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Contemporary Challenges of Space Debris Removal: Overview and Outlook

Master's thesis

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Declaration

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In Prague on 10.2.2021 Eliška Vojáková

References

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Abstract

The sustainability of the outer space environment is necessary for all actors to execute all existing and future human space operations safely. While the severe negative consequences of the uncontrolled space debris population are not new, government agencies and intergovernmental organizations' initiatives to lessen the predicament continue to be insufficient. Scientific research and simulation models show that mere mitigation measures cannot stop the ongoing degradation of the outer space environment polluted from the past space missions. Instead, research supports the development of space projects designed with a primary objective to remove debris from space. National administrations attempt to cooperate at the international level to formulate uniform debris mitigation standards and hold each other mutually accountable for worsening the space debris situation. However, joint public international missions to actively remove debris remain unthinkable. The privatization of space projects and operations continues to open the door to the commercialization of space and reduces the relevance of states as the primary players dominating the outer space domain, adding another dimension to solving the issue of space debris. This thesis examines the unrealized potential of operational debris missions while also investigating their ever-present technical and legal obstacles. The thesis contends that outer space's future stability depends on private entities' aspirations and accomplishments to develop and execute active space debris removal missions and the international community's willingness to give way to private entities to become self-sufficient space actors.

Abstrakt

Udržitelnost vesmíru je nezbytná k tomu, aby současní i budoucí vesmírní aktéři mohli bezpečně provádět všechny potřebné vesmírné operace. I přesto, že negativní důsledky nekontrolovatelně rostoucí populace kosmického odpadu jsou dlouhodobě známé, iniciativy vládních agentur a mezivládních organizací, které by měly vést ke snížení objemu kosmického odpadu a tím i k poklesu nesnází jím způsobených, jsou i nadále nedostatečné. Vědecké výzkumy a simulační modely ukazují, že pouhá preventivní opatření nemohou zastavit pokračující degradaci vesmírného prostředí, znečištěného již dávno vypuštěnými vesmírnými objekty. Výzkumní pracovníci se stále více věnují zkoumání vesmírných projektů, jejichž primárním cílem je odstranění orbitálních úlomků z vesmíru. Národní správy se pokouší spolupracovat na mezinárodní úrovni a formulovat jednotné standardy, které by zmírnily tvorbu nových orbitálních úlomků a stanovily by vzájemnou odpovědnost za zhoršení situace vesmírného odpadu, avšak uskutečnění společných mezinárodních misí za účelem aktivního odstraňování úlomků se nedaří. Privatizace vesmírných projektů a operací nadále otevírá dveře komercializaci vesmíru a také díky tomu dochází k poklesu relevance států jako primárních aktérů dominujících pro tuto oblast, což přidává řešení problému další rozměr. Tato diplomová práce shrnuje potenciál dosud nerealizovaných operačních misí pro odstranění vesmírné tříště a zároveň zkoumá jejich všudypřítomné technické, právní a politické překážky. Tato práce vede k závěru, že budoucí stabilita vesmíru závisí na aspiracích a úspěších soukromých subjektů při vývoji a realizaci aktivních misí pro odstraňování vesmírného odpadu a na ochotě mezinárodního společenství ustoupit soukromým subjektům, aby se staly soběstačnými vesmírnými aktéry.

Keywords

Space debris; Orbital debris; Space security; Active debris removal; Sustainability; International space law; Space exploration

Klíčová slova

Vesmírný odpad; Orbitální úlomky; Vesmírná bezpečnost; Zabezpečení kosmického prostoru Aktivní odstraňování vesmírného odpadu; Udržitelnost; Kosmické právo; Průzkum vesmíru

Title

Contemporary Challenges of Space Debris Removal: Overview and Outlook

Název práce

Současné výzvy odstraňování vesmírného odpadu: souhrn a perspektiva

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1. Introduction

The advancement of both civilian and military technology has enabled governments and private entities to explore and use the opportunities given by outer space. Acquisition of sufficiently sophisticated IT solutions, the development of new satellites, and breakthrough research have made various actors understand that full utilization of outer space offers a window of opportunity to advance their strategic goals. While states look to outer space and think of it as having a crucial and decisive strategic importance, private entities look to the domain to execute their ambitious projects and make new profits. With these ambitions in mind, states and private companies continue to develop new space assets at an ever-increasing rate. However, with the increase in the number of space assets in outer space since the space age began in the middle of the 20th century, problems associated with outer space exploration multiplied.

Space debris, or the so-called orbital debris, refers to non-functional human-made objects left behind in the Earth's orbit. The number of uncontrollable and dysfunctional space objects grew exponentially since the space arms race between the United States and the Soviet Union. The increase of space debris came not only because of the rise in the number of new space missions and space satellites but also because of several space events, including the 2007 Chinese anti-satellite missile test and the 2009 collision between the Iridium 33 and the Cosmos-2251 satellites. Space debris poses a threat to nations and their security and control over the political reign, companies, and their demanding research and space missions, but moreover, to any future attempt of the world civilization to reach outer space again.

The effect of space debris on the future arrangement of all space operations is conspicuous. All countries rely to a varying extent on space assets to conduct many of their functions, be it military, economic, social, or other, managed on land, in the air, or at sea. Out of all countries, the United States relies the most on its space assets for all sorts of operations via various Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) solutions (Defense Intelligence Agency, 2019). The United States owns the most comprehensive network of communications, reconnaissance, early-warning, positioning, and weather satellites, which enable the United States to relish the position of the world's leader in outer space affairs (Ibid.). At the same time, countries such as China try to use the window of opportunity that space offers to continue developing space assets as an area yet to be discovered and fully utilized (Ibid.). Another great actor in space operations is the European Space Agency (ESA), the forerunner on many space initiatives. ESA cooperates with a significant number of other European space agencies, including the Italian Space Agency (ASI), the British National Space Centre (BNSC), the French Space Agency (CNES), the German Aerospace Agency (DLR), and many others. Although dwarfed by the United States' presence, other actors in space, Russia, India, or Japan, also continue to have distinct motives to engage in a race to rule the space domain (Ibid.).

Yet, while most countries aim to reach the skies, their efforts to face and overcome the problem of space debris is somewhat limited. As space debris poses a significant threat to all of the space actors, it would be safe to assume that they would extend substantial endeavours to secure their chances of conducting space operations or even the chances of ever reaching the space again. In cooperation, countries have implemented numerous debris mitigation measures to wither off the dim future of a debris-clustered outer space, believing that limiting the creation of new space debris might solve the space environment's sustainability. However, researchers came hastily with a different prediction, claiming that even with the preventive measures in place, or even no new space operations, the space debris is on a course to multiply further (Liou & Johnson, 2006).

International guidelines for conducting sustainable space operations are insufficient to entirely prevent the number of non-functional objects and satellite fragments in space from increasing. Furthermore, the policies' implementation and prosecution are still challenging and burdensome. While, being aware of the bleak reality, international collaboration has not yielded more consequential attempts to diminish the risk posed by space debris by removing the human-made fragments from outer space altogether through active space debris removal missions. Simultaneously, countries, and their respective national space agencies, struggle to deal with the issue on an individual basis due to the exponential costs and efforts associated with active debris removal missions. However, the environment of space is changing, and privatization and, in turn, commercialization of the outer space environment might offer a way out to the states and state-owned entities struggling to mitigate the issue of space debris.

Since people first started to explore the space domain in the 1950s, states were the main actors, utilizing space for their national activities. Around the 1980s and 1990s, private actors' involvement in public space activities increased, mainly due to significant contributions to the development of advanced propulsion technologies (Iliopoulos & Esteban, 2020). Moreover, the split between public and private space activities blurred further with commercial cargo and crew mixing (Ibid.). Now, the private sector's pursuit of venturing into outer space to increase their profits and business value is replacing state actors' dominance. The authors such as Dr. Paikowsky refer to this change in the control over space activities as an overarching theme called the "New Space" (Paikowsky, 2017). New Space refers not only to private firms and agencies that are increasingly involved in global space activities but also to current technological trends, modern entrepreneurial activities, research and development initiatives, and goals of new space exploration missions (Paikowsky, 2017). In general, New Space summarizes the complexity of outer space's ongoing private commercialization (Paikowsky, 2017). Companies that previously supported public agencies, including NASA, in launching their operations are today competent and ready to launch their satellites into space (Iliopoulos & Esteban, 2020).

Another term used for today's space era is "Space 4.0" (Bohlman & Petrovici, 2019). Space 4.0 refers to the rise in the number of new space actors and the rapid technological advancements in the field as private investments, scientific progress, and university research fuelled society's interest in outer space propositions (Bohlman & Petrovici, 2019). While states continue to have the primary position in dealing with space affairs, privatization and commercialization of space, cooperation among intergovernmental organizations and non-governmental organizations, and the utilization of new business models have all influenced the traditional space activities exemplary in the 1950s. Space 4.0 mirrors Industry 4.0, a concept that describes technological progress and new industry models that continue to revolutionize modern production trends (Bohlman & Petrovici, 2019). The two arenas are strongly interlinked, as space operations' advancements depend on Earth's technological advancements (Bohlman & Petrovici, 2019). Simultaneously, space missions, space exploration, and new satellite deployment can increase connectivity, and remote operations can help solve the global challenges that industries face back on Earth.

On the one hand, the commercialization of space adds complexity to the issue of space debris. On the other hand, it poses an opportunity for rapprochement. Many companies such as

Amazon, OneWeb, or SpaceX announced earlier that they plan to release their mega-constellations into the LEO (OneWeb, n.d.; Starlink, n.d.; Henry, 2020). Mega-constellations, consisting of thousands of small satellites, will undoubtedly cause a spike in the number of orbital debris risks. However, the companies' pursuit of attaining a global telecommunications coverage is still very plausible and possible, if accompanied by thoughtful space debris solutions.

Contrary to the common belief that private space actors (and their mega-constellations) will cause only negative externalities, the opposite is more likely. Understanding that further human-caused deterioration of the space environment could seriously threaten all future commercial space explorations, private actors are willing to cooperate and conform to stricter regulations to avoid creating more space debris. Private entities, such as SpaceX, lead the way in improving the quality of their new satellites, rockets, and other equipment. By improving the equipment's structural integrity and manoeuvrability, SpaceX and other private space actors attempt to stabilize the already fragile outer space situation and avoid the creation of further space debris.

This thesis draws on and contributes to the already existing knowledge, as reflected in academic literature, and offers additional input into the often-undebated issue of active space debris removal, which is crucial in ensuring that all future space operations can be safe. While space debris poses a considerable danger, countries refrain from much more prudent cooperation to eliminate it due to obvious long-established bureaucratic reasons. However, this allows the private sector and commercial space agencies to advance their efforts and fill the void. As this thesis shall demonstrate, understanding that to safely conduct new space missions that would drive their businesses and profits, private actors are more inclined to investigate the means to dispose of space debris. While promoted by public funds from intergovernmental organizations and national space agencies, private actors are stepping up to execute needed active debris removal missions.

This thesis explains why countries that are incapable of prudent cooperation should support private actors capable of eliminating space debris from the Earth's orbit and why the private sector's initiatives to conduct sustainable space missions should be praised. At the same time, this thesis will demonstrate that all space actors must still attempt to improve and implement the outer space regulatory framework to reflect the economic and political backdrop of the 21st century. Until the space actors control the threat of space debris, they should investigate ways to decrease the rate of the creation of new space debris by, for example, limiting the number of brand-new spacecraft and satellite launched to outer space. As such, this thesis must answer the following several research questions. What threat does space debris pose? What are the leading international space debris mitigation measures? Who are the main actors in space, and what is the current status of their space debris countermeasures? Who should be responsible for the clean-up of space debris? What are the reasons for active debris removal missions? What are the prospects, dangers, and legal and technical limitations of space debris removal? What are the current ADR technologies discovered and used? And finally, what is the outlook for any cooperation among states or between state and non-state actors regarding space debris removal, and what is the prospect for the sustainability of the outer space environment?

Contrary to the delivered thesis project, the thesis structure focuses more on international or domestic public and private space agencies instead of individual governments' motivations.

Instead of mainly analysing why countries and national authorities of the various space actors (including the main actors such as the United States, Russia, China, and the European Union) restrain from much more prudent cooperation to eliminate space debris, this thesis takes this as given. Instead, it focuses on the more relevant topic of the private sector's involvement in alleviating the threat of space debris in place of governments. As the thesis shall further demonstrate, the change reflects the findings that the environment of space has changed, and private actors make up a very significant portion of all the current space initiatives. Simultaneously, all the existing active debris removal missions are prepared and run by private entities (although still under the umbrella of a state entity). It is easy to distinguish between the existing space debris removal projects due to the private companies' business rivalries. The project's changes were necessary to ensure that the thesis indeed covers the contemporary challenges of space debris removal and adds new suggestions to the already existing insights in the problematics of space debris.

1.1. Conceptual framework

When analysing the feasibility, prospects, and the technical and legal risks associated with any potential space debris removal missions, it is critical to keep in mind the outer space domain's anarchical nature through the structural realist thought lens. Its characteristics make the outer space domain an ungovernable territory. As standard features, such as borders, are missing, attributing responsibilities and accountability to space actors is challenging. Moreover, it is essential to recognize that the lack of obligatory binding regulations allows the space actors to act as they best see fit and feed the presumptions of individualism and mistrust among actors' motivations. States' attempts to mitigate debris from space is still perceived primarily as a state's covetous action to get ahead. Simultaneously, the existing space laws and regulations in place are loose, to say the least, with Cold War-like treaties such as the Outer Space Treaty, active since 1967, falling behind the swift technological advancements and the changing political nature, including the ever-flourishing participation of the private sector (UN COPUOS, n.d.). The legal framework does not account for or protect private entities' interests and does not administer arrangements to protect their property rights and obligations. Although the private sector's ongoing engagement in national and intergovernmental space missions adds another dimension to the field, states remain the primary actors in all outer space operations. While this thesis looks at active debris removal projects developed by private firms, an association with a national entity prevails.

1.2. Research hypothesis

Due to the space domain's anarchic characteristics and the lack of accountability associated with outer space and space debris, countries will continue to refrain from conforming to international regulations, making them bide or even stricter. Due to the lack of funds and dedicated budgets for outer space operations, nations and national space agencies will avoid conducting comprehensive cooperative operations to clean up outer space from space debris. As such, the space debris removal operations are likely to drag on as countries will choose to execute individualistic actions with their domestic assets instead of contributing to group projects. On the contrary, politically independent space agencies and private entities will continue to step up to actively remove space debris from orbit on behalf of nations limited by bureaucratic constraints. Profit and competitiveness-driven entities using public funds and donations have a greater chance and likeliness of executing necessary steps to complete active debris removal missions. Simultaneously, the international community's unwillingness to alter the global legal space framework to emancipate private entities as standalone space actors will continue to pose an obstacle to those same private entities in achieving their goals.

