] [93] [94]
Tether gripper	• Allows a large capturing distance • Short capture operation time • Lower mass and cost	• Difficult to test on ground • Grappling point required • Lower reliability	ROGER TSR	ESA China	[92] [95]
Harpoon	• No grappling point required • Allows a stand-off	• Risk of generating fragments • Risk of breakup	GS e.Deorbit	Astrium ESA	[96] [84]

distance to target • Compatible with different target types (rocket body or satellite)	• Flexible connection, difficult to redirect the movement of the target			

5.1.1 Stiff connection space debris capturing

5.1.1.1 Tentacles capturing

There are two methods proposed for capturing space debris through tentacles. The first uses a robotic arm to hold the target before the tentacle clamps onto the space debris. After the contact is achieved, the chaser increases its velocity having as a result the deorbit of the two objects as one mass [84]. This approach, however, leads to higher complexity, mass, cost and hazardousness in regard to the one that uses no robotic arm [97]. To achieve capturing by tentacles without using a robotic arm, the space debris should be embraced by the tentacles before there is any touching. This way, the chaser spacecraft will not bounce. When the tentacles are in position, the clamping mechanism is locked and the two objects come close to each other, becoming a stiff mass [98]. The materials that can be used for the tentacles can be anywhere from Zylon+ VITON or PES [85] for the belt type tentacles, to metal for the flexible robot arm-like tentacles [86] [87]. In Figure 14 four different types of tentacles capturing methods are shown.

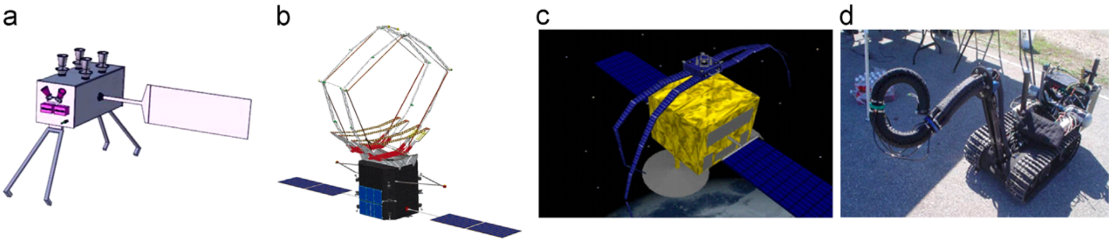


Figure 14. Tentacles capturing: (e.Deorbit/ CADET/ TAKO/ OctArm) [66]

5.1.1.2 Single arm capturing

Orbital space debris is non- cooperative nature as it can be a non- operational satellite, fragments from a catastrophic failure that will provide no information to the chaser spacecraft, or they may even tumble. Therefore, applying robotic arms in space debris capturing missions is quite challenging. The German Aerospace Center has been developing a program for capturing a non-cooperative and tumbling space debris target under the name Deutsche Orbital Servicing Mission (DEOS) [88].

To simulate the process, DLR has developed a ground-based simulator that simulates the entire process [99]. The challenges single arm capturing presents are being researched and some innovative ideas have been proposed. The three main areas where this research is aimed are the minimization of impact influence, attitude synchronization and de- tumbling. To minimize the impact influence, indicative research proposes a method to minimize the attitude disturbance by controlling the direction of relative velocity between the space debris and the chaser spacecraft [100]. Moreover, visual servoing for capturing a non-cooperative target through a Kalman filter that is used to predict the

respective motion between the target space debris and the chaser spacecraft [101].
As far as the de-tumbling is concerned, the residual angular momentum of the space debris objects makes them tumble, bringing difficulties for capturing via robotic arm method. According to research from JAXA, tumbling rates below 3º per sec do not create significant problems, while tumbling rates above 30º per sec cannot be regarded as target due to the impracticality of capturing. Rates between 3º and 30º per sec can be de-tumbled using brush contact as shown at Figure 15 [102].

When the tumble rate is relatively law, there is no need for de-tumbling, the two objects (target/ chaser), however, shall be attitude synched so that the capturing point is always directed towards the chaser spacecraft. Attitude synchronization consists of two aspects. The first has to do with tracking the relative position and the second with attitude reorientation. For these to happen, a translation control law and an attitude control law has been developed by Subbarao (2008) [103].

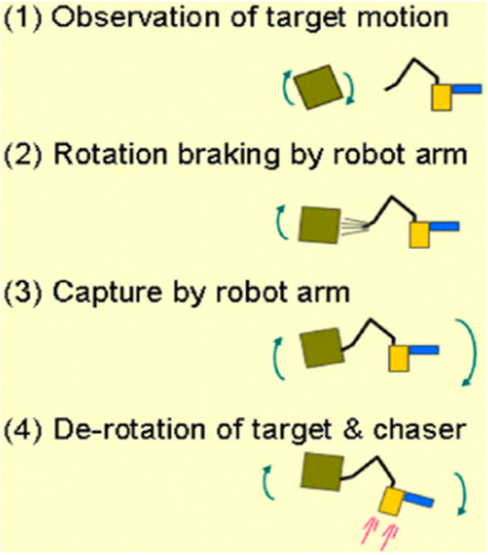


Figure 15. Brush contactor [60]

5.1.1.3 Multiple arms capturing method

Multiple robotic arms can be used for space debris capturing purposes. The second arm can be used to stabilize the satellite or to accomplish difficult tasks cooperating with the other one. ATLAS (Advanced Telerobotic Actuation System) program shows the capability of controlling robotic arms in space from the ground Figure 16 [91] [104].