1.3. Analytical technique

This thesis uses sources such as historical and legal documents and academic articles to summarize the current magnitude of the threat of space debris and its dangers. The thesis then refers to many official international and national legal norms on conducting outer space operations, including debris mitigation standards and regulations, and compares them across countries. The thesis then summarizes several scientific articles and subject-specific research articles from experts on the prospects, technical limitations, possible dual-use threats, and the legal obstacles to active debris removal missions. After describing the different types of active debris removal scenarios' theoretical possibilities, the thesis contains a comparative case study research of the existing operational debris removal missions. Finally, the last part of the thesis holds the formulation of a possible outlook of the possible next steps in countering the threat of space debris, subject to discussion. The study's apparent limitation is that any perspectives on active space debris removal are highly debatable as any solutions or efforts to actively mitigate space debris are subject to external factors such as economic, political, and societal issues and norms. Classified government documents that contain more insights into planned national space operations, including possible national or intergovernmental debris removal missions, pose a limitation to this study.

2. The threat of space debris

Before examining the subject of debris removal, it is necessary to revive the seriousness of the threat posed by space debris. At any time, any actor launches an object into space, they unintentionally generate space debris in some form or another. Waste that any space activity generates, including solid-fuel rockets, aluminium alloys, copper or steel chips, explosive bots, fragmented pieces of paint, can cause significant damage to any functional object in space. The magnitude of the problem at hand is illustrated, for example, in NASA's Technical Memorandum of 1995 (Edelstein, 1995). In the memorandum, NASA contends that over its 14 years of existence, the Space Transportation System (STS) fleet encountered 177 different collisions with space debris chips (Ibid.). These collisions considerably damaged the STS's exterior window on several occasions (Ibid.). In several instances, the damage was so exponential that it meant whole replacements of the shuttle's window glass, which posed an enormous financial burden to the operations (Ibid.).

In 2009, on the 60th International Astronautical Congress, NASA contended that collisions between catalogued objects are relatively low in number (accidents are prone to happen once every five years) (NASA, 2009). However, the threat is primarily stemming from untracked debris that can cause small but very significant damage to satellites and other operational space equipment (Ibid.). Due to the high risks associated with long-term satellite deployment, satellites' insurance in the lower Earth orbit (LEO) is usually not longer than the first year (Ibid.). In addition to the natural debris arising from space exploration, the most notable accidents causing a sharp increase in the amount of space debris are the 2007 Chinese anti-satellite test and the collision of Iridium 33 and Cosmos 2251 on February 10, 2009 (Ibid.).

In 2019, India copied the Chinese anti-satellite missile test and created approximately 6500 new pieces of trackable space debris and even more fragments smaller than 2 centimetres (McFall-Johnsen, 2020). The clash of Iridium 33 and Cosmos 2251 produced the most significant increase in the number of uncontrolled freely flying bodies in space (NASA, 2009). The debris further multiplied at an exponential rate like never before, with orbital planes of the newly created revolving bodies covering a certain altitude most of Earth's orbit in the long-term (Ibid.). In comparison, Cosmos 2251 dispersed into a more significant number of small objects than its counterpart and now spreads over an immense latitude (Ibid.). While as any object in space faces natural decay characteristics, particles from the collision will still be orbiting Earth in more than 40 years, according to NASA's predictions (Ibid.).

To prevent similar collisions, such as the Iridium 33 and Cosmos 2251 collision, the Joint Space Operations Centre of the United States Strategic Command conducts collision assessments (NASA, 2009). The reviews focus primarily on United States' satellites (Ibid.). Still, per request (or own inquiry), the Command also performs examinations for any other orbiting objects that might be on a track to an accidental collision (Ibid.). Due to the conjunction assessments, it is then possible to adjust the pathway of functional objects in space and move them to a safer trajectory, thus manoeuvring them out of the way of a likely crash (Ibid.). Fortunately, the International Space Station and the Space Shuttle, critical space assets, do not face many collision threats and have to conduct manoeuvres to avoid collision on average less than once per year (Ibid.). On the contrary, the rest of the NASA fleet must execute, on average, two manoeuvres per year (Ibid.).

According to the United Nations' Online Index of Objects Launched into Outer Space, to this day, space actors launched over 10 620 objects to space, with over 60% still being in outer space now (UN, n.d.). The United Nations obtains information about most of the launched objects from sources other than official communication by countries to the United Nations (Ibid.). Governments continuously disregard the accepted Convention on Registration of Objects Launched into Outer Space and General Assembly resolution 1721 B (XVI) that request for countries to officially inform the international community about launching new objects to space (Ibid.). The United Nations' Online Index does not track non-functional objects at the moment, including space debris (Ibid.). Yet, from 1957, the number of launched satellites is exponential, even without considering the remaining space assets (Ibid.).

The threat of space debris is a subject of many studies. In their article, A. M. Bradley, and L. M. Wein (2009) determine through differential equations the space debris model in outer space and calculate the chances of collisions between objects during their lifetime (Bradley & Wein, 2009). In most studies that discuss space debris, scholars focus on analysing the altitude between 900 and 1000 kilometres (Ibid.). That altitude contains the highest number of uncontrollable space objects and is, as such, the most densely populated region of outer space. In the article by Althea V. Moorhead and Mark Matney (2021), the authors state that the altitudes between 600 and 800 kilometres have an exceptionally high concentration of space debris, mainly due to the collision mentioned above, that is, between Iridium 33 and Cosmos 2251, and due to the Fengyun-1C anti-satellite test that took place in 2007. Although between the altitudes of 600 to 1300km orbital risks to newly deployed functional space objects stem primarily from the debris population, at other altitudes, namely at altitudes below 270km and above 4800km, human-made items face threats of the impacts that originate from naturally present meteoroids

(Moorhead & Matney, 2021). It is essential not to fall for the misconception that human-made space debris poses the only risk to the existing functioning satellites and other functional space assets. However, as outer space is naturally dangerous, any space actor's duty not to increase that danger through its operations becomes even more crucial.

According to the information retrieved on January 5, 2021, the European Space Agency records around 3 300 operational satellites, around 18 920 pieces of space debris as tracked by the Space Surveillance Networks, and approximately 550 estimated collisions or other accidents that are likely to cause more space debris (ESA, 2021). Nonetheless, more striking are the approximate calculations of different statistical models that estimate the total amount of space debris to be nearly 129 million, out of which 128 million objects have between 1mm to 1cm in size (Ibid.).

As the number of functional and non-functional objects in space increases, so does their collision risk. In an article by Kessler and Cour-Palais (1978), the authors describe the growing number of artificial satellites in the outer space environment and the rising probability of future collisions. The Kessler effect describes the circular process, where satellite collisions create space debris leading to further clashes and even more freely floating orbiting fragments (Kessler & Cour-Palais, 1978). An unstopped flux in space debris would generate a belt of debris surrounding Earth and make all future space missions impossible (Ibid.). While the authors predict through a distinguished mathematical model the rate at which a debris belt might surmount into an intractable problem, all collisions would ultimately accelerate this rate (Ibid.). Inarguably, the magnitude of the space debris' worriment is exponential.

3. Decreasing the likeliness of new space debris: Space debris mitigation

3.1. The international space debris mitigation guidelines

The term sustainability, popularized in the 1970s, made people look critically at the effects their actions and behaviour have on the environment around them. As such, sustainability and environmentally friendly movements stormed primarily over the western culture and steadily across the world. While it is true that more and more people, as well as governments, incline towards the 'sustainability' concept when seeking protection of Earth's natural environment and the preservation of life as we know it, the sustainability of space is rather abstract for many, including scientific researchers (Iliopoulos & Esteban, 2020). In the most common terms, space missions conducted sustainably avoid human extinction or damage to the human existence on Earth, the degradation of the space environment (including space debris), and add to the knowledge of humankind by advance in research and data supply (Iliopoulos & Esteban, 2020). But by the end of the 20th century, countries became aware of the magnitude of the threat that is space debris and the risks associated with conducting new missions to the Earth's orbit and beyond.

Various international agencies started forming committees and subcommittees dedicated to space debris and guidelines for critical space debris mitigation. A common theme in all of them is data collection and sharing, precautions when designing and manufacturing new satellites, cooperation among states and agencies, increasing awareness, and dedicating funds to continuous research and development. Essential are also recommendations for the end-of-life disposal of satellites. Ideally, all satellites in the LEO region, including their stages, should re-enter Earth's atmosphere within 25 years post-mission use (ESA, n.d.). Satellites in the GEO region should be placed on a graveyard orbit approximately 300km top of the GEO ring (Ibid.). Satellites located at Lagrange points, where gravitational forces of two large co-orbiting bodies cancel out, must also conduct a deorbiting manoeuvre at the end of their lifetime (Ibid.). All satellites should deplete their energy reservoirs by the end of their lifespan to avoid exploding post-mission during a so-called passivation phase (Ibid.). Passivation includes planned depletion burns, ventilation, and batteries removal (Ibid.). Finally, all new satellites' design and manufacturing must follow the co-called 'design for demise' engineering process that ensures that any accidental re-entry of space equipment will not harm anyone or anything on Earth (Ibid.).

3.1.1. The Inter-Agency Space Debris Coordination Committee (IADC): Space Debris Mitigation Guidelines

In 1993, the Inter-Agency Space Debris Coordination Committee (IADC) highlighted the importance of space debris mitigation in the IADC Space Debris Mitigation Guidelines. The IADC's members are thirteen space agencies, including American NASA (National Aeronautics and Space Administration), British UKSA (United Kingdom Space Agency), Canadian CSA (Canadian Space Agency), Japanese JAXA (Japan Aerospace Exploration Agency), Korean KARI (Korea Aerospace Research Institute), Russian ROSCOSMOS, Ukrainian SSAU (State Space Agency of Ukraine), Chinese CNSA (China National Space Administration), European ESA (European Space Agency), German DLR (German Aerospace Centre), Indian ISRO (Indian Space Research Organisation), Italian ASI (Agenzia Spaziale Italiana), and French CNES (Centre National d'Etudes Spatiales) (Francillout, 2020, p. 2). The last annual meeting of the Committee occurred in April 2020 in France, where over a hundred experts gathered to discuss issues and share new information on space debris (Ibid., p. 5).

The Inter-Agency Space Debris Coordination Committee aims to facilitate the exchange of space debris information among its members, create an environment for sharing the progress status of members' research activities, and facilitate cooperation among the members to support the quest for debris removal methods. The IADC is a non-regulatory organization that only provides recommendations to its members and other willing space actors. IADC is a member of the UN COPUOS and also the Scientific and Technical Subcommittee (STSC).

The Committee's structure consists of a principal Steering Group controlling four distinguished Working Groups, dedicated to measurement (Working Group 1: Measurement), database (Working Group 2: Environment and Database), protection (Working Group 3: Protection), and space debris mitigation (Workin Group 4: Mitigation) (Francillout, 2020, p. 4). The campaigns of the Measurements Working Group includes a campaign of a 24-hour Lower Earth Orbit (LEO) radar survey to monitor the change in the population of space debris, a campaign to understand the movement of Active Space Debris (ADR) in space by measuring the optical light curves of large LEO objects, and a campaign to exchange and share information about space debris measurements of all members of the Committee (Ibid., p. 7). The Environment and Database Working Group analyses, for example, the dangers of a delay in implementing Post-Mission Disposal and Active Debris Removal and the dangerous prospects of deploying a large number of constellations to lower orbits (Ibid., p. 9). The third Working Group for Protection describes approach, methodology, risk assessment, and plans to guide space agencies to avoid space collisions and interference with space debris (Ibid., p. 10). One of the last achievements of the final Working Group for Mitigation is the creation of the IADC Space Debris Mitigation Guidelines to justify the Committee's position on the breakup of equipment during operation, the success of post-mission disposals in LEO and Geosynchronous Equatorial Orbit (GEO), the maximum time for presence in Lower Earth and Geosynchronous Equatorial Orbits, and the projection of re-entry accidents (Ibid., p. 12).

Governments adopted the IADC Space Debris Mitigation Guidelines in 2002 at the Second World Space Congress in Texas (IADC, 2005). Following the mitigation guidelines' adoption, the IADC also presented them to the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) Scientific and Technical Subcommittee (STSC) in November 2002. IADC members and IADC member states updated the document on several instances with new data and requirements following revisions, while the structure and base of all guidelines unchanging (IADC, 2007). The IADC divides the mitigation procedures into four main sections. First (Section 5.1), IADC describes mitigation measures limiting the amount of space debris that spacecraft and space assets release during usual operations (IADC, 2007). Second (Section 5.2), IADC describes mitigation measures when minimizing the likeliness of on-orbit breakups (IADC, 2007). In the third section (Section 5.3), the IADC describes mitigation measures for the safe disposal of ex-operational equipment following the end of their lifetime (IADC, 2007). Finally (Section 5.4), IADC describes mitigation measures when preventing the chances of on-orbit collisions of space equipment with naturally occurring space objects and other human-man equipment in space (IADC, 2007). The IADC Space Debris Mitigation Guidelines is the leading document accompanied by documents such as the "Support to the IADC Space Debris Mitigation Guidelines" and the "Procedure for Re-orbit from GEO" (IADC, 2005). Other records include the Assessment procedure for Re-entry Safety and other IADC documents

(IADC, 2005). The supporting documents help explain the mitigation guidelines of the IADC by numerical justification and explanation of their origin and rationale. Furthermore, they provide applicable references and specific examples.

3.1.2. The Committee on the Peaceful Uses of Outer Space (COPUOS): Space Debris Mitigation Guidelines

Accompanying, in 1994, the COPUOS officially added space sustainability and space debris on its agenda. In 1996, the Committee and the COPUOS Scientific and Technical Subcommittee agreed to conduct a thorough study of the space debris issue's scale. Within three years, in 1999, the Subcommittee published its first elaborate Technical Report on Space Debris. The report informed the United Nations of space debris' number and urgency, modelling outer space's environment, and providing mitigation measures to prevent further uncontrolled escalation of the space debris problem (UN, 1999).

After more years of research, debates, and preparations, the COPUOS Subcommittee set forth its own concrete United Nations guidelines for space debris mitigation in 2005 (UN OOSA, 2010). The guidelines, now available in the document called the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space, were endorsed by the General Assembly in 2007 to be voluntarily accepted by the United Nations member states (Ibid.). The previously mentioned IADC Space Debris Mitigation Guidelines served as the basis for these United Nations' mitigation recommendations. The document contains seven general guidelines aimed at mitigating space debris during the space asset's normal operations, during breakups, and deorbiting (Ibid). The guidelines also advise limiting the probability of accidental collisions and avoiding hazardous activities (Ibid., p.2-3). Furthermore, guideline number 5 states that satellites should have only a minimum of stored energy onboard when their mission is complete (Ibid., p.3). Guideline 6 then states that operating states should make maximum effort to deorbit satellites from the Lower Earth Orbit at the end of their life (Ibid., p.3).