Figure 16. Multiple robotic arms capturing method ATLAS [74]

5.1.2 Flexible connection space debris capturing

5.1.2.1 Net capturing method

A capturing method that is getting much attention by institutions and universities is the net capturing method. ESA is developing such a mechanism by the name Robotic Geostationary Orbit Restorer (ROGER). The net capturing mechanism consists of four weights, one in each corner of a net. The net is expanding by the weights upon shootout and thus wraps up the target debris [92]. Another similar to ROGER, in operation, system is e.Deorbit project [105]. Net capturing method is considered as one of the most promising methods for capturing space debris due to its advantages, such as cost efficiency, the fact that the net is light weighted and flexible and due to the fact that there is no need for close rendezvous and docking between the two subjects is not mandatory [83]. What is more to research in this matter has to do with the possibility of tumbling of the combined system after the capture and how that could be eliminated and also ways to stabilize the system if tumbling becomes uncontrollable. In Figure 17 four net capturing systems are shown.

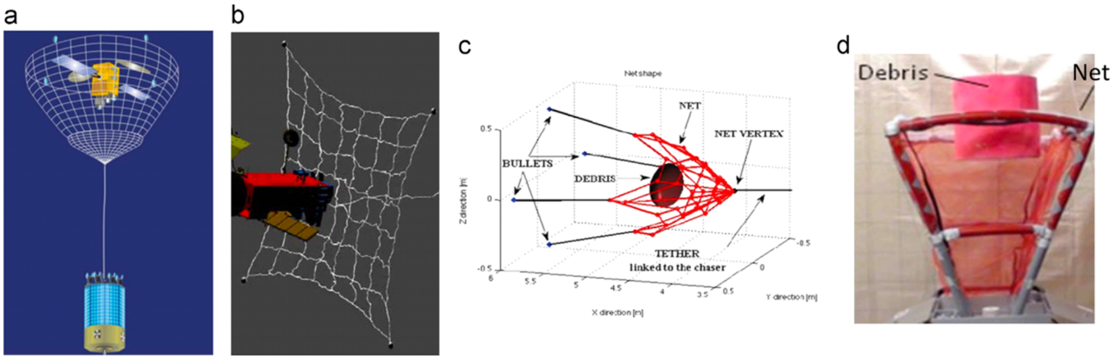


Figure 17. Net capturing systems: (ROGER/ e.Deorbit/ D-CoNe/ REDCROC) [66]

5.1.2.2 Tether-gripper mechanism method

The tether-gripper mechanism is another alternative for ROGER system. The operation of the two (net/ tether gripper) is similar as the only that differs is the end effector, for the first being a net and for the latter a 3-finger gripper which catches a part of the target with precision [92]. Another research under the name Tethered Space Robot (TSR) indicates that a tether-griper robot could benefit not only in capturing, but also attitude control, post-capture control and de-tumbling missions [95]. The riskiest part of the operation is the travel of the combined system after the capturing, as there is a high probability of collision between the target and the chaser spacecraft. For that to be avoided the tether must be in tension all the time and the force vector of the chaser spacecraft must coincide with the tether direction so as a safe transportation to reentry is assured [106].

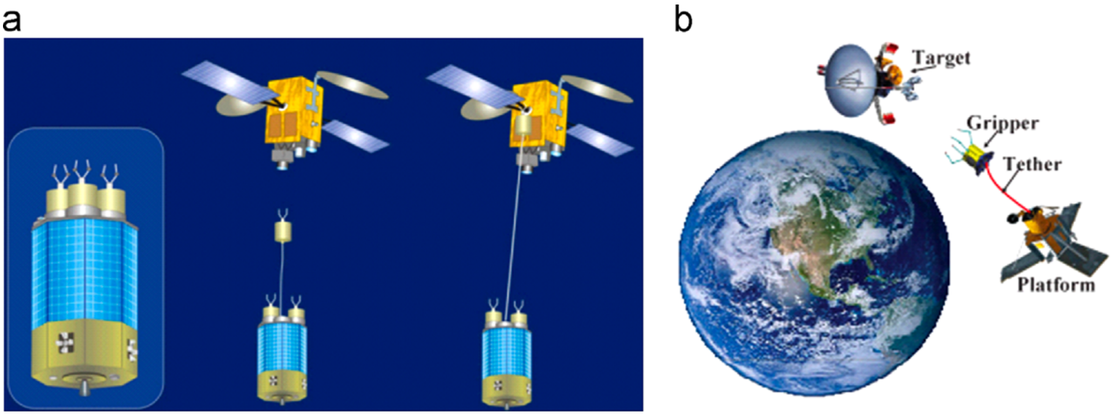


Figure 18. Tether–gripper capturing methods: (ROGER/ TSR) [66]

5.1.2.3 Harpoon mechanism method

Harpoon mechanism is a method that uses harpoons shot to the target, penetrating it and then either re-entering it, or pulling it to the graveyard orbit. Being able to capture targets with different shapes, needing no grappling point and being able to shoot the harpoon from a stand-off distance makes this method quite attractive. However, due to the penetration of the target, there is a high possibility of generating new space debris. In comparison with the net capturing method, the harpoon mechanism method is suggested by ESA for its easiness to be tested on ground [107].

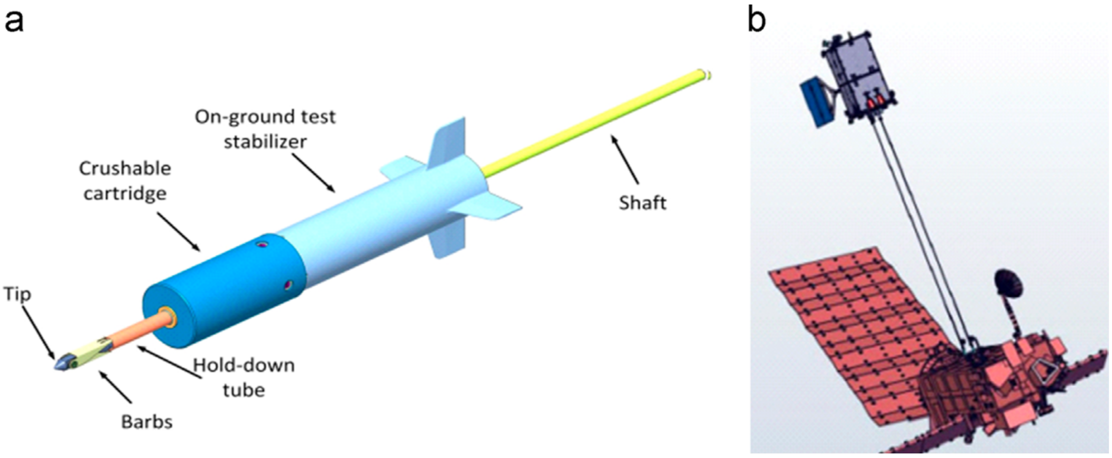
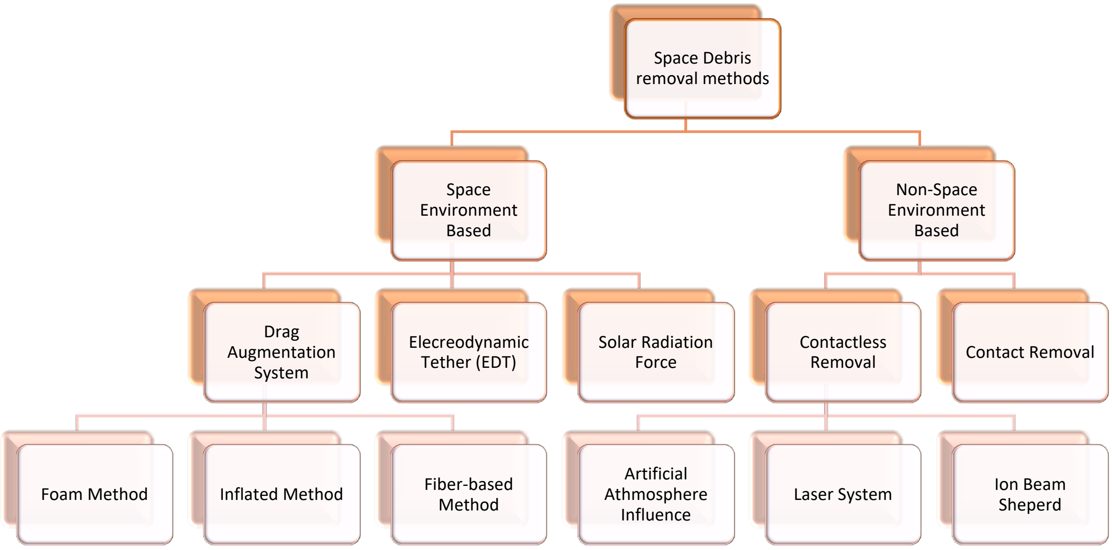


Figure 19. Harpoon capturing methods: (GS harpoon/ e.Deorbit) [66]

5.2 Space Debris removal methods

Space debris removal methods differ from those of space debris capturing. Some removal methods require capturing as well, but in most cases removal methods are designed to avoid capturing at all. The most promising methods are electro-dynamic tether (EDT), drag augmentation method (DAS), contactless removal methods and by contact removal methods [83] and these are going to be issued below as being the most relevant. Graph 10 below shows the concept diagram of the existing space debris removal methods, while in Table 6 the characteristics, advantages and disadvantages of removal methods are summarized.



Graph 10. Concept Diagram of removal methods [66].

Table 6. Overview of space debris removal techniques [66]

Removal Methods	Advantages	Disadvantages	Existing Research	Institute	Reference
Drag Augmentation System	• Allows a large distance • Compatible with different size space debris	• Risk of breakup • Less efficient	Foam Inflated Fiber-based	ESA GAC US-Patent	[108] [109] [110]
Electro-dynamic tether	• No need for propulsion system • High TRL	• Capture needed • Unavailable in GEO	EDT	JAXA	[111]
Contactless removal	• Allows a long distance • Compatible with different sizes of debris	• Less efficient • Unavailable in GEO	Artificial atmosphere Laser system Ion beam shepherd	US-Patent LODR ESA	[112] [113] [114]
Contact removal	• Multiple targets removed • Short working period	• Rendezvous needed • Complex control system	Slingshots Adhesive method	USA Astroscale	[115] [116]

5.2.1 Drag augmentation system

To accomplish the space debris reentry without having to perform docking or close distance rendezvous between the target and the chaser, the drag augmentation system is proposed. What is more, the chaser satellite does not have to pull the target into dense atmosphere for re-entry s this is accomplished by the atmosphere drag influence. Lastly, this method can be implemented in a wide range of space debris size. The main drawback is the fact that due to the atmosphere density distribution, this method can only be used for space debris orbiting at LEO [83].

Three drag augmentation methods gain attention as described below and are depicted in Figure 20.

5.2.1.1 Foam space debris removal method

As discussed above, the foam space debris removal method is a drag augmentation removal method using foam as a means to increase the area-to-mass ratio of the target space debris. When the chaser spacecraft has approached the target, it ejects foamy material that sticks all around the target turning it into a foam ball. The bigger area-to-mass ratio at this point leads the target space debris to re-enter due to atmospheric drag [117].