Continuing in their ambitions, in 2010, the COPUOS established a Working Group dedicated to the Long-Term Sustainability of Outer Space Activities. This Working Group's main task was to come up with a set of guidelines to be followed by all space actors that would limit the danger to the environment of outer space. In 2018, the Working Group finished its task and came forth with 21 guidelines with United Nations member states' advice to implement them in the upcoming years (UN COPUOS, 2018a). The guidelines are divided into four main sections, focusing on policy and regulations, including data collection, safety, cooperation and awareness, and research and development (UN COPUOS, 2018a). Guidelines that mention the issue of space debris are guidelines A.2 2. (b), A.2 2. (f), B.3 1., B.7 5. (b), B.8 2., C.4 4., and D.2 (UN COPUOS, 2018a).

Guideline A.2 2. (b) asks countries to consider implementing space debris mitigation measures outlined in the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space (UN COPUOS, 2018a). Guideline A.2 2. (f) then asks countries to consider abiding by the Inter-Agency Space Debris Coordination Committee's recommendations regarding space debris measures (Ibid.). Guideline B.3 1. asks countries to collect and share information about space debris among other nations and the United Nations (Ibid.). Guideline B.7 5. (b) asks countries to consider the effects of weather when calculating pathways of objects at the end of their life when they shall deorbit or reach a designated graveyard orbit (Ibid.). Guideline B.8 2. asks governments and international intergovernmental organizations to give incentives to the manufacturers of their space equipment to design and produce products that would not cause excessive space littering (Ibid.). Guideline C.4 4. asks countries to cooperate with non-state entities that have a crucial role in raising awareness and future improvements to the field, including developing more sustainable approaches to new space activities (Ibid.). Finally, whole guideline D.2, the last of the 21 policies, is dedicated to measures that would foster investigation and the development of new standards that could manage the problem of space debris and decrease it in the long term (Ibid.).

The main issue with the guidelines is their vagueness and lack of enforcement. While the United Nations' Space Debris Mitigation Guidelines and the Guidelines for the Long-term Sustainability of Outer Space Activities are not legally binding, some countries have implemented the space debris regulations outlined in the documents into their national legislation (UN COPUOS, 2019).

3.1.3. Other crucial international debris mitigation guidelines

There are four more fundamental international documents worth mentioning in addition to the UN COPUOS and the IADC debris mitigation guidelines. Firstly, the International Organization for Standardization's ISO 24113:2019 applies to most objects launched into space. The current ISO replaces the ISO space debris standards from 2011 (ISO 24113:2011). Secondly, similar to the ISO, there is the International Telecommunications Union's Recommendation ITU-R S.1003.2. Furthermore, in 2014, the ESA Director General's Office issued a document binding to all ESA's projects, the Space Debris Mitigation Policy for Agency Projects (ESA, 2014). The document recognizes the need for ESA's projects to minimize any impact on the orbital environment. The policy incorporates the 2nd edition of ISO 24113 Space

Systems – Space Debris Mitigation Requirements. Finally, the European Code of Conduct for Space Debris Mitigation (first drafted in 2004) applies to all operations of the Italian, British, French, and German national space agencies and the European Space Agency (ESA, 2004). The first European space agency to sign the Code of Conduct was the French space agency (CNES) in 2004 (ESA, 2005).

3.2. The implementation of the space debris mitigation guidelines

States' willingness to cooperate and mutually accept overarching space debris regulations is considerable, as countries understand that such steps are in their self-interest. State actors incorporate into their domestic law sections from the space debris mitigation guidelines or turn to policies outlined in the European Code of Conduct for Space Debris Mitigation, ESA Space Debris Mitigation for Agency Projects, the ISO 24113:2019 (Space systems — Space debris mitigation requirements), or the S.1003-2 (12/2010) Environmental protection of the geostationary-satellite orbit of the International Telecommunications Union (ESA, 2004; ESA, 2014; UN COPUOS, 2018b; ISO, 2019; ITU, 2010).

In 2018, Czech Republic, Germany, and Canada formulated a comprehensive overview of the legal mechanisms addressing space debris across countries (UN COPUOS, 2018b). The Compendium is continuously updated by the overlooking countries, with the last updates dating 2019 (UN COPUOS, 2019). The Compendium serves as a necessary input for sharing and tracking information about countries' space debris mitigation measures to UN COPUOS Committee and Subcommittees dealing with the debris problematics (Ibid.). While not offering an exhaustive list of countries and their space debris mitigation guidelines, the document serves all United Nations member states as a template or benchmark for review when developing similar country standards (Ibid.). The Compendium includes European countries like Austria, Belgium, Czech Republic, Finland, France, Germany, Italy, Greece, the Netherlands, Poland, Slovakia, Spain, Switzerland, and the United Kingdom. Countries like Australia, Canada, Indonesia, Japan, Ukraine, and the United States also appear in the document (Ibid.). Still, only some of these countries have national mechanisms addressing space debris on top of respecting and supporting the international guidelines.

3.2.1. European countries

Austria's national legal framework includes the 2011 Austrian Outer Space Act and the 2015 Austrian Outer Space Regulation (UN COPUOS, 2019). The former legislation states that all activities in space and their operators must account for special considerations for the mitigation of space debris (Ibid.). Operators must abide by the international guidelines and take special precautions to avoid accidentally creating waste fragments through the space vehicle's standard operations (Ibid.). In their legislation, Austria shows a strong understanding of the importance of the threat posed by space debris, and their commitment to follow the internationally recognized rules, even though they are nonbinding, is evident (Ibid.). The Austrian Outer Space Regulation of 2015 outlines the space debris mitigation guidelines' implementation details, including the different considerations for functional and manoeuvrable, and non-manoeuvrable objects (Ibid.). While operators must mitigate the chances of breakups and collisions or working satellites, they must also take sufficient measures when deorbiting non-functional satellites and removing them from high-frequency orbits (Ibid.).

In Belgium, the state passed the Law of 17 September 2005 on Activities of Launching, Flight Operation or Guidance of Space Objects and Royal Decree of 19 March 2008 (UN

COPUOS, 2019). While these documents do not explicitly contain any space debris mitigation guidelines, they enable the Minister to impose regulations adopted by international bodies or non-governmental organizations on the Belgian operators (Ibid.). The state then has the right to supervise that all operators abide by the rules and may ask experts to check their compliance on their behalf (Ibid.). That is why Belgium concluded a separate agreement with ESA to support Belgian entities in conducting reviews (Ibid.). Finland adopted the Decree of the Ministry of Economic Affairs and Employment on Space Activities, stating that all vessels in Finland or registered in Finland must ensure that their operations do not lead to the creation of space debris (Ibid.). In the French Space Operations Act n°2008-518, France reserves the right to demand operators' compliance with regulations to protect public health and the environment, including protection from the creation of excess space debris (Ibid.). In 2011, France also passed a Decree on Technical Regulation issued pursuant to the French Space Operations Act n°2008-518 that outlines lengthy space debris mitigation provisions (Ibid.). The act and the decree apply to all operations carried out from French territories, launched by a French entity, or controlled by a French operator or a French operator from a foreign country (Ibid.). The Netherlands regulates its space activities with the 2007 Space Activities Act, enabling the government to engage in prudent cooperation with other European countries and space agencies (Ibid.). However, there are no specific debris mitigation guidelines that would govern the Netherlands' activities in this regard (Ibid.).

Since 2012, Germany's Space Agency (Deutsches Zentrum Für Luft- Und Raumfahrt E.V. (DLR)) must abide by the Product Assurance and Safety Requirements for DLR Space Projects (UN COPUOS, 2019). This mechanism contains all the provisions in the international space debris mitigation guidelines that German authorities helped draft (Ibid.). Germany's commitment to space debris mitigation is evident from its proactive presence at international meetings on this topic. Contrary to the DLR, the Italian Space Agency (ASI) does not abide by any national legislation (Ibid.). Instead, since 2005, ASI primarily follows the European Code of Conduct for Space Debris Mitigation when managing Italy's space operations. Knowing that Italy already released assets into space before adopting the European Code of Conduct, ASI tried to apply the European provision to those missions to the greatest possible extent (Ibid.). For example, ASI attempts to deorbit and dispose even of its oldest satellites. By conforming to the European space debris standards, ASI also indirectly conforms to the other international debris mitigation guidelines (Ibid.).

In the United Kingdom, all nationals are subject to the Outer Space Act (OSA) of 1986 (UN COPUOS, 2019). The act guards and protects public health and limits negative externalities caused by any space activity (Ibid.). The OSA gives the Secretary of State the right to grant and withhold licenses from entities that do not conform to the regulations as stated in the act (Ibid.). The United Kingdom Space Agency upholds the Outer Space Act's safety requirements and conforms to the other international recommendations (Ibid.). Countries like Czech Republic, Poland, Slovakia, Spain, and Switzerland, while not having any national regulations on space debris mitigation or removal, support the internationally accepted guidelines (Ibid.).

3.2.2. European Space Agency (ESA)

The European Space Agency set up its first Space Debris Working Group already in 1986 (Flury, 1993). Based on the Space Debris Working Group's outcomes and findings, the ESA's Council defined ESA's objectives and a plan of activities to reduce the growth of the space debris threat. At that time, ESA formulated five main areas to focus on, including minimization of the creation of any more space debris, secondly, reduction of the risks for new space flight, thirdly, reduction of the risk of space debris re-entry, fourth, generation of further space debris data, and finally, the study of legal aspects of space debris (Flury, 1993).

The European Space Agency has access to its database to track the number and the position of space debris, the DISCOS database. DISCOS, Database and Information System Characterizing Objects in Space, is the essential source of all relevant information for ESA's Space Debris Office (DISCOS, n.d.). ESA uses its DISCOS data to analyse all possibilities of collisions, re-entry accidents and serves as the basis for operational processes. The data is also useful for various academic and industry reporting (DISCOS, n.d.). On top of DISCOS, ESA also analyses information and data returned from experiments such as EURECA and the Hubble Space Telescope's solar arrays.

On top of its initiatives, the ESA tries to maintain open relations with other space actors to tackle outer space issues, including space debris. The ESA maintains an observer status at the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), which at times deliberates on space debris and its removal. Due to ESA's presence, the agency may express its opinions on the matter, which increases its collaborative image on the topic. The ESA also cooperates closely with NASA, the Russian Space Agency, and Japan. These four actors first joined forces on space debris in 1993 at the First European Conference on Space Debris. At that meeting, the four actors created the Space Debris Coordination Committee, which established regular meetings to exchange information and space debris experiences. Due to the cooperation between the four countries, the ESA also gained access to the other three actors' surveillance networks and facilities that now enrich the DISCOS database (Flury, 1993).

In 2019, ESA's Council at Ministerial Level, Space19+, endorsed an ambitious plan for ESA's future operations (ESA, 2019a). At the Space19+ meeting in November, ESA's members, together with additional European observers and Canada, discussed new programs aiming to strengthen and secure the Earth and the Solar System (Ibid.). The ESA ambitions include ensuring an ongoing Europe's access to space, developing new technologies and bolstering knowledge, and growing the European space economy (Ibid.). Securing the possibility of ESA's operations requires considerable funding. Understandably, adding even more to the understanding of the human universe is costly. However, ESA and its members approved and committed themselves to the largest budget in its history (Ibid.). As such, ESA ministers gave the green light to an eventful future. ESA will continue to send its astronauts into space, each for a second time, and continue to recruit new astronauts to participate in ESA's upcoming missions (Ibid.). ESA will send its astronauts to the Moon for the first time, and the organization also confirmed the launch of a Mars Sample Return mission on which ESA will cooperate with NASA (Ibid.).

ESA also respects the new environment of space, New Space, and seeks to help private entities fearlessly and seamlessly invest their resources in outer space gadgets and inventions. ESA plans to be the first to develop a satellite system, fully compatible with 5G networks and futuristic optical technology, creating an interconnected communications network (ESA, 2019a). ESA also designated a budget for commercial companies' funding to develop new navigation applications (Ibid.). The agency continues to implement new technologies, including newly developed space launchers, Ariane 6, and Vega-C (Ibid.). Committed to space sustainability, ESA will be launching its new space operations in a reusable spaceship, the Space Rider (Ibid.). To develop new space equipment, modernize its operations, guarantee to keep up with the changing environment of space, and the ongoing digitization and transformation of markets, ESA stresses the importance of cooperation (Ibid.). The ESA Member States work closely together to achieve the agency's goals, and the actors strongly cooperate with the other international space agencies.

ESA's commitment to space sustainability is evident through its adoption of Space Safety as a new pillar of its fundamental operations (ESA, 2019a). ESA's goal is to automatize space traffic control to enable a more effective way to warn and lower the potential cause of harm to Earth and space assets from asteroids, solar flares, or space debris (Ibid.). ESA's studies show that the only way to stabilize the home of orbiting objects is to remove large non-operational items from space actively (ESA, 2019b). For that, ESA is long developing crucial navigation systems and technologies, enabling the capture of space objects under the umbrella of the Active Debris Removal/ In-Orbit Servicing – ADRIOS project (Ibid.).

3.2.3. Countries outside of Europe

Outside of Europe, while Australia did not adopt the international guidelines in its national mechanism, it has two policies that mention Australia's commitment to the mitigation of space debris while adhering to the United Nations Space Debris Mitigation Guidelines (UN COPUOS, 2019). The guidelines are the 2013 Australia's Satellite Utilisation Policy and the Guidelines for Applicants seeking to apply for an Overseas Launch Certificate (Ibid.). Similarly to Australia, Indonesia has not yet implemented the international debris mitigation guidelines in full (Ibid.). Still, it takes space debris mitigation into account in its domestic law Number 21 of 2013 on Space Activities (Ibid.). Canada commits to space debris mitigation standards in the 2007 Canadian Remote Sensing Space Systems Regulations and the 2014 Canadian Client

Procedures Circular (CPC) for Licensing of Space Stations (Ibid.). Moreover, the Canadian Space Agency officially adopted the IADC Space Debris mitigation guidelines in 2012 and since then is bound by the regulations when conducting any space missions (Ibid.).

Japanese Aerospace Exploration Agency (JAXA) demands that all of its missions and contractors conform to the JAXA-Management Requirements (JMR-003B) (UN COPUOS, 2019). The requirements updated the NASDA "Space Debris Mitigation Standard" (NASDA-STD-18) document when NASDA merged into and became JAXA and when Japan also wanted to include provisions outlined in the ISO 24113 requirements (Ibid.). The Japanese space debris mitigation guidelines were among the world's first standards to emerge (Ibid.). The guidelines are very technical, detailed, and specific, while at the same time not as precise as the standards that NASA has in place (Ibid.).

Another country with considerable outer space ambitions is Nigeria. Nigeria established the National Space Research and Development Agency (NASRDA) in 1999, and since then, Nigeria has placed several satellites in space (Ikpaya et al., 2016). NASRDA's mitigation standards are a part of the founding National Space Research and Development Agency Act 2010 No.9 A1255 (UN COPUOS, 2019). The National Space Council oversees Nigeria's outer space activities and supervises that all projects consider protecting the space environment and other actors' assets (Ibid.). Nigeria fully supports the international debris mitigation guidelines and is a proactive member of the specialized United Nations Committee and Subcommittees (Ibid.).