5.2.1.2 Inflation space debris removal method

An alternative to foam removal method is the concept of inflated method. According to this, an inflatable ball is attached on or in the satellite to be de-orbited and inflates around it, making it drag into the atmosphere ad re-enter. Gossamer Orbit Lowering Device (GOLD) is a representative of this method. The drawback here is that in case of the inflated ball is ruptured by a space debris fragment the whole re-entry mission is compromised [118].

5.2.1.3 Fiber-based space debris removal method

If the material used for increasing the area-to-mass ratio of a space debris target becomes fiber, then the fiber-based space debris removal method emerges. It is of the same concept as the previous two having fiber extruded by a heat source on the chaser spacecraft and wound around the target expanding its area [110].

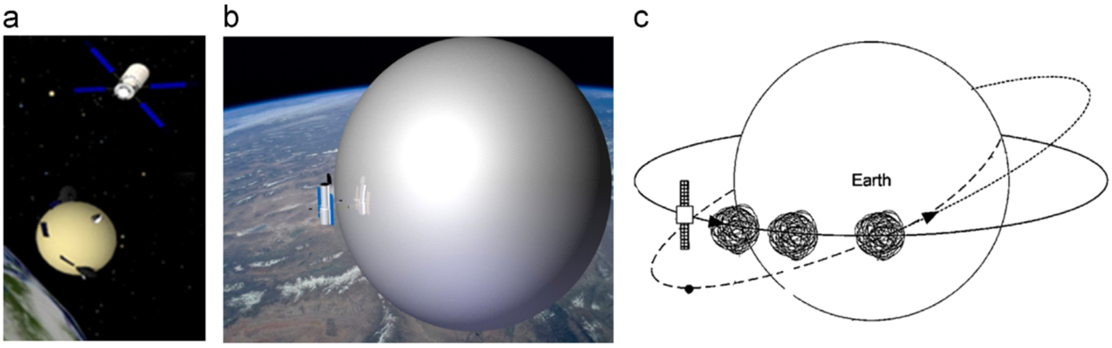


Figure 20. Drag augmentation: (foam/ Inflated/ Fiber-based method) [66]

5.2.2 Electro-dynamic tether removal method

In Electro-dynamic tether method, the earth's geomagnetic field is used to lead a space debris subject into reentry. To accomplish that, an electro-dynamic tether is installed to the target, after the chaser space system initially captures the target either via a harpoon or a robotic arm. The Lorentz force [119] generated from the interaction between the electromagnetic tether's current and the earth's geomagnetic field leads the space debris target to lower its altitude and eventually re-enter [120]. One of the advantages of electro-dynamic removal method is the fact that the chaser space system could continue to another space debris target after finishing with the first one. What is more to research is the material for the tether as it must be able to withstand the extreme space environment during the de-orbital period [121].

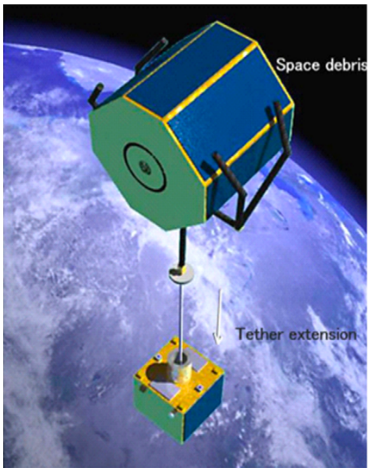


Figure 21. JAXA electro-magnetic tether removal method illustration [66].

5.2.3 Solar radiation force removal method

Johnson and Young (2002) made an extensive research on solar sail propelled missions. According to this method, a non-operational space system could use solar sails and exploit solar radiation in order to lower its orbital altitude so that it eventually re-enters. For the solar sails to be effective, they should be rotated fully facing the sun when moving towards it and parallel to it when moving away from it [122]. For this method to de-orbit a satellite in GEO would take at least 5.8 years [123]. However, for altitude below 750km solar radiation force is considered not applicable. This means that, probably, a combination of removing methods (i.e. solar radiation & drag) should be used on one mission [124].

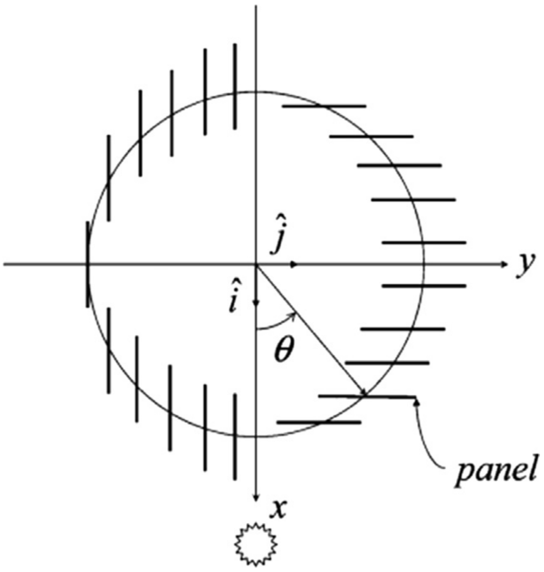


Figure 22. Concept of solar radiation force removal method [66].

5.2.4 Contactless removal method

To avoid the possibility of a situation where the system would become uncontrollable during capture and removal missions due to contact between the chaser system and the target, the contactless method is used. The contactless removal methods suggest that the de-orbit could be possible without physical interaction between the chaser and the target. To accomplish the above, a contactless removal mission has as a scope to reduce the velocity of the target and thus to lower its altitude by ejecting some medium objects through their trajectories [83].

5.2.4.1 Artificial atmosphere influence removal method

To lower the altitude of the target without contact, the artificial atmosphere influence removal method is proposed. According to this method, atmospheric type particles are ejected through a delivery system in an orthogonal to the path direction, having as a result the space debris target to decelerate and lower its altitude. Due to the fact that the ejected gases are causing no harm to other operational satellites and eventually fall back into the atmosphere the artificial atmosphere influence method is considered “green”, and also one of the most promising removal methods overall [125].

5.2.4.2 Laser system removal method

Another method to remove space debris is laser systems. Their goal is to decrease space debris’ velocity, thus lowering its altitude and make it re-enter. To achieve that, they use pulsed laser beam shoots. It is stated, that by the earth-based system ORION all space debris sized above 1 cm and having a mass below 500kg could reduce their altitude to below 1000km in a 4 years’ time period. The main drawbacks of the laser system are that it needs considerable power, is susceptible to weather conditions if based on earth and poses a risk to generate new space debris [126].

5.2.4.3 Ion beam shepherd removal method

Ion beam shepherd removal method uses a highly collimated neutralized plasma beam onto a space debris target lowering this way its altitude. In this method, a propulsion system is required, due to the fact that the chaser and the target need to remain within a distance of 10-20 meters, thus the propulsion system is needed to keep the above distance. The concept of Ion beam shepherd can be used to LEO and GEO orbits and what is more, it could be used to deflect an asteroid so as to avoid a catastrophic collision with earth [127].

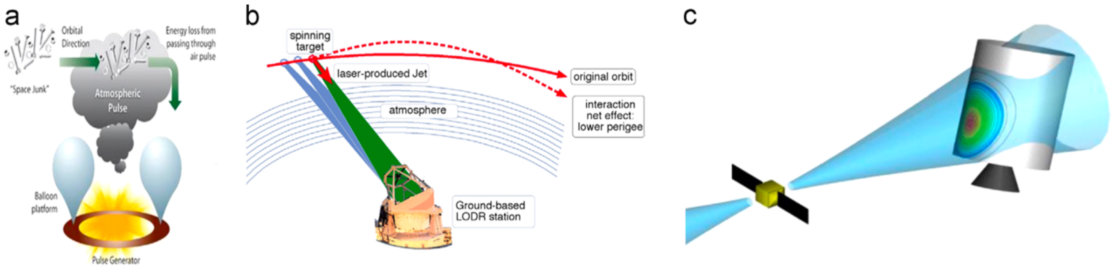


Figure 23. Contactless removal: (Artificial atmosphere/ Laser system/ IBS) [66]

5.2.5 Contact removal method

Contact removal methods, as it refers from their name, use space systems that come into contact with the target space debris. The two most promising approaches are the slingshot method and the adhesive method.

The slingshot method uses a space system which captures a target and therefore ejects it towards the inner atmosphere. The momentum force that is generated by the ejection sequence is then used by the chaser spacecraft to move to another space debris target [128].

The adhesive method uses a de-orbiting kit with a propulsion system that adheres onto the space debris target. It then removes the space debris from its orbit. The de-orbiting kit is carried by a mothership and is deployed accordingly. For the target to be objective, it should not have a tumbling rate more than 1°-2 ° per sec [116].

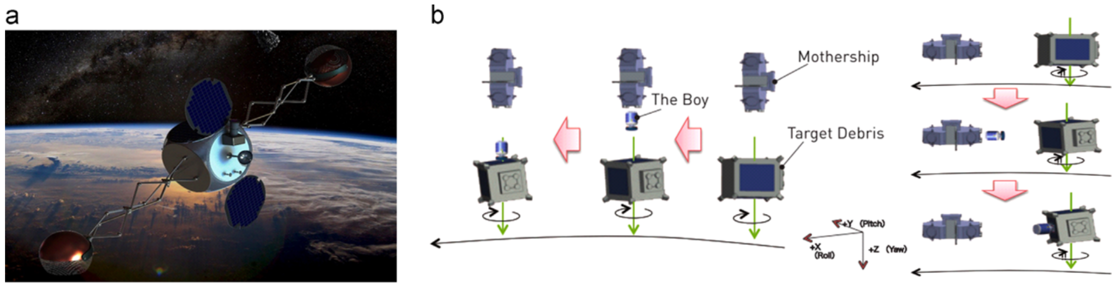


Figure 24. Contact removal methods: (a) Slingshots (b) Adhesive method [66]

6. SPACE DEBRIS ACTIVE REMOVAL METHOD EVALUATION SYSTEM PROPOSAL

In the previous chapters the general frame of space debris problem and the already proposed mitigation actions have been discussed. What hasn't been discussed is the attributes that an «ideal» space debris removal system should have. From the already discussed issues, it is easily derived that an ideal space debris removal system should fulfill certain political, economic, legal and technical requirements.

An example of political requirements, that should be fulfilled for a space debris removal system to be «ideal», include transparency in the development, deployment and operational phase, so that the system would be trusted from any other space-faring nation as to not be intentionally used to cause harm to other nations' in orbit satellites. Economic requirements for a space debris removal system to be most effective sum up to a reasonable cost-to-benefit ratio, so that the imported funding would bring a noticeable improvement in the space debris problem.

Legal requirements shall ensure compliance as much with the already established international laws and standards, in particular the five United Nations treaties on outer space, as with the potential new ones, that are needed to be established as discussed in the previous chapters. Lastly, technical requirements shall include maximum use of proven technologies, quick development and deployment and as minimum as possible new mass introduction into orbit.

The above considerations have brought upon the need for introducing an objective assessment method of Active Debris Removal projects and consequently the proposal of the as close as possible to ‘‘ideal’’ Active Debris Removal method by concluding the best strategies in each field being assessed. In order for the assessment to be most effective, it is of utmost importance a multidisciplinary evaluation to be performed, as a space mission is multidisciplinary in its nature.