Late in 2020, India and Nigeria signed a Memorandum of Understanding (MoU) and tied their mutual interest in cooperating when exploring outer space (South Asia Monitor, 2020).

The Indian Space Research Organization (ISRO) is also committed to international mitigation measures and seeks to cooperate with Nigeria and other countries on maintaining outer space sustainability. The ISRO has a debris tracking software enabling it to conduct necessary adjustments to its satellites' path, continues to work on more sustainable launching methods, and introduced adequate propellant margins for successful deorbiting of inoperable satellites (Adimurthy & Ganeshan, 2006).

The Russian Federation's State Corporation ROSCOSMOS is legally obliged to take precautionary measures to protect Earth's outer space environment and design and manufacture satellites and missions with a minimum negative impact on outer space (UN COPUOS, 2019). In the "Fundamentals of the Russian Federation's State Policy in the Field of Space Activities for the Period up to 2030 and beyond, Russia commits to protecting Earth's orbit from artificial pollution and preventing the rise in the volume of space debris (Ibid.). New modern Russian space missions are designed in such a way to avoid unintended breakup or destruction of operational and inoperable space satellites (Ibid.).

China as a space actor, understands the fragility of the outer space environment. Still, China National Space Administration (CNSA), the Chinese main space body, mentions the debris issue mainly originates from satellite launches and general on-orbit breakups, instead of events like the 2007 Chinese anti-satellite missile test. In 1993, the Chinese CNSA joined the IADC and founded two new bodies, the Chinese National Space Debris Office and the Chinese Space Debris Advisory Group of Experts (Gong, 2016). These bodies coordinate Chinese space debris research and related activities in the country (Ibid.). Moreover, in 1999, China established the official Chinese National Expert Committee of Space Debris research and dedicated a separate budget to its activities (Ibid.). Chinese space debris activities include measurement and modelling, protection, and mitigation (Ibid.). To show its ongoing support of debris mitigation research and action, China held the 32nd IADC Conference (Ibid.). There are several mitigation standards with which each space agency in China must conform. The 2006 China National Industry standard QJ3221-2005 holds the Requirements for Orbital Debris Mitigation (Ibid.). The industry standard underwent revision in 2015 and is now accompanies by related technical specifications and standards for debris mitigation (Ibid.). At the same time, China respects the United Nations Space Debris Mitigation Guidelines and the IADC Space Debris Mitigation Guidelines (Ibid.).

Ukraine's mechanism is the 1996 law on Space Activity and the 2006 Industrial standard URKT-11.03 Limitation of the Near-Earth Orbital Debris Making at Operation of Space Technical Equipment (UN COPUOS, 2019). The Ukrainian government commits to the international debris mitigation guidelines and overtly bans Ukrainian space actors' nonconformity in these documents (Ibid.).

Finally, the United States has the highest number of national norms with provisions for space debris and its mitigation. Firstly, all United States Government Departments and Agencies are subjects to the National Space Policy, the United States Government Orbital Debris Mitigation Standard Practices (UN COPUOS, 2019). The United States Department of Defense must comply with Directive 3100.10 (Space Policy) and Instruction 3100.12 (Space Support) (Ibid.). All United States nationals, entities, and commercial launches from the United States soil must conform to the Regulations of United States Commercial Space Transportation (Ibid.). Commercial operators must also respect all provisions from the National Oceanic and

Atmospheric Administration (NOAA) regulations and the Federal Communications Commission (FCC) regulations (Ibid.). NASA has on-top norms, the NASA Procedural Requirements for Limiting Orbital Debris applicable to all entities involved in space activities, and the NASA Process for Limiting Orbital Debris relevant to all NASA space activities (Ibid.).

3.2.4. National Aeronautics and Space Administration (NASA)

NASA adheres to the United States National Space Policy, which was last updated in 2020. The 2020 United States National Space Policy replaces the previous version of the policy published in 2010. The 2010 National Space Policy, published by the former President Barack Obama (2010), outlines six primary goals. First, space assets and the development and manufacturing of new satellites and satellite-based services should foster competitiveness among industries globally (Obama, 2010). Secondly, the United States shall pursue cooperation and mutually beneficial space missions to increase the overall usage and benefits of space through partnerships and critical information sharing (Ibid.). Third, the United States shall promote measures for the responsible use of outer space while avoiding collisions and any damage to the present systems and space networks that would threaten Earth's operations, including strengthening measures designated to mitigate the threat of space debris (Ibid.). The fourth goal is to increase the security of private and public satellites and space assets against all forms of disruption, ranging from a human error to environmental threats and hostile attacks (Ibid.). The fifth goal is to incentivize new technologies that would exceed the national and international standards and enhance the world's understanding of the universe (Ibid.). The final goal is to improve observation capabilities and monitor the weather and the natural environment to respond to natural disasters (Ibid.) swiftly.

The problem of space debris occurs in several instances in the 2010 National Space Policy. Mitigation of space debris is a part of the policy's third goal (Obama, 2010). Next, the policy identifies space surveillance and the monitoring of space debris as an area for potential cooperation among countries (Ibid., p.7). To minimize space debris and preserve the environment of space as a safe place for future human exploration missions, the United States shall continue to update and adhere to strict debris mitigation standards, including the United Nations Debris Mitigation Guidelines (Ibid., p.7). Moreover, when launching and operating satellites and launching services, the United States shall strictly follow the United States Government Orbital Debris Mitigation Standard Practices (Ibid., p.7). These practices should, in turn, ensure that the United States' missions are as cost-effective and as safe to humans and the space environment as possible (Ibid., p.7). To minimize space hazards, the United States should continue to utilize commercial and non-commercial intel from space situational awareness (SSA) programs to detect non-compliance with space guidelines (Ibid., p.7). Finally, NASA and the Secretary of Defense shall dedicate the necessary funds to the research and development of methods and techniques required to mitigate and remove debris from space (Ibid., p.7).

Overall, the 2010 National Space Policy stresses the importance of space sustainability and international cooperation among states and international space agencies. Compared to the previous administration's National Space Policy, it focuses more on the prospects of international cooperation and cooperation between the public and the private sectors (Smith, 2011). Simultaneously, the ambitions described in the National Space Policy reserves to offer answers about the implementation and funding for the proposed goals (Smith, 2011). As opposed to Obama's National Space Policy, Trump's 2020 policy provokes more leadership and

United States' expansionism in its outer space activities. While Trump's policy also mentions the need for international cooperation, it should occur only when it is in the United States' interests while protecting its position and values (Trump, 2020). The United States' technologies and details of all operations should only be used in common with United States' partners while avoiding any data sharing with United States' enemies that could use the knowledge to their advantage (Ibid.). Security of the United States' assets from natural or human-induced attacks is crucial. The United States shall improve data collection, systems, and infrastructure to withstand cyber threats, threats to supply chains, and potential damage from space debris (Ibid.). Simultaneously, the United States shall protect the outer space environment from further deterioration by inventing more sustainable practices (Ibid.). Foremost, the 2020 National Space Policy goals emphasize the economic benefits of space and the potential that outer space offers an opportunity to establish new international and national markets for American space goods and services (Ibid.). The policy supports and promotes the private industry and commercial actors to innovate and build new technologies while projecting the United States as the only suitable partner for the most-developed businesses in the international space industry (Ibid.).

Both last two National Space Policies mention the issue of space debris to the same extent. The focus of the two policies is on mitigation measures that would prevent space debris' further creation. Simultaneously, the guidelines emphasize monitoring the current situation and development and adhering to the international regulations and obligations while launching new objects into space. The 2020 National Space Policy describes ADR as a potential long-term strategy that the United States shall pursue in coordination with its strategic partners (Trump, 2020).

NASA Orbital Debris Program Office (ODPO) is a body designated to the issue of space debris. The ODPO adheres to and promotes strict mitigation guidelines to limit any new waste creation in space (Astromaterials Research and Exploration Science, n.d.). ODPO's main job is to monitor space debris status and develop new or improved mitigation methods (Ibid.). The office uses three main models to monitor space debris, the ORDEM 3.1, LEGEND, and the Debris Assessment Software (DAS 3.1.0) (Ibid.). However, the ODPO, nor any other United States agency or office, does not have ADR in the scope of its activities (Ibid.).

4. Incline towards active space debris removal

As stated before, due to space debris' sheer danger, researchers concluded a need to take positive action to reverse the current status quo. Indeed, while mitigation measures preventing further space debris creation are necessary to limit the current situation from deteriorating, mitigation measures are not enough. Even without any new human launches of objects into space, the space debris population will increase in the future (Liou & Johnson, 2006). Instead, the view shifted from mitigation measures to more invasive tactics that would turn the situation around. The shift in thought occurred as early as the 1980s when researchers started to develop the vastly theoretical concepts of first debris removal methods (Liou, Johnson & Hill, 2010). Researchers first used the term active debris removal (ADR) to refer to the techniques, technologies, or strategies intended to clear free-floating space debris (Force, 2016). Namely, ADR methods or processes focus on removing large objects from congested orbits (Dunstan & Werb, 2009). Earth's lower orbit's current debris population is too exponential and too unstable that without ADR technologies, the situation will naturally deteriorate further (Liou & Johnson, 2006). As such, space actors are turning to active space debris removal methods, but these entail considerable dangers.

In 2010, researchers contended that the LEO could become stable within the next 200 years if space actors manage to artificially remove five large debris pieces from space every year starting in 2020 (Liou, Johnson & Hill, 2010). With the inaction of space actors and the lack of progress, this estimation cannot hold, making the outlook for the future state of the outer space environment dim. Liou, Johnson, and Hill (2010) also state that with a higher number of massive objects removed from space per year, the environment can become even safer than it is today. Researchers based this prediction on NASA's estimations and their long-term projection model, LEGEND, that tracks space debris movement in the lower and medium Earth orbit and the geosynchronous orbit regions (Ibid.). LEGEND provides information about the debris characteristics to the NASA Orbital Debris Program Office that evaluates the model's findings (NASA, n.d.). LEGEND bases its projections on the DBS launch database, PROP3D and GEOPROP, the two most efficient propagators, and the NASA Standard Breakup Model (NASA, n.d.). Since the LEGEND can transform the data into a three-dimensional evolutionary model, NASA must only execute mild optimization measures to finalize and produce a well-rounded picture of the space debris environment's characteristics (NASA, n.d.). For better visualization, NASA also developed additional models accompanying the LEGEND projection model (NASA, n.d.).

There are currently many different theoretical active debris removal methods, but few turn to practical and feasible projects. The most recognizable limitation of any ADR mission is its technical feasibility. Developing profound ADR tools takes long research, dedicated teams, expensive equipment, and resources, requiring considerable funds and investment. As such, national and international authorities must solve legal and liability matters to accommodate investors willing to fund ADR projects. On top of finding investors, technical obstacles, and financial imperatives, actors attempting to develop and release an ADR mission face daunting legal barriers. Relevant guidelines and policies written by experienced and well-informed policymakers must accompany the development of any ADR technologies. However, legal norms and the current interpretation of space law does not count with the possibility of ADR and creates a void of unknown regulatory obstacles.

4.1. The importance and methods of active space debris removal

Due to the sheer amount of space debris in outer space and the risk associated with the release of mega-constellations and other satellites and equipment into space, researchers increasingly approve of active space debris methods. In an article by C. P. Mark and S. Kamath (2019), the authors categorize debris removal methods into eight main categories: Collective, laser-based, ion beam shepherd-based, tether-based, sail-based, satellite-based, unconventional, and dynamical system-based. The methods vary in their concept, functionality, and ability as each can capture and remove different forms of space debris from space based on its size and location in outer space (Mark & Kamath, 2019).

The collective ADR process consists of a bundle of ADR methods, starting from debris prioritization to sorting non-technical challenges such as economic, financial, and legal obstacles, developing and launching an autonomous spacecraft non-cooperative analysis, prototyping, and ground validation (Mark & Kamath, 2019). A collective ADR method means that all of the systems must work synchronously (Ibid.). While the authors offer an overview of the possible ADR solutions, researchers need to dedicate more time and effort to validate and determine which removal technique is truly the most efficient (Ibid.).

Laser orbital debris removal (LODR) methods use an impulse from a ground-based laser's pulse to slow down and alter the movement of a piece of debris when reaching its surface (Phipps, 2012). LODR is capable of deorbiting large as well as small space debris. The International Coherent Amplification Network (ICAN) designed such an example of a high-power pulsed laser system that could operate in space (Soulard, 2014). The laser system would be advantageous when tracking tiny debris traveling at hyper-velocity (Ibid.). However, the

ICAN faces the pitfalls of realistically building and releasing a functional laser system with such sophisticated capabilities (Ibid.). Some theories are as ambitious as to suggest an autonomous laser that would shoot down medium-sized space objects if scientists could precisely calculate the interception point at which the velocity of the debris to the laser system is zero (Gambi & García del Pino, 2017). While much research remains unfinished, many researchers and scientists continue to analyse all potential laser-based solutions (Shuangyan et al., 2014; Schmitz et al., 2015; Yang et al., 2016; Wen et al., 2017; Shuvalov et al., 2017, and other). LODR is considered a cheap and feasible ADR option; however, the range of, especially ground-based lasers, is limited (Mark & Kamath, 2019).

The ion beam shepherd-based (IBS) methods use a "chaser" satellite that projects ion beams on the targeted piece of debris to move its trajectory and push it out of its orbital path (Mark & Kamath, 2019). While the IBS methods are as feasible to execute as LODR methods, it requires much more power (Ibid.). Many concepts, such as the quasi-neutral plasma, secondary propulsion systems, electrical propulsion, electrostatic forces, propulsion subsystem, and the discoveries of long-term dynamics of the debris and the atmosphere's effect on IBS, all helped develop the method to its current position (Bombardelli et al., 2011; Merino et al., 2013; Kitamura et al., 2014; Schaub et al., 2014; Cichocki et al., 2016; Aslanov & Ledkov, 2017; Shuvalov et al., 2017; Chichocki et al., 2018; Hakima & Emami, 2018; Ledkov & Aslanov, 2018).

Another method is the tether ADR concept that involves attaching a few kilometres long charged wire to a piece of orbiting debris. The Earth's magnetic field then acts as a strong attraction force, pulling the unwanted asset closer to Earth, letting the waste deorbit and burn in the Earth's atmosphere. The concept was first introduced in the early 1990s in an article by Sanmartin and others, with scientists improving the tether removal methods ever since (Sanmartin et al., 1993; Guang et al., 2012; Benvenuto et al., 2015; Shan et al., 2016; Shan et al., 2017; Sharf et al., 2017). This method's advantage is that it requires no power and maintenance once successfully attached to a piece of debris (Mark & Kamath, 2019). On the other hand, pulling the space debris down into the atmosphere is a prolonged and gradual process (Ibid.).