The fields to be assessed in order to come up with the ideal proposal include the four previously discussed attributes, thus the Political Framework (PF), the Economic Framework (EF), the Legal Framework (LF) and the Technical Framework (TF). Emanuelli et.al, (2014) [34] have proposed these frameworks as crucial to be assessed when it comes to an ADR mission evaluation.

These frameworks will be assessed with specific criteria which will be given certain weight and will be identified with certain value. Political and Legal Framework will be considered as one, due to the close relationship and interconnection between the two. The proposal that will be given according to the assessment of the above criteria constitutes an early indication of the overall performance of a space debris Active Removal method and should be continued in later research by introducing more indicators that couldn't be introduced in the present research.

6.1 Evaluation method

The method followed for the assessment of the ADR systems is a scoring method that evaluates the performance of the ADR systems in the aforementioned frameworks. Each framework is assigned with points that measure the effectiveness of the project in each field. In each framework specific criteria are evaluated, given a score that is obviously lower than the total allowable for the general framework. The highest overall score would be 21 points and the lower -2. The specific criteria and the framework are representing, with the weaknesses that this research may have, all the possible schemes of an ADR mission. As it was presented in the previous chapter the ADR missions will be divided into capturing and removing phases and technological proposals in each phase will be scored separately. After indicating the scoring for each framework and its specific criteria the evaluation of the existing ADR projects will be assessed and the overall best scoring one will be presented. In addition, the possibility of matching two or more ADR methods, so that the ‘‘ideal’’ one is produced, will be researched.

6.1.1 Political and legal framework

Five specific criteria have been chosen for the evaluation of the Political (PF) and Legal Framework (LF). These criteria indicate the strategy that is used, the influence of the laws (international and national), the number of countries involved, the type of cooperation and whether the discussed ADR method could be possibly used for military scopes. The five criteria are indicated below:

i. Strategy
ii. Legal framework
iii. Type of cooperation
iv. Countries involved
v. Probability of military use

6.1.1.1 Strategy

For this specific criterion higher value will be given if a project lies within an elaborated strategy, that is developed by a space agency, another kind of organization or a cooperation in-between. The elaborated strategy is given the higher value due to the fact that it has better chances in facing the challenges that would emerge at legal economic and technical level. Biggest score here will be 2 and the lowest 0.

Table 7. Strategy Scoring

Capturing method	**Strategy scoring**
Tentacles	1
Single robotic arm	2
Multiple arms	1
Net capturing	2
Tether gripper	2
Harpoon	1

Removal method	**Strategy scoring**
Drag augmentation	1
Electro-dynamic tether	2
Contactless removal	1
Contact removal	0

6.1.1.2 Legal framework

In the previous chapters the complexity of the space law had been discussed. Active space debris removal has not yet clearly conceptualized in a legal framework due to the unclear definition of space debris, the complicated liability regulation and the lack of internationally approved licensing regulations. These legal uncertainties expose both public and private efforts at risk. The scoring in this criterion will depend on whether new legal procedures should be created or the ADR method is ready to follow the legal framework of the already established international space law. Highest score will be 2 and lowest 0.

Table 8. Legal framework scoring

Capturing method	**Legal framework scoring**
Tentacles	1
Single robotic arm	1
Multiple arms	1
Net capturing	2
Tether gripper	1
Harpoon	0

Removal method	**Legal framework scoring**
Drag augmentation	1
Electro-dynamic tether	2
Contactless removal	2
Contact removal	1

6.1.1.3 Type of cooperation

Space history has shown that the cooperation between nations give excellent results (i.e. International Space Station). The same applies to space debris mitigation strategies. By having many participants in a project, not only reduces the cost of the project development and operation, but also gives more opportunities that the object to be removed will fall into the legal jurisdiction of a member of the cooperation [34]. Thus, the higher score will be given in a multilateral cooperation. Highest score will be 2 and lowest 0.

Table 9. Type of cooperation scoring

Capturing method	**Type of cooperation scoring**
Tentacles	1
Single robotic arm	2
Multiple arms	1
Net capturing	1
Tether gripper	1
Harpoon	1

Removal method	**Type of cooperation scoring**
Drag augmentation	0
Electro-dynamic tether	1
Contactless removal	0
Contact removal	1

6.1.1.4 Countries involved

Given the current regulatory legal framework, the country involved in an ADR project influences greatly the success of the project. The country involved influences the technology available to be used, the economic resources being available and most importantly the space debris objects that can under the current legal framework be deorbited. On a national level the scoring will be law, due to the above reasons, while in an international cooperation the scoring will be higher, with the highest given when in the international cooperation USA or Russia is involved, due to the fact that these two countries have the higher number of orbiting space debris under their influence. Highest score will be 3 and lowest 0.

Table 10. Countries involved scoring

Capturing method	**Countries involved scoring**
Tentacles	2
Single robotic arm	3
Multiple arms	1
Net capturing	2
Tether gripper	2
Harpoon	1

Removal method	**Countries involved scoring**
Drag augmentation	2
Electro-dynamic tether	1
Contactless removal	2
Contact removal	3

6.1.1.5 Probability of military use

In this criterion the scoring is the lowest in the event that an ADR method could be possibly used by a state for weaponizing reasons or for non-peaceful use, thus violating the OST and international space law framework and the highest when the ADR method is used according to the above regulatory concepts and only for peaceful use. The lowest score will be negative (-2) and the highest 2.