Scientists and researchers also investigated the concept of sail-based ADR methods that use large drag sails and the power of trapped solar radiation pressure to slow down space debris and augment its deorbiting. Contributing to this method were researchers such as J. M. Fernandez et al. (2014), L. Visagie et al. (2015), and P. W. Kelly et al. (2018), and others. Similar to the tether ADR concept, the sail-based one is also slow and, what is more, uncontrollable, meaning that there is a chance such missions could do more harm than good (Mark & Kamath, 2019).

As opposed to the mentioned methods, satellite-based ADR methods are among the most complex. Researchers describe multiple types of procedures involving satellites to remove debris from space, including microsatellites that operate robotic arms to capture and later cause debris to deorbit (Nishida et al., 2009). However, it is challenging and time-consuming to capture debris with these small satellites that have to move between different orbits (Ibid.). In his article, Marco M. Castronuovo (2011) describes the launch of a large satellite that would carry a series of deorbiting microsystems. The satellite would meet a debris target from a preidentified list and attach itself to the debris by a robotic arm (Castronuovo, 2011). Another robotic arm would then connect the deorbiting device to the non-operational space object and, once detached, would activate the deorbiting phase (Ibid.). The satellite would then travel to meet its next debris target (Ibid.). The satellite would continue in an ongoing sequence of smaller ADR missions that could remove up to 35 large objects from the LEO in seven years (Ibid.). Vincent Dubanchet et al. (2015) also describe a similar concept of a satellite with a robotic arm that would have the capabilities of removing massive pieces of debris from LEO. The researchers analyse models that would enable control over the robotics arms that rely on an altered Newton-Euler algorithm and other algorithms (Dubanchet et al., 2015). Other satellite-based ADR methods include deorbiting space objects with electric propulsion that dramatically decreases the propellant mass consumption needed to manoeuvre debris (Ruggiero et al., 2015). Other ADR methods use dynamical systems to deorbit unwanted objects from space using naturally and artificially generated static disturbances. These concepts require very advanced mathematical computations and time for calculation (Mark & Kamath, 2019).

C. P. Mark and S. Kamath (2019) also describe several unconventional ADR methods, including removing debris by spouting expanding foam on unwanted space objects or by utilizing magnetic field-controlled plasma. The theoretical concept of foam expansion around a piece of space debris explores the idea of increasing the area-to-mass ratio of the item and letting the atmospheric drag pull the matter into the atmosphere at a faster rate (Andrenucci et al., 2011).

Gabriele Guerra et al. (2017) propose a “drag augmentation system” that would use an expanded foam, which would engulf space debris and increase the area-to-mass ratio of the space waste and, as such, heighten the chances of natural atmospheric drag and solar pressure on the matter (Guerra et al., 2017). The drag augmentation system, as described in the article, requires a stable docking system, from which the debris would be in the final stage un-docked, and the resulting uncontrolled re-entry of the matter into space would mean a burn up of the objects together with the induced foam in the atmosphere (Ibid.). If implemented successfully, the drag augmentation system using two satellites would remove up to five large non-functional dangerous bodies from outer space within a year (Ibid.). Simultaneously, the method works together with an electric propulsion system that increases the chance of successful removal missions (Ibid).

The atmospheric pull is lower the smaller a satellite is because of its small area-to-mass ratio. While reserve propellants can be added to small satellites to deorbit them, this method is expensive and increases the cost of the already costly missions (Chopra & Chandra, 2018). Instead, Chaitnya Chopra and Rohan Chandra (2018) look at plasma particles that have a destabilizing effect on space objects. Especially plasma particles, that mix with neutral particles in the Earth's lower atmosphere, have a high drag effect on surrounding pieces of debris (Ibid.). A system that incorporates plasma and geomagnetism functionality can result in an economical and easily adoptable debris mitigation measure (Ibid.). While such methods are, in theory, very efficient, their execution is very demanding and needs much technological research.

The active debris removal missions of larger satellites have, in theory, a much greater success potential than the removal of small-scale debris. The reason for that is that space detection systems still have a problem with tracking the smallest pieces of space debris, which can even cause considerable damage. What's more, today's systems cannot individually track the smallest fragments. One proposed method to removing objects only a few centimetres in size is to inject micron-scale dust grains to spread over an area deemed to have a high concentration of small debris objects (Ganguli, 2011). This way, the drag on the small debris present in a clustered region will increase without having any negative impact on the larger space objects in the same area, including operational satellites (Ibid).

4.2. Space law and legal barriers to active space debris removal

While researchers investigate the different possibilities of active debris removal systems, the current international space law offers no help on how active debris removal should occur and its implications for states' relations. Some necessary international legal space arrangements exist; however, they are vague and leave much to interpretation. Legal ambitions for ADR have been historically weak as consolidating political support for such a matter is extremely difficult. Instead, most space actors are satisfied to avoid accountability for the inoperable objects in space left from their missions. The willingness to conform to the duty of cleaning up outer space is relatively low among countries. Simultaneously, space actors face the usual obstacle of agreeing on a complex topic in a multilateral agreement that has historically proven challenging to do. Most satellites in space, including space debris, belong to the three traditional rivals and world powers, the United States, Russia, and China (Bowen, 2014). These powers then naturally distrust mutual ADR argumentation with the suspicion of the infringement of intellectual property, debris ownership, lack of accountability, and payment for damages (Ibid.).

Today, all space actors must comply with only five main international space treaties agreed at the United Nations in the 1960s to 1980s and their supplements. The main United Nations treaty is the Outer Space Treaty (Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies), in force since October 1967 (UN OOSA, n.d.). A year later (1968), countries adopted the Rescue

Agreement (Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space) (UN OOSA, n.d.). In the 1970s, countries adopted the Convention on International Liability for Damage Caused by Space Objects and the Convention on Registration of Objects Launched into Outer Space, respectively (Ibid.). Finally, in 1984 the United Nations passed the nonbinding Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (Ibid.).

Five major declarations and legal principles accompany the treaties mentioned above. That is the Declaration of Legal Principles Governing the Activities of States in the Exploration and Uses of Outer Space (1963), the Principles Governing the Use by States of Artificial Earth Satellites for International Direct Television Broadcasting (1982), the Principles Relating to Remote Sensing of the Earth from Outer Space (1986), the Principles Relevant to the Use of Nuclear Power Sources in Outer Space (1992), and the Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries (1996) (UN OOSA, n.d.).

The vast majority of the treaties and accompanying declarations came into effect when two space actors, the United States, and the USSR, dominated the space domain. Military superiority, outer space surveillance, and military advancement were the key objectives behind the signed treaties. Involved states agreed that the space domain should be free of any ownership due to the orbit's movement. Instead, ownership rights should only apply to the objects that are in space. The space actors at the United Nations agreed not to breach the ownership integrity of each other's space assets. However, while at the time, this solution was admirable, it poses legal constraints on the potential private and commercial ownership of space objects today (Force, 2016).

Even though ADR is possible if the country owning an identifiable piece of debris, gives consent to its removal, and the parties in the ADR scenario resolve among each other the terms of liability, costs, and risk. However, problems arise with the non-consensual use of ADR (Force, 2016). The international space law does not have a functional framework for prioritizing the debris' immediate threats between the threatened party and the owner's budgetary obligations, interests, and liability constraints (Ibid.). This gap in the existing frameworks means that legal issues would arise if an identifiable piece of space debris would directly threaten a state or multiple states, but the owner would not provide explicit consent for its removal (Ibid.). The same stalemate would occur if the object's owner remained unidentified due to the debris' characteristics (Ibid.). Such situations are yet to arise, but the scenario is likely to occur shortly with the rising debris population (Ibid.). The main issue described here is the applicability of the perpetual ownership rule. The rule gives the owner of an object complete rights over it, even if it ceases to function or is no longer controllable (this includes non-functional satellites and space debris) (Ibid.).

While drafting an entirely new space treaty or adding articles to existing treaties poses too much difficulty, lawyers attempt to find ways to make existing treaties engulf ADR activities in their scope. In a report by M. K. Force (2016), the author states that governments should adopt an internationally recognized understanding of the treaty language, which would best reflect the original intent. Namely, the treaty language should consider the word 'use' as constructive, meaning that non-functional space objects, including space debris, would not meet such criteria (Force, 2016). The International Telecommunication Union (ITU) approves of a constructive approach to the phrase 'use of space,' where requirements shall determine any object's benefits and usability in space (Ibid.). Failing to meet the criteria would mean that another actor can remove the item from outer space (Ibid.). An example of such a policy is the "authority removal" laws, giving United States authorities the rights to clear not-in-use vehicles from the highways, regardless of their ownership, to ensure other highway users' protection (Ibid.). As such, due to a constructive interpretation, disputed or unclear legal clauses and policies uncovered by recent ADR systems developments could offer legitimate solutions (Ibid.). Simultaneously, through treaty interpretation, construing space law would mean no additional treaties to be agreed or amended among countries at the national and international levels, which would be very difficult and time-consuming (Ibid.).

In a different interpretation of international law by Jie Long (2017), any recognizable space debris by definition still ultimately belongs to the original space objects released into space, as stated in the Outer Space Treaty (OST). Countries that owned the space objects at the beginning of their missions have the right to remove the remains of that object from outer space and should proactively aim to do so under the threat of punishment for non-compliance of the OST (Long, 2017). At the same time, countries with ADR capabilities should have the right to remove threatening pieces of space debris whose owner cannot be determined or if the owner is another space actor who does not want to or cannot remove the debris from space (Ibid.). In that case, any actor with ADR technologies should have the right to remove dangerous space debris from outer space, given that the actor can justify and show proof of the existing threat in due time (Ibid.). However, an issue may arise if the same piece of debris or debris owned by the same actor threatens multiple actors, and the parties cannot agree on who should bear the responsibility. Simultaneously, the international community may accept such interpretation only after resolving other pressing technological, financial, and other legal issues.

4.3. Threats of active space debris removal

Understandably, governments fear the development and the use of ADR technologies due to concerns that these technologies could develop into weapons. For any actor, outer space's environment is dangerous due to its specific natural characteristics and harsh conditions, including electromagnetic radiation, freezing temperatures, cosmic rays, meteor showers, cosmic dust, et cetera. On top of the naturally occurring threats, countries fear each other's competitiveness to rule over the domain (Bowen, 2014). Within the realist understanding of international politics, the presumption holds that countries must protect their interests and power. Therefore, governments naturally strive to explore and utilize the Earth's orbits due to the outer space domain's essence. However, in the case of active removal methods, securitization is counterproductive. The danger that space debris poses is much more eminent than the potential threat of ADR systems (Ibid.). As such, states shall approach all environmental threats and threats to the outer space environment's sustainability constructively and without existential and cutthroat security concerns (Ibid.). Suppose space debris becomes a part of the ongoing decades-long discussion about space weaponization. In that case, the establishments seeking their active removal ambitions will clash with their international counterparts, thus becoming paralyzed (Ibid.). All actors' efforts to move forward with new research will stagnate.

While it is true that all ADR methods, including those mentioned in the previous sections, are dual-use systems, considering them as threats to national security in a broader definition of space security would inevitably bear no prosperity (Bowen, 2014). Instead, the space debris discussion must include a much narrower definition of security that also underlines the devastating threat of space debris itself (Ibid.). Conversely, deescalating the issue of space debris could lead to a more significant security threat in the future to all space actors and human exploration because of the neglected Kessler syndrome (Ibid.). International policy and regulations must reflect a difference between the terms ‘space weapons’ and ‘ADR’ to ensure that the same operational restriction will not apply to both systems (Ibid.). Of course, making such a distinction is very challenging in real life, but rather, while there is always a chance that any space actor may misuse their space assets, such an occurrence is not highly likely.

In the article, *To Clear or to Eliminate? Active Debris Removal Systems as Anti-satellite Weapons*, the authors state that although active debris removal technologies can attack working satellites in space and become weapons, their destructive capabilities are not exponential (Dobos & Prazak, 2019). The international community should not exponentially fear space debris removal technologies and should not stand in the way of further research into their improvement (Ibid.). On the contrary, space actors should spend more funds on further ADR research and development and shall incentivize even private actors to do the same. Improved removal technologies will then be safer and more reliable, and trustworthy to the global actors (Ibid.). Furthermore, to counterbalance the possibilities of technology misuse, all space actors should seek to build closer relations and trust to ensure that they hold confidence in mutual space operations (Ibid.). Simultaneously, simply creating transparency around ADR development is not enough to mitigate fears and, on the contrary, might yield more suspicion (Bowen, 2014).

However, there is a way to change governments’ perception and normalize ADR missions. Firstly, it is crucial that space actors, especially the main space actors, including the

United States, China, and Russia, that own the most considerable portion of space assets, agree on the necessity of debris removal missions. Recognition of the importance of active debris removal is ongoing, with mitigation measures and protocols slowly but surely evolving into binding regulations. With more push and mutual understanding, activities to remove even a small number of wasteful objects from space, while rules of each removal mission are previously defined, would not threaten the acting space actors' trustfulness. Routinizing space missions regularly could lead to greater consensus and mutual acceptance. However, there are long historic misalignments between the world powers, and agreeing on an international level on any issue is demanding (to say the least). Governments will perceive the launch of satellites with ADR capabilities to signal space weaponization even with the best intent and best interest in mind. Here, it would be beneficial to boost private space actors' involvement in the research, development, and launch of ADR technologies. Private space agencies have the underlying advantage that they do not have to (for the most part) crumble under the pressure of intricate international relations.

New ADR research programs should not be run (only) by international governmental organizations or state actors. Instead, they should also involve commercial entities in planning and conducting the required tests and assessments. Commercial actors have room to provide new opportunities to solve even the space debris crisis and flourish new space discoveries. Evidently, without the determination of private actors to advance this scientific field, investments into the research on debris removal techniques would always be insufficient. Simultaneously, the benefits of private space actors' involvement and their investments rest on the robustness of international space laws, which are currently missing.

5. Existent active debris removal missions

Regardless of the obvious technical, legal, and economic barriers, private space actors, most financed by public space agencies and international organizations, are rising to the challenge of removing space debris from orbit. This section contains an overview of their activities.

5.1. ClearSpace

ClearSpace is a relatively young company, established in 2018. A non-state actor, developing new On-Orbit Services and new technologies that aim to remove problematic space debris from Earth's orbit, namely large non-operational and non-functioning satellites (ClearSpace SA, n.d.). ClearSpace's founders and employees are well-experienced researchers in the field of space debris located at the Ecole Polytechnique Fédérale de Lausanne (EPFL) research institute (Ibid.). Today, ClearSpace has over thirty employees and trained engineers that have experience from missions like DeepSpace2, Avanti, Prisma, and OneWeb (Ibid.). Due to its progressiveness, ClearSpace attracted Microsoft's interest and became a member of the Microsoft Global Social Entrepreneurship program that helps similar technology start-ups bring new ideas to life (Microsoft Schweiz, 2020). ClearSpace is also separately supported by Switzerland, Germany, Romania, Great Britain, Sweden, Poland, Czech Republic, and Portugal (ClearSpace SA, n.d.).