Table 11. Probability of military use scoring

Capturing method	**Probability of military use scoring**
Tentacles	1
Single robotic arm	1
Multiple arms	1
Net capturing	-1
Tether gripper	2
Harpoon	1

Removal method	Probability of military use scoring
Drag augmentation	1
Electro-dynamic tether	2
Contactless removal	-1
Contact removal	-2

6.1.2 Economic framework

As described in the previous chapters, economic considerations for Active Debris Removal missions are quite broad and complex. For the purposes of this thesis only three specific criteria will be assessed. The first one has to do with the nature of the business involved, the second one with the estimated cost per mission and the last one with the estimated cost per kilogram of space debris deorbited.

6.1.2.1 Type of business

As discussed previously, a public-private partnership would be the ideal type of business cooperation to tackle the space debris problem. Therefore, the highest score for this criterion will be given to this type of cooperation, while the lowest will be given equally to public or private as standalone solutions. The highest score will be 2 and the lowest 1.

Table 12. Type of business scoring

Capturing method	Type of business scoring
Tentacles	1
Single robotic arm	2
Multiple arms	1
Net capturing	1
Tether gripper	1
Harpoon	2

Removal method	Type of business scoring
Drag augmentation	1
Electro-dynamic tether	1
Contactless removal	1
Contact removal	1

6.1.2.2 Estimated cost per mission

To define the estimated cost per mission (ECM), the total cost minus the development phase cost should be considered [34]. Thus, the definition of cost per mission includes three phases, those of operation, launch and manufacturing. While the cost of manufacturing and operation could be decreased as the missions succeed its other, the launch cost seems to get the greatest share of the total cost. Therefore, it is of great importance that the ADR missions' operators will find a way to reduce this cost, either by finding low cost launching solutions (i.e. reusable rockets), or by finding better logistics (i.e. ‘‘piggyback’’ solutions). The highest scoring will be 2 and the lowest 1 and will mostly be affected by the capability of the mission to be carried by reusable rockets and/or piggyback solutions.

Table 13. ECM scoring

Capturing method	**ECM scoring**
Tentacles	1
Single robotic arm	2
Multiple arms	1
Net capturing	1
Tether gripper	1
Harpoon	1

Removal method	**ECM scoring**
Drag augmentation	1
Electro-dynamic tether	1
Contactless removal	1
Contact removal	2

6.1.2.3 Estimated cost per kilogram deorbited

The estimated cost per kilogram deorbited (ECKD) measures the cost of a mission in an operational basis. It does not include the cost of the launch, due to ECKD being measured only for the orbital phase of an ADR mission. It is obvious that the more kilograms per mission of space debris deorbited, the more cost effective the mission would be. Highest score will be 3 and lowest 1.

Table 14. ECKD scoring

Capturing method	**ECKD scoring**
Tentacles	1
Single robotic arm	2
Multiple arms	2
Net capturing	3
Tether gripper	1
Harpoon	1

Removal method	**ECKD scoring**
Drag augmentation	2
Electro-dynamic tether	1
Contactless removal	1
Contact removal	2

6.1.3 Technical framework

Every new technology, before being implemented in a system, is firstly subjected to experiments, refinement and testing. This is due to the fact that the operators need to be, as much as possible, certain that the new technology will not cause harm, or that it will not cause financial disturbances in the program. After the new technology is tested and evaluated positively, it can then be implemented into a system or subsystem. In order to evaluate the readiness of a technology to be incorporated in real life systems/ subsystems, Technology Readiness Level (TRL) is used. TRL is a measure to assess if a new technology is mature enough to be incorporated in a technology project. It concerns the devices, the materials, the components, work processes, software and hardware in general. Aeronautic technology and especial instruments and spacecraft subsystems lie on a scale between 1-9 [34]. The TRL is scored in this research, due to its importance on possible delays and subsequent cost overruns.

The definition of each step in a Technology Readiness Level scale is as shown below [129]:

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment

- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

For the purposes of this thesis, TRL1-4 ADR systems will be scored with 1 point, TRL 5-7 ADR systems will be scored with 2 points and TRL 8-9 ADR systems will be scored with 3 points.

Table 15. TRL scoring

Capturing method	**TRL scoring**
Tentacles	2
Single robotic arm	2
Multiple arms	2
Net capturing	1
Tether gripper	2
Harpoon	3

Removal method	**TRL scoring**
Drag augmentation	1
Electro-dynamic tether	3
Contactless removal	1
Contact removal	1

6.2 Final scoring

Concluding the above scorings, they were summed up and are presented below as total scoring for both capturing and removal methods. Continuously there will be an effort to propose the best combination of capturing /removal method and the best ADR method according to the scoring results.

Table 16. Total scoring

ADR method	**Total scoring**
Tentacles	12
Single robotic arm	18
Multiple arms	11
Net capturing	12
Tether gripper	13
Harpoon	10
Drag augmentation	10
Electro-dynamic tether	14
Contactless removal	8
Contact removal	9

Highest
Second Highest
Lowest

As it is shown on Table 16 above, what appears to be the best capturing method, is single robotic arm method, while the best removal method appears to be the Electro-dynamic tether. Combining the two, an ADR method consisting of a mother space craft that would approach and grasp the space debris with a single robotic arm and continuously installs an electro-dynamic tether to it, so as the space debris-tether system would re-enter taking advantage of the Lorentz force and the earth's geomagnetic field interaction, arises.

The results show that the single robotic arm method excels in the below fields:

- Strategy (Elaborated strategy is used)
- Type of cooperation (many participants)
- Countries involved (USA-EU)
- Type of business (public-private partnership)
- Estimated Cost per Mission (reusable rockets practice)
- Technological Readiness Level (Between TRL 7 and TRL 9)

The results, also, show that single robotic arm method should improve in the below fields:

- Legal framework (complicated liability regulation and lack of internationally approved licensing regulations)
- Probability of military use (Could be used for capturing another nation's satellite after military orders)
- Estimated Cost per Kilogram Deorbited- ECKD (High cost)

For the Electro-dynamic tether as a removal method, the results show that it excels at the below fields:

- Strategy (Elaborated strategy is used)
- Type of cooperation (many participants)
- Probability for military use (Not probable due to slow times of mission completion needed)
- Technological Readiness Level (Between TRL 7 and TRL 9)

The results, also, show that Electro-dynamic tether method needs improvement at the below fields:

- Countries Involved (Mostly Japan)
- Estimated Cost per Mission-ECM (High cost)
- Estimated Cost per Kilogram Deorbited- ECKD (High cost)

It needs to be researched whether the above combination of capturing and removal methods, would really be the best solution in real operation and whether it could really become a reality technically.

Furthermore, research needs to be done on whether another combination of capturing and removal method, even if not between the highest scores, would give same or better results (i.e. Tether gripper/ score 13, with Electro-dynamic-tether/ score 14).

7. CONCLUSIONS

Concluding, the challenge of space debris is a significant danger to the near space environment, which threatens not only the integrity of space systems, but also the integrity of astronauts in orbit. The problem, although it has been recognized almost since the dawn of the space age, has not yet found a doable solution and remains a complex game between technological, economic, legal and political embankments. The large size range, the difficulty of observation and recording, and the general difficulty of constructing space systems are some of the technical problems that arise. Apart from the above however, there has not yet been an international legal decision that clarifies the legal elements of the general situation in space and consequently of space debris.

The space debris issue must be addressed holistically from the scientific, political and economic community, as a non-taking action mentality will mathematically lead to serious threats on safety and security not only for the orbiting humans and space systems, but also for the life on earth as we know it. The biggest threats for the orbiting space systems as well as for orbiting astronauts, comes from the possibility of collision with a space debris fragment and the threat for the on-earth systems comes from the degradation of the interconnecting space systems' capabilities due to space catastrophic collisions.

We believe that there is a need to take practical political decisions at the international level, which will pave the way for the legal coverage of efforts to remove space debris. Another area that creates significant embankments is the high cost of space depletion efforts. The private sector, having as its main goal the profit, can hardly decide to focus its efforts on something that will not bring in an immediate positive financial result. Therefore, it is the state or supranational space agencies, such as ESA, which, with the support of the governments of developed countries, will move in this direction, putting long-term gain in security and flexibility, over immediate economic benefit.

The space debris tracking, capturing and removal technology is not yet ready to perform in an operational environment, but the research that has been already be done can lead to quick results, if there exists an international cooperation for the legal, political, strategic, technological and economic bargains to be lifted.

The score model that was presented, gave an insight on which technologies seem to be more ready to immediate be implemented, but more research has to be done on whether there are other combinations of capturing and removal methods that could give better and/or quicker results.

Furthermore, we believe that more research is to be completed on the financial basis of Active Debris Removal projects. Technology has come to a high level of readiness; however, economic issues are becoming a bargain, resulting in these projects rarely coming near the operational testing stage. A new, more flexible business model should emerge through private companies and public space organizations' cooperation for these problems to be resolved. It seems, however, that for this to happen, further research on this matter should be done, as the new space era brings new ways of space business structure and operation.

What we think shall be emphasized the most, is the urgency of the need to take action as humanity, or else what we have managed to achieve in the space race could be very soon be compromised by our own thoughtlessness, demurrage and lack of international political agreement will.

ABBREVIATIONS- ACRONYMS

ADR	Active Debris Removal
AOD	Adaptive Optics Demonstrator
ASAT	Anti-Satellite Weapons
ATLAS	Advanced Telerobotic Actuation System
ATM	Air Traffic Management
CAM	Collision Avoidance Maneuvers
CARA	Conjunction Assessment Risk Analysis
CCD	Charge-Coupled Device
CDM	Conjunction Data Message
CMOS	Complementary Metal Oxide Semiconductor
CSpOC	Combined Space Operations Center
DARPA	Defense Advanced Research Project Agency
DAS	Drag Augmentation Method
DEOS	Deutsche Orbital Servicing Mission
DLR	German Aerospace Center
ECKD	Estimated Cost per Kilogram Deorbited
ECM	Estimated Cost per Mission
EDT	Electro-Dynamic Tether
EPFL	Swiss Federal Institute of Technology in Lausanne
ESA	European Space Agency
ESO	European Southern Observatory
GEO	Geosynchronous Earth Orbit
IAA	International Academy of Astronautics
IADC	Inter-Agency Space Debris Coordination Committee
ILRS	International Laser Ranging Ser
IMO	International Maritime Organization
ISO	International Organization for Standardization
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
ITU	International Telecommunication Union
JAXA	Japanese Aerospace Exploration Agency

KITE	Kounotori Integrated Tether Experiment
LC	Liability Convention
LEOP	Launch and Early orbit Phase
LODR	Laser Orbital Debris Removal
MEO	Medium Earth Orbit
OST	Outer Space Treaty
ROGER	Robotic Geostationary Orbit Restorer
RSAA	Research School of Astronomy and Astrophysics
SLR	Satellite Laser Ranging
SSA	Space Situational Awareness
SSN	Space Surveillance Network
STM	Space Traffic Management
TCA	Time of Closest Approach
TCP/IP	Registration Convention
TIRA	Tracking and Imaging Radar
TNT	Tri Nitro Toluene
TRL	Technology Readiness Level
TSR	Tethered Space Robot
UN COPUOS	United Nations Committee of Peaceful Uses of Outer Space
USSTRATCOM	U.S. Strategic Command
UTM	Unmanned air Traffic Management
WEF	World Economic Forum

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