5.1.1. ClearSpace-1

In 2019, ESA called for bids for an ADR mission within the Space Safety program. Out of twelve candidates, ESA procured the operation as a service contract with the Swiss start-up

ClearSpace led consortium (ESA, 2019b). Given the name ClearSpace-1, the space mission will launch in 2025, a date long overdue (ESA, 2019b). The ClearSpace-1 mission's target is the upper stage of the Vega Secondary Payload Adapter (Vespa), left in orbit at 600 to 800 km altitude once detached from the ESA Vega launcher in 2013 (Ibid). The Vespa is a suitable target for the ClearSpace-1 mission because it has a simple shape and sturdy construction (Ibid.). The Vespa has the same mass as a small satellite and poses an excellent opportunity for practice before an actual satellite becomes the target of ESA's ADR missions (Ibid.). The chaser will first undergo a series of tests in a lower orbit at 500 km altitude (Ibid.). Only then will the chaser be elevated to the target orbit to meet and capture Vespa with robotic arms (Ibid.). Upon the catch, both space objects will deorbit and plummet down until they burn in the atmosphere (Ibid.). In its mission, ClearSpace should set the first precedent for similar space debris removal missions that shall follow.

5.2. The Surrey Space Centre

The Surrey Space Centre is one of the leading private space engineering centres in the world. It started its research into space operations in 1979, becoming the Surrey Satellite Technology Ltd (SSTL) (University of Surrey, n.d.a). The SSTL became a part of Astrium in 2009, thus starting its long strategic cooperation with the advanced aerospace manufacturer (Ibid.). At the time, Astrium was a part of the European Aeronautic Defence and Space Company (EADS), which later became a part of the Airbus Defense and Space. The Airbus Defence and Space is a branch of Airbus S.A.S., second in size only to its main competitor, Boeing, and its Defense, Space & Security branch. The Surrey Space Centre can pride itself on numerous mission studies and missions, three of which aim to showcase active debris removal methods.

5.2.1. DeOrbitSail

In 2011, the Surrey Space Centre kicked off a project called DeOrbitSail (University of Surrey, n.d.b). The project aimed to build a 3U CubeSat sized satellite that would demonstrate advanced deorbiting using a drag sail that would increase a satellite's aerodynamic drag and deorbit the satellite faster (Ibid.). The satellite with the deorbiting components could deorbit in less than half a year from its orbit at 600km altitude (Ibid.). The satellite had imaging capabilities and would regularly communicate with the ground to track and show the deorbiting process (Ibid.). If successful, the satellite and the 4mx4m drag sail would burn up in the atmosphere (Ibid.). This project's primary sponsors were the Seventh Framework Programme (running between 2007 to 2013) and the European Commission (Ibid.). The project aimed to demonstrate new deorbiting opportunities and advance the research and development of new ADR technologies (Ibid.). The project's secondary objective was to show the designed satellite's new manoeuvre capabilities (Ibid.). The designed satellite was attached and integrated with a rocket in 2015 (Ibid.).

5.2.2. InflateSail

An even more advanced drag sail project kick-off occurred in 2012 (University of Surrey, n.d.c). The InflateSail project was a part of the Large Deployable Technologies for Space (DEPLOYTECH) project funded primarily by the European Commission, the Seventh Framework Programme, and other sponsors, including Airbus Defence & Space, the University of Cambridge, CGG Technologies, and TNO (Ibid.). Again, the InflateSail project involved the attachment of a drag sail to a standard 3U CubeSat (Ibid.). Yet, this time, a gas generator system and tiny inflatable booms accompanied the drag sail's deployment (Ibid). Inflatable booms are attractive to space engineers designing new space satellites (Ibid.). That is because they can be incredibly lightweight due to thin membranes, so they do not add much extra weight, and they do not require much space on a deployed satellite (Ibid.). The main objective of the InflateSail project was to increase the technology readiness level (TRL) of the mentioned ADR method and collect information about the ways to improve the removal technique to be used on real satellites in the future.

5.2.3. RemoveDEBRIS

To date, the largest ADR project run by the Surrey Space Centre is the project RemoveDEBRIS. RemoveDEBRIS is the first collection of designed and trialed ADR missions. The RemoveDEBRIS consortium consists of the Surrey Space Centre, Airbus Defence & Space, ArianeGroup (previously Airbus Safran Launchers joint venture), the Innovative Solutions In Space B.V., the Centre Suisse d'Electronique et de Microtechnique SA, the French Institute for Research in Computer Science and Automation, and the Stellenbosch University (University of Surrey, n.d.d).

The ADR missions showcased the capabilities and potential of a Net Capture System, a Harpoon Capture System, a Vision-Based Navigation System, and a Dragsail system (Forshaw et al. 2020). Among other objectives, including identifying the most suitable and efficient ADR techniques, the RemoveDEBRIS project's focus was to determine which ADR technology would be the cheapest to execute regularly (Aglietti et al.,2020). The team worked with the launching authorities, including NASA, and the ISS regulations already when starting to design the mission to avoid any problems and retrofit later on (Ibid.). Still, the mission had to overcome many technical challenges before launching (Ibid.). Instead of an individual launch, the satellite was a part of the 14th SpaceX Commercial Resupply Service mission to the ISS, launched in April 2018 by the SpaceX Falcon 9 Thrust rocket (Ibid.). The RemoveDEBRIS satellite was then deployed from the ISS by the Nanoracks deployer system, a cheaper and safer alternative to other means available (Ibid.). The KABER interface of the Special Purpose Dexterous Manipulator (SPDM) released the satellited from the Japanese Module's Airlock at the ISS (Ibid., p.321). All experiments but the DragSail system tested successfully (Ibid). The DragSail experiment findings showed mixed results, and incomplete data and monitoring prevented the researchers from validating its outcomes (Ibid.). However, scientists monitoring all of the experiments took away many valuable lessons to improve future ADR methods (Ibid.). Jason L. Forshaw et al. (2019) and Guglielmo S. Aglietti et al. (2020) exhaustively describe the mission's complete design, execution, and outcomes in their papers *The active space debris removal mission RemoveDebris* parts 1 and 2. While the RemoveDEBRIS presented valuable technological findings, it was also heavily publicized (Aglietti et al., 2020). The mission and the Surrey Space Centre's efforts attracted considerable media attention, which in turn grabbed the public's interest in the problematics of space debris and the necessity of ADR missions (Ibid.).

5.3. Astroscale

Astroscale Holdings Inc. (Astroscale) is a renowned space agency that projects its deep desire to lead the way of space exploration among its other competitors. The company is fully aware of the necessity of a sustainable orbit and invests in innovative technologies to tackle space debris. Among Astroscale's ADR projects are the End-of-Life Services by Astroscale-demonstration (ELSA-d) mission, being a part of Phase I of the Japan Aerospace Exploration Agency's Commercial Removal of Debris Demonstration (CRD2) project, and the Astroscale satellite life-extension platform.

5.3.1. End-of-Life Services by Astroscale-demonstration (ELSA-d)

In November 2020, Astroscale announced that its first commercial ADR demonstration mission, ELSA-d, will occur in March 2021 (Astroscale, 2020a). The GK Launch Services will launch ELSA-d from the Baikonur Cosmodrome in Kazakhstan (Ibid.). Astroscale will release two objects, a "servicer," intended to catch the "client," portraying a piece of unwanted debris (Ibid.). The servicer will be required to locate the client outside of its sensor field view, which will dramatically increase the whole test mission's difficulty (Ibid.). The servicer with several ADR technologies will capture and then release the client several times to test variants of its rendezvous capabilities, including non-tumbling and tumbling docking (Ibid.). Experts will monitor the mission through Astroscale's In-Orbit Servicing Control Centre National Facility (IOCC) in the United Kingdom, specially equipped to monitor such satellite servicing missions. This mission will be more advanced than any previous ADR trial, namely because it will use a semi-autonomous capture system of a non-responsive makeup satellite (Ibid.).

5.3.2. Japan Aerospace Exploration Agency's Commercial Removal of Debris Demonstration (CRD2)

In February 2020, the Japan Aerospace Exploration Agency (JAXA) chose Astroscale Holdings Inc. to lead the first part of the CRD2 mission to reach and investigate a Japanese non-functional rocket upper stage (Astroscale, 2020c). The contract binds Astroscale to explore the Japanese rocket upper stage by 2023 (Ibid.). Astroscale will be responsible for the mission end-to-end, from design to manufacturing, launch, data collection, and analysis (Astroscale, 2020d). Astroscale assumes that it will already demonstrate its mission by the end of the Japanese 2022 fiscal year (Ibid). Following the first part of the CRD2 mission, JAXA will issue another tender for a commercial removal of the same piece (part 2 of the CRD2 mission) (Ibid.). The removal of the upper stage would then have to take place any time before March 2026 (Ibid.). The involvement of Astroscale with JAXA represents an essential milestone for the company that is gaining popularity in Japan. Before winning JAXA's tender, Astroscale won a multi-million-dollar grant from the Innovation Tokyo Project granted by the Tokyo Metropolitan Government dedicated to the commercialization of active debris removal missions (Ibid.).

5.3.3. Astroscale satellite life-extension platform

The United States branch of Astroscale acquired the intellectual property and other assets and staff of the Israeli Effective Space Solutions R&D Ltd. (ESS) (Astroscale, 2020b). Due to this merger, Astroscale will be the only company capable of servicing operational satellites in LEO and GEO orbits (Ibid.). On-orbiting servicing is an increasingly useful alternative to the expensive reinstatement of new satellites into space after their predecessors decommission due to age or malfunctioning (Ibid.). For example, the launch of new satellites to GEO may cost over $200 million, money that can be saved and invested elsewhere (Ibid.). While this is not an example of an ADR mission, even such projects as the life-extension platform help mitigate the debris problem and make outer space more sustainable for future generations. Astroscale will create another branch, the Astroscale Israel Ltd., led by the past ESS employees (Ibid.). From Tel Aviv, the company will serve clients, including the United States governments and others, in prolonging the lifetime of existing and future satellites (Ibid.).

5.4. SpaceX

Out of the several commercial space actors, SpaceX is leading the way in pursuing its space sustainability ambitions. SpaceX began in 2002 as Elon Musk's small but ambitious space company, turning its worth in 2020 into $42 billion (Das, 2020). Around 25% of the company's value comes from the travel and launching components of SpaceX operations (Ibid.). One of SpaceX's launching activities is, for example, a $2.6 billion contract with NASA's Commercial Crew Program (Wall, 2020). As part of the program, SpaceX is to fly out six NASA crewed missions to the International Space Station (Ibid.).

Yet, most of SpaceX's value stems from its operational Starlink satellites (Das, 2020). SpaceX already launched over 900 satellites into the LEO region, significantly increasing the outer space traffic (Rovira, 2020). Moreover, similarly to the ambitions of Amazon or OneWeb, SpaceX also has the intention of launching many more Starlink satellites to create the Starlink mega constellation. If established and operational, the Starlink satellites could nearly quadruple SpaceX's valuation to $175 billion (Das, 2020). Understandably, the introduction of mega-constellations inflates space debris' threat and highlights the changes of uncontrollable multiplication of non-operational space objects in outer space. Accordingly, some studies already focus on preliminary analyses of the ADR missions to accompany mega-constellations' launching into space (Huang et al., 2020).

5.4.1. Starship rocket system

Although SpaceX has ambitious plans, it also takes necessary precautions not to harm the outer space environment. The planned Starlink mega-constellation should be located only at an altitude of around 550km (Rovira, 2020). It will take a non-functional satellite only between one to five years to deorbit naturally (Ibid.). Simultaneously, all of the Starlink satellites should still have de-orbiting mechanisms, making deorbiting even faster (Ibid.). The satellites will also have autonomous collision-avoiding manoeuvre capabilities, allowing them to dodge crashes based on data from the United States Department of Defense's debris-tracking system (Ibid.).

SpaceX engineers are also developing an accompanying Obsolete Spacecraft Capture and Removal satellite (OSCaR) with nets and tether capabilities to remove unnecessary satellites from the orbit if needed (Rovira, 2020). The satellite is a small 3U CubeSat type satellite with comprehensive capabilities, including communication, navigation, propulsion, and control systems. OSCaR is already ready to be tested by the Rensselaer Polytechnic Institute (Ibid.).

Finally, SpaceX is developing a new Starship that will have the primary purpose of carrying persons and objects to and from space (Rovira, 2020). However, the Starship’s side capability should be to collect unwanted space debris from outer space as a space trash collector. SpaceX should release more information about the Starship and its properties early in the 2020s (Ibid.).

5.4.2. The landings of Falcon 9 first stages and Falcon Heavy rocket after lift-off

SpaceX also projects its sustainability ambitions when refurbishing and reusing its Falcon 9 first stages after lift-off and the company’s signature mega-rocket, the Falcon Heavy. The reasons for the reuse of the space equipment are two-fold. First, reusability allows the company to cut the high cost of space flights exponentially, dramatically improving SpaceX operations' business case and allowing the firm to offer customers competitive prices (Wall, 2020). Secondly, reusability is vital in enabling the company to achieve its goals of being the first to create a profound space travel system that will allow humans to explore outer space at a rate and comfort like never before (Ibid.).

SpaceX landed the first stage of the Falcon 9 back on Earth following an orbital launch in 2015 (Wall, 2015). It was then the first-ever rocket landing of such kind following years of trials and testing (Ibid.). The second stage of the Falcon 9 currently stays in space and burns up in the atmosphere upon deorbiting. However, SpaceX researchers are already working on ways to make even the second stage reusable. For the first time in 2020, the first part of the two-stage Falcon 9 rocket returned and landed safely back on Earth after launching a crewed mission, Demo-2 (Wall, 2020). Aboard the mission Demo-2 were Bob Behnken and Doug Hurley, two NASA astronauts heading to the International Space Station (Ibid.).

6. Outlook

Today, governments and space agencies release more satellites into orbit than ever before. The number of new satellite missions will further increase exponentially, namely with the development and future launch of mega-constellations. Furthermore, due to the rapid expansion of outer space, many newly produced satellites are manufactured at lower and lower costs while their failure rates rise accordingly (Jacklin, 2019). Failed satellites then add to even more space debris. According to a NASA report, one out of two new satellite missions is likely to fail, which puts extra pressure on the already exploited outer space and increases the risks for the successful execution of all space missions to come (Jacklin, 2019). As the number of uncontrollable space objects increases, the dangers of outer space multiply. Given the already described state of debris operations, this section offers an outlook on some of the steps that could shape the prospect of future outer space operations.

6.1. Centralization of ADR operations at a dedicated intergovernmental organization

As discussed, ADR will be crucial in ensuring the feasibility of any future space exploration missions, and the current space actors must overcome the existing legal challenges and give way to new ADR technologies. Researchers such as Ram S. Jakhu, Yaw Otu M. Nyampong, and Tommaso Sgobba (2017) speak of establishing a new international intergovernmental organization that would overcome the legal and bureaucratic constraints of ADR. The organization would be in charge of protecting and conducting all necessary actions to remove and prevent further uncontrollable space debris formation. Furthermore, the authors discuss the benefits of setting up an operational, institutional, and international regulatory framework for debris removal (Jakhu et al., 2017). Correctly, the authors state that private companies cannot execute ADR missions without a government to oversee their operations under the current regulatory framework (Ibid.). A state always has jurisdiction over a private company that launches any mission into space. At the same time, these states are then liable for any operation's success or failures (Ibid.). At the moment, ADR operations can only remove objects from space with the prior consent of the launching state or by the launching space as a national operation or if the launching state declares a spacecraft abandoned, meaning that any government with appropriate capabilities may remove it (Ibid.). At the same time, states must execute ADR missions in such a way as not to cause any damage to a third party (Ibid.). The authors claim that an international organization would resolve these issues if participating states would be willing to share liability and funds via the organization that would oversee and be liable for ADR of assets belonging to the member states (Ibid.). An international pool of resources could facilitate ADR missions that are expensive and require a significant level of expertise (Ibid.). The International Telecommunications Satellite Organization (INTELSAT) and the International Maritime Satellite Organization (INMARSAT) server as a template for an international organization for ADR (Ibid.). The ADR organization would require that governments agree on their obligations and the scope of activities while incorporating such duties into domestic laws as proof of commitment (Ibid.).

However, this approach has several downfalls. First, countries are unwilling to agree on the international level about Earth's sustainability, let alone something as abstract as space sustainability. For example, the struggle to enforce the Kyoto Protocol or the Copenhagen Accords illustrates just how challenging it is for countries to adhere to predefined goals and targets even if covered by a comprehensive multilateral framework (Hovi et al., 2013). The bottom line of the success of establishing an international ADR organization rests on the states' willingness to consent to a collaborative effort. The authors state that INTELSAT and INMARSAT show that only the consensus of few parties at the international level might trigger the necessary impulse to create an ADR organization (Jakhu et al., 2017). However, to this day, this did not happen. Additionally, writing new or even updating the current international space regulatory framework is unimaginably challenging due to bureaucratic obstacles.

Nonetheless, some international cooperation is necessary to spread ADR missions' immense costs across multiple liable parties. In an article by Klima et al. (2018), the authors conclude that a decentralized approach to space debris removal and an individualistic approach to determining active debris removal strategies is more costly than a centralized effort. The authors build on their previously defined space debris simulator to present an accurate picture of the current space debris removal methods' problematization while evaluating single-agent and multi-agent ways of dealing with space debris (Klima et al., 2018). Considering the significant investments and considerable resources needed for the successful execution of each space debris removal mission and the calculated 10% increase in costs of a decentralized strategy for conducting the space mission, the authors conclude that multi-actor solutions are much more reasonable and pragmatic (Ibid.). According to the authors, space debris removal would be much more efficient if countries would coordinate their strategies at the global level rather than organize their missions individually (Ibid.). Instead of competing, agencies or governments should form coalitions or cooperative projects (Ibid).

6.2. Commercialization of ADR missions

But while cooperation among states might languish, individual states should instead turn to the private sector for help. Private companies currently invest heavily in three main areas, manufacturing cheap space launch vehicles, accommodating future space tourism, and investigating space mining opportunities (Gomes et al., 2013). Motivated by profit and monetary gains, private enterprises know that ADR will be necessary to launch new space missions. While it might seem unlikely, Earth's orbits are a limited natural resource and can even become too crowded for any new satellite in the foreseeable future if space actors do not take the necessary steps (Ghelani, 2018). The crowding of space endangers any potential offered by new space satellite inventions, threatening companies' investments and future profits from projects. Simultaneously, building sustainable satellites and launching vehicle systems also pose a cost-saving opportunity through reusability and material recycling. As companies, including OneWeb, SpaceX, Amazon, and others, demonstrate their plans to release mega-constellations into outer space, they simultaneously project their aims and leadership in space sustainability (OneWeb, n.d.; Starlink, n.d.; Henry, 2020). SpaceX demonstrated its reusable launch systems on several occasions, lastly by bringing home the Falcon 9 first stage after launching the rocket as a part of the Demo-2 mission in June 2020. Simultaneously, entities such as Astroscale Holdings Inc. or Airbus, through the Surrey Space Centre and the European ClearSpace, control and manage the only current ADR operations while using public investments and funds from international intergovernmental organizations, including the European Union.

Indeed, private entities need government support to succeed with their space projects (Gomes et al., 2013). That is why ESA and NASA started implementing some new policies to support small national space companies, with ESA focusing primarily on European entities and NASA on American entities (Ibid.). New investors are also investing in the private space sector due to these actors' visionary objectives (Ibid.). Furthermore, the rise in the global economy, digitization, and the worldwide market's turn towards technology dependency all boost the space sector (Ibid.). With the right technological and financial support and investment, private actors can develop new products better and faster than national space agencies (Ibid.)

Unfortunately, the international legal framework's underdevelopment restricts the commercialization of the space sector that portrays a window of opportunity (Davalos, 2016). States at the international level try to adjust the existing space regulations to include commercial actors (Ibid.). However, severe ambiguities and gaps in the legal documents and their interpretations are evident (Ibid.). The lack of evolution in the international space law holds back the potential benefits arising from the willingness of private space actors to execute the needed ADR missions, as well as their desires to advance humankind by sponsoring projects such as private tourist trips to space, building permanent space stations, and asteroid mining initiatives (Ibid.).

6.3. Limiting the number of newly released satellites

Although thanks to private actors, ADR missions are likely to continue to grow in number, the progress is stagnating. Thus, some researchers look at new possible ways to forestall new space debris creation and propose confronting the debris challenge at its roots by limiting the number of newly launched space vehicles. Research by Abid Murtaza et al. (2020) points to two optimized approaches (Murtaza et al., 2020). The first is the creation of multi-mission satellites, and the second is the formation of a robust Space Information Network (SIN).

Presently, most satellites in space have a single purpose, meaning that operators must release a significant number of them into space to execute all necessary orbital tasks (Ibid.). Instead, the authors propose to build multifunction satellites that would be more expensive but would decrease the total costs of space operations in the long run by reducing the number of satellites necessary to orbit the Earth (Ibid.). It would be instrumental if new mega-constellations would contain multifunction satellites instead of single-function satellites (Ibid.). They would provide global coverage and constant inflow of data for several operations and purposes (for example, providing internet services and at the same time observation images for surveillance), thus minimizing the need for a significant number of such mega-constellations (Ibid.). Examples of multifunction satellites are the COMS (Communication, Ocean, and Meteorological satellite) and the EGNOS (European Geostationary Navigation Overlay Service) (Ibid.). While multifunction satellites face operational and technological difficulties, space actors should invest in research in their development (Ibid.). However, the proposition of multifunction satellites goes against the ambitions of private entities such as OneWeb, SpaceX, Amazon, and others, as they strive to release their constellations to compete as providers of unique services. It is unlikely that the companies would change their business models without considerable incentives (for example, government incentives or mutually beneficial business agreements ordained by anti-monopoly bodies).

Space Information Networks offer yet another advantage to traditional satellite operators. While satellites operated individually may transfer data to Earth only when visible to the ground station, satellites connected by an inter-satellite link (ISL) and connected to a satellite located in the Geostationary orbit can transfer data to Earth at any time (Ibid.). This capability allows, for example, useful non-stop traffic and security surveillance. Interconnected satellites through SIN must not belong to a single government or space agency. Instead, data may be shared, meaning that the number of space assets necessary for needed space operations could decrease, thus mitigating the number of space objects and minimizing the creation of further debris fragments. Examples of SIN are NASA’s Space Network (SN), European Union’s

Broadband Radio Access for IP-based Network (BRAIN), and Japan's MIRAI (Ibid.). Once again, the SIN projects face backlash from the challenges of limited cooperation among the space entities seeking to safeguard their data and information security and competing ambitions.

6.4. Orbital-use fees

Economically, governments or intergovernmental organizations could use both sticks and carrot techniques to limit the creation of new space debris and boost its proactive removal from orbit. The public entities could collect from space actors money into an ADR fund or require them to purchase high space asset insurance that could then fund ADR missions (Dunstan & Werb, 2009). On the other hand, governments or international governmental organizations could incentivize ADR operators to build more sustainable space assets by determining prices and setting up schemes for removing actors' space assets from space (Dunstan & Werb, 2009). Furthermore, overseeing organizations could set rules that would require new space contracts to contain quality and performance prerequisites and debris control clauses (Dunstan & Werb, 2009). In their paper, J. E. Dunstand and B. Werb (2009) also mention developing a similar system replicating the existing carbon trading scheme among countries. While the incentives are plausible, they all rely on states' cooperative nature and their willingness to put effort into solving the complexity of ADR technologies and missions.

A more drastic measure to relieve the outer space environment from the sheer number of new space objects is to impose orbital-use fees before ADR missions become regularly occurring. Researchers Akhil Rao, Matthew G. Burgess, and Daniel Kaffine (2020) state that satellite operators do not have the proper incentives to consider the possibility of space collisions induced by their space assets. As such, the authors introduce a possible orbital-use fee that would even quadruple the satellite industry in the next twenty years (Rao et al., 2020). While launch fees are a near equivalent option, it does not account for possible collisions or unpredictable satellite breakups (Ibid.). Due to the lack of international cooperation, the system of orbital-use fees might be unthinkable at first. However, the authors refer to the Vessel Day Scheme that regulates tuna fisheries (Ibid.). Here, it would be sufficient if states would agree on a level of harmonization of the fees internationally while determining the actual fee rate would remain in the sole authority of the state responsible for the space agency's launch (Ibid.). While provisions of the Outer Space Treaty prohibit national appropriation of the outer space environment, it has a hole. It does not restrict the exercise of private property rights that could, in theory, enable a market for orbital permitting to exist (Ibid.).

6.5. Accountability

Another precautionary measure for actors to adhere to stricter debris mitigation standards before private entities start executing ADR missions in bulk is to incentivize space agents to conform to sustainable space behaviour. The World Economic Forum's Global Future Council on Space Technologies came up with the Space Sustainability Rating (SSR) concept to rate a mission's sustainability level (World Economic Forum, n.d.). The project's partners include companies such as the Airbus Defence & Space, Boeing, Bryce Space and Technology, the European Space Agency (ESA), Lockheed Martin, Massachusetts Institute of Technology (MIT) Media Laboratory, OneWeb, Planet Labs, the University of Texas, and the Voyager Space Holdings (Ibid.). The project will run voluntarily. Manufacturing and launching organizations or agencies will have to fill in questionnaires to become a part of the evaluation process (Ibid.). On top of the data provided individually by the participating entities, the Council will use external data and a mathematical model to calculate the mission's ratings (Ibid.). The Council's assessment will reflect all of the internationally recognized guidelines on sustainability and hold all participants to the same standard (Ibid.). The participating bodies will be free to publish their scores without disclosing any sensitive information (Ibid.). The rating will help the participating organizations improve their PR and potentially obtain monetary benefits such as more favourable insurance options (Ibid.). Admirable scores might even incentivize investors and stakeholders to invest in the entities' missions (Ibid.).

7. Conclusion

The thesis summarized space actors' primary efforts to mitigate the dangerous space debris from the Earth's orbits. While many space debris mitigation guidelines exist, outer space's anarchic characteristics and the lack of accountability allow countries to refrain from conforming to international regulations unpunished. No purely state-owned ADR missions exist due to the lack of funds and dedicated national outer space operations budgets. At the same time, nations cannot agree on an international approach to conducting ADR missions. Instead of contributing to group projects, states opt to support their chosen actors, including independent private entities. Politically independent space agencies and private entities have the benefit of being free of bureaucratic constraints. At the same time, they remain tied by insufficient legal frameworks that do not count with their participation. The continuing international community's unwillingness to alter the global legal space framework to emancipate private entities as standalone space actors will continue to pose an obstacle to those same private entities in achieving their goals. However, they must understand that it is the profit-driven entities that are the most likely to execute necessary steps to complete active debris removal missions while using public funds and donations.

The thesis answered the following research questions: what threat does space debris pose? What are the leading international space debris mitigation measures? Who are the main actors in space, and what is the current status of their space debris countermeasures? Who should be responsible for the clean-up of space debris? What are the reasons for active debris removal missions? What are the prospects, dangers, and legal and technical limitations of space debris removal? What are the current ADR technologies discovered and used? And finally, what is the outlook for any cooperation among states or between state and non-state actors regarding space debris removal, and what is the probable future for the sustainability of the outer space environment?

Firstly, space debris poses an existential threat to all space actors' future space operations and even threatens the health and safety of humans on Earth and Earth's environment. Space debris endangers the use of the majority of today's technical assets, which puts the whole international community under severe pressure in today's modern world.

The primary international space debris mitigation measures are the IADC Space Debris Mitigation Guidelines, the UN COPUOS Space Debris Mitigation Guidelines, ESA's Space Debris Mitigation Policy for Agency Projects, the joint European Code of Conduct for Space Debris Mitigation guidelines, the ISO Standard 24113, and finally the ITU Recommendation ITU-R S.1003.2. While the provisions in the debris mitigation guidelines are not binding, many countries began to adopt these or similar guidelines into their national legislations.

Undeniably, the main space actors in the 1950s and 1960s were the United States and the USSR. In due time, additional states also became involved, including China, India, Japan, Canada, and notably the European Union and its member states. However, with the rise of private enterprise, state actors' missions started to involve progressively more inputs and help from the private sector. Today, the outer space environment changes as private companies are increasingly more involved in developing and launching new space missions. The primary conventional space agencies are NASA, CNSA, ESA, Roscosmos, JAXA, DLR, ASI, CNES, the Canadian space agency, and other national or international space agencies. Commercial actors back these conventional actors in the planning and development of new missions.

Simultaneously, commercial actors such as Amazon, OneWeb, or SpaceX work on their standalone programs. Apart from the implementation of debris mitigation standards, most countries do not invest in active debris removal activities apart from the most significant players, including NASA, ESA, and JAXA. However, these agencies conduct their ADR initiatives in cooperation with private actors, such as ClearSpace, Airbus Defense and Space, or Astroscale.

While the United States, Russia, and China are responsible for most of all space assets and the most considerable portion of all space debris, space debris is a shared problem and all countries (and future private space actors) are responsible for its removal. The United States owns most of the operational space objects. In contrast, the two most notable accidents that led to an immense rise in space debris involved China and Russia (Chinese 2007 anti-satellite missile test and the 2009 collision of Russian Iridium 33 satellite and the Chinese Cosmos 2251 satellite). More recently, the internationally condemned Indian anti-satellite missile test in 2019 caused a significant rise of new space fragments (McFall-Johnsen, 2020). In general, the launching state has the sole right to deorbit its non-functional space object. Therefore, it should be the launching state's responsibility to clean up the debris originating from its assets. However, this standard is unrealistic, as not all states have debris removal technologies, money, or clear incentives. Simultaneously, there is no approach to attributing responsibility for deorbiting unidentifiable objects in space that have no identified responsible owner.

Reports by NASA and other notable space agencies all point to the urgency of fixing and turning back the degrading effects of space debris. The number of new satellite missions will further increase exponentially, namely with the development and future launch of mega-constellations. As such, at the end of the 20th century, researchers and scientists' attention turned to active debris removal. Research stresses the necessity for active debris removal in addition to mere mitigation measures due to the Kessler phenomenon. The Kessler effect explains that even without the execution of new space missions, the amount of space debris will rise due to the now orbiting bodies' imminent collisions.

There are many theoretical ADR possibilities, ranging from laser-based to ion beam shepherd-based, tether-based, sail-based, satellite-based, and many others. Each method has its benefits and technical pitfalls, mainly due to feasibility as well as monetary issue. Many mechanisms are not a part of this thesis due to its scope and size. Nevertheless, all research into new potential ADR methods is fascinating and offers endless changes of further exploration. While technical barriers of the most standard or down-to-Earth ADR solutions are solvable, legal limitations to all ADR missions, regardless of type, pose a more intricate obstacle. Since the chances of states agreeing on new international legally binding legislation or adjusting the current space regulations are minuscule, lawyers and legal researchers place faith in changing the interpretations of the provisions and terminology used in the existing legal norms. Different interpretations of terms such as the ‘use of space’ of the Outer Space Treaty could allow actors to perform ADR missions and relieve outer space of objects ‘not in use.’

While aware that all states must cooperate and invest heavily in ADR technologies to successfully remove debris from outer space, such a scenario is unlikely. Since the end of the 20th century, private actors have been taking the steering wheel when designing, manufacturing, and launching national space agencies' current space missions. The cooperation between the private and the public sector led to swift advancements in the field. Simultaneously, private entities grew stronger on their own, developing projects on their footing, driven by their private investors and commercial interests. It is not the nations but commercial entities heading the way of viable ADR missions with the first real chance of succeeding.

Meanwhile, governments, intergovernmental organizations, and national space agencies favourably perform the role of backbone support. It must be contended that states and intergovernmental agencies must involve private agencies, to an even greater extent than today, to help them tackle the threat posed by space debris. Thereby, governments should lend more steering power over to the public sector to manage ADR operations and allow pro-profit decision making to lead the way to overcome the existing challenges. Adequate legal adjustments shall accompany the private sector's involvement and the commercialization of space to ensure a safe environment for private entities and the feasibility of private or semi-private ADR missions.

Until the space community resolves the technical limitations and, more importantly, the legal drawbacks currently confining ADR missions' deployment, the actors can investigate other means to help slow down the degradation of the polluted outer space environment. The opportunities may lie in the described design and manufacture of multi-mission satellites, the establishment of Space Information Networks, the imposition of orbit-use fees, or the encouragement of voluntary accountability incentives.

8. References

Adimurthy, V. & Ganeshan, A. S. (2006). Space debris mitigation measures in India. *Acta Astronautica, 58*(3), 168-174. https://doi.org/10.1016/j.actaastro.2005.09.002.

Aglietti, G. S., Taylor, B., Fellowes, S., Salmon, T., Retat, I., Hall, A., Chabot, T., Pisseloup, A., Cox, C., Zarkesh, A., Mafficini, A., Vinkoff, N., Bashford, K., Bernal, C., Chaumette, F., Pollini, A., & Steyn, W. H.. (2020). The active space debris removal mission RemoveDebris. Part 2: In orbit operations. *Acta Astronautica*, *168*, 310–322. https://doi.org/10.1016/j.actaastr o.2019.09.001.

Andrenucci, M., Pergola, P., Ruggiero, A. & Olympio, J. (2011). *Active Removal of Space Debris - Expanding foam application for active debris removal*. ESA Final report. Retrieved January 27, 2021, from https://www.esa.int/gsp/ACT/doc/ARI/ARI%20Study%20Report/ACT-RPT-MAD-ARI-10-6411-Pisa-Active_Removal_of_Space_Debris-Foam.pdf.

Aslanov, V. S. & Ledkov, A. S. (2017). Attitude Motion of Cylindrical Space Debris during Its Removal by Ion Beam. *Mathematical Problems in Engineering*. https://doi.org/10.1155/2017/1986374.

Astromaterials Research and Exploration Science. (n.d.). *Debris Remediation*. Astromaterials Research and Exploration Science. Retrieved January 18, 2021, from https://orbitaldebris.jsc.nasa.gov/remediation/.

Astroscale. (2020a). *Astroscale Announces March 2021 Launch Date for World's First Commercial Active Debris Removal Demonstration Mission*. Astroscale. Retrieved February 2, 2021, from https://astroscale.com/astroscale-announces-march-2021-launch-date-for-worlds-first-commercial-active-debris-removal-demonstration-mission/.

Astroscale. (2020b). *Astroscale U.S. Enters the GEO Satellite Life Extension Market*. Astroscale. Retrieved February 2, 2021, from https://astroscale.com/astroscale-u-s-enters-the-geo-satellite-life-extension-market/.

Astroscale. (2020c). *SpaceNews: Astroscale wins first half of JAXA debris-removal mission*. Astroscale. Retrieved February 2, 2021, from https://astroscale.com/spacenews-astroscale-wins-first-half-of-jaxa-debris-removal-mission/.

Astroscale. (2020d). *Astroscale Selected as Commercial Partner for JAXA's Commercial Removal of Debris Demonstration Project*. Astroscale. Retrieved February 2, 2021, from https://astroscale.com/astroscale-selected-as-commercial-partner-for-jaxas-commercial-removal-of-debris-demonstration-project/.

Benvenuto, R., Salvi, S., & Lavagna, M. (2015). Dynamics analysis and GNC design of flexible systems for space debris active removal. *Acta Astronautica, 110*, 247-265. https://doi.org/10.1016/j.actaastro.2015.01.014.

Bombardelli, C. & Pelaez, J. (2012). Ion Beam Shepherd for Contactless Space Debris Removal. *Journal of Guidange, Control, and Dynamics, 34*(3), 916-920, https://doi.org/10.2514/1.51832.

Bowen, B. E. (2014). Cascading Crises: Orbital Debris and the Widening of Space Security. *Astropolitics, 12*(1), 46-68. https://doi.org/10.1080/14777622.2014.890489.

Castronuovo, M. M. (2011). Active space debris removal—A preliminary mission analysis and design. *Acta Astronautica, 69*(9–10), 848-859. https://doi.org/10.1016/j.actaastro.2011.04.017.

Chopra, C. & Chandra, R. (2018). *Small Satellite Deorbital System using Magnetic Field Controlled Plasma*. 2018 SpaceOps Conference, 28 May - 1 June 2018, Marseille, France. https://doi.org/10.2514/6.2018-2705.

Cichocki, F., Merino, M., & Ahedo, E. (2018). Spacecraft-plasma-debris interaction in an ion beam shepherd mission. *Acta Astronautica, 146*, 216-227. https://doi.org/10.1016/j.actaastro.2018.02.030.

Cichocki, F., Merino, M., Ahedo, E., Smirnova, M., Mingo, A., & Dobkevicius, M. (2016). Electric Propulsion Subsystem Optimization for “Ion Beam Shepherd” Missions. *Journal of Propulsion and Power, 33*(2), 370-378. https://doi.org/10.2514/1.B36105.

ClearSpace SA. (n.d.). *Clearspace today*. ClearSpace SA. Retrieved November 14, 2020, from https://clearspace.today/.

Das, B. (2020). *NASA vs SpaceX – How Different They Are?*. RankRed Media Private Limited. Retrieved February 4, 2021, from https://www.rankred.com/nasa-vs-spacex/.

Davalos, J. (2016). International Standards in Regulating Space Travel: Clarifying Ambiguities in the Commercial Era of Outer Space. *Emory International Law Review,* *30*(4), 597-622. Retrieved February 4, 2021, from https://law.emory.edu/eilr/content/volume-30/issue-4/comments/standards-regulating-space-travel-ambiguities-outer-space.html.

Defense Intelligence Agency. (2019). *Challenges to Security in Space.* Defense Intelligence Agency. Retrieved March 30, 2020, from https://www.dia.mil/Portals/27/Documents/News/Military%20Power%20Publications/Space_Threat_V14_020119_sm.pdf.

DISCOS. (n.d.). *Database and Information System Characterising Objects in Space for ESA's Space Debris Office*. DISCOS. Retrieved November 14, 2020, from https://discosweb.esoc.esa.int/.

Dobos, B., & Prazak, J. (2019). To Clear or to Eliminate? Active Debris Removal Systems as Anti-satellite Weapons. *SPACE POLICY*, *47*, 217–223. https://doi.org/10.1016/j.spacepol.2019.01.007.

Dubanchet, V., Saussié, D., Alazard, D., Bérard, C., & Le Peuvédic, C. (2015). Modeling and control of a space robot for active debris removal. *CEAS Space Journal, 7*, 203–218. https://doi.org/10.1007/s12567-015-0082-4.

Dunstan, J. E. & Werb, B. (2009). Legal and Economic Implications of Orbital Debris Removal: Comments of the Space Frontier Foundation In Response to: DARPA Orbital Debris Removal (ODR) Request for Information for Tactical Technology Office (TTO), Defense Advanced Research Projects Agency (DARPA). Solicitation Number: DARPA-SN-09-68. Retrieved January 14, 2021, from https://www.scribd.com/document/23379988/Legal-and-Economics-Implications-of-Orbital-Debris-Removal.

Edelstein, K. S. (1995). *Orbital impacts and the Space Shuttle windshield.* NASA Technical Memorandum Document ID 19950019959. Retrieved November 14, 2020, from https://ntrs.nasa.gov/citations/19950019959.

European Space Agency (ESA), Italian space agency (ASI), British National Space Centre (BNSC), French space agency (CNES), German space agency (DLR). (2004). European Code of Conduct for Space Debris Mitigation. 28 June 2004. Issue 1.0. Retrieved February 9, 2021, from https://www.unoosa.org/documents/pdf/spacelaw/sd/2004-B5-10.pdf.

European Space Agency (ESA). (2005). *Space debris mitigation: the case for a code of conduct*. ESA. Retrieved February 9, 2021, from https://www.esa.int/Enabling_Support/Operations/Space_debris_mitigation_the_case_for_a_code_of_conduct.

European Space Agency (ESA). (2014). Space Debris Mitigation Policy for Agency Projects. ESA/ADMIN/IPOL(2014)2. Paris, 28 March 2014.

European Space Agency (ESA). (2019a). *ESA ministers commit to biggest ever budget*. ESA. Retrieved January 17, 2021, from http://www.esa.int/About_Us/Corporate_news/ESA_ministers_commit_to_biggest_ever_budget.

European Space Agency (ESA). (2019b). N° *23–2019: ESA commissions world's first space debris removal*. ESA. Retrieved January 17, 2021, from http://www.esa.int/Newsroom/Press_Releases/ESA_commissions_world_s_first_space_debris_removal.

European Space Agency (ESA). (2021). *Space debris by the numbers*. ESA. Retrieved January 7, 2021, from https://www.esa.int/Safety_Security/Space_Debris/Space_debris_by_the_numbers.

European Space Agency (ESA). (n.d.). *Mitigating space debris generation*. ESA. Retrieved February 2, 2021, from https://www.esa.int/Safety_Security/Space_Debris/Mitigating_space_debris_generation.

Fernandez, J. M., Visagie, L., Schenk, M., Stohlman, O. R., Aglietti, G. A., Lappas, J. P., & Erbb, S. (2014). Design and development of a gossamer sail system for deorbiting in low earth orbit. *Acta Astronautica, 103*, 204-225. https://doi.org/10.1016/j.actaastro.2014.06.018.

Flury, W. (1993). *European Activities on Space Debris. Mission Analysis Section, ESA/ESOC*. Proceedings of the First European Conference on Space Debris, Darmstadt, Germany, 5-7 April 1993 (ESA SD-01). Retrieved November 14, 2020, from https://conference.sdo.esoc.esa.int/proceedings/sdc1/paper/4/SDC1-paper4.pdf.

Force, M. K. (2016). Active Space Removal: When Consent Is Not an Option. *Air and Space Lawyer, 29*(3), 9–13.

Forshaw, J. L., Aglietti, G. S., Fellowes, S., Salmon, T., Retat, I., Hall, A., Chabot, T., Pisseloup, A., Tye, D., Bernal, C., Chaumette, F., Pollini, A., & Steyn, W. H.. (2020). The active space debris removal mission RemoveDebris. Part 1: From concept to launch. *Acta Astronautica*, *168*, 293–309. https://doi.org/10.1016/j.actaastro.2019.09.002.

Francillout, L. (2020). *The Inter-Agency Space Debris Coordination Committee (IADC) an overview of IADC's annual activities*. 57th Session of the Scientific and Technical Subcommittee United Nations Committee on the Peaceful Uses of Outer Space. 3-14 February 2020. Retrieved November 14, 2020, from https://www.unoosa.org/documents/pdf/copuos/stsc/2020/tech-22E.pdf.

Gambi, J. M. & García del Pino, M. L. (2017). Autonomous shooting at middle size space debris objects from space-based APT laser systems. *Acta Astronautica, 131*, 83-91. https://doi.org/10.1016/j.actaastro.2016.11.026.

Ganguli, G. (2011). *Active elimination of small-scale orbital debris*. 2011 XXXth URSI General Assembly and Scientific Symposium, General Assembly and Scientific Symposium, 2011 XXXth URSI, 1. https://doi.org/10.1109/URSIGASS.2011.6051098.

Ghelani, J. (2018). *An essential resource to human survival and progress after clean water, land and air.* European Space Agency. Retrieved February 9, 2021, from https://blogs.esa.int/cleanspace/2018/05/24/adding-earth-orbits-to-the-list-of-limited-natural-resources/.

Gomes, J. R., Devezas, T. C., Belderrain, M. C., Salgado, M. C. V., & de Melo, F. C. L. (2013). *The Road to Privatization of Space Exploration: What is missing?*. Institute for Aeronautics and Space. 64th International Astronautical Congress, Beijing, China. Retrieved February 9, 2021, from https://www.researchgate.net/publication/289635460_The_road_to_privatization_of_space_exploration_What_is_missing.

Guang, Z. & Jing-rui, Z. (2012). *Space Tether Net System for Debris Capture and Removal*. 4th International Conference on Intelligent Human-Machine Systems and Cybernetics, NanChang, China, August 26-27, 2012, 257-261. https://doi.org/10.1109/IHMSC.2012.71.

Guerra, G., Muresan, A. C., Nordqvist, K. G., Brissaud, A., Naciri, N., & Luo, L. (2017). Active Space Debris Removal System. *INCAS Bulletin, 9*(2), 97–116. https://doi.org/10.13111/2066-8201.2017.9.2.8.

Hakima, H. & Emami, M. R. (2018). Assessment of active methods for removal of LEO debris. *Acta Astronautica, 144*, 225-243. https://doi.org/10.1016/j.actaastro.2017.12.036.

Henry, C. (2020). *Amazon's Kuiper constellation gets FCC approval*. SpaceNews.com. Retrieved February 4, 2021, from https://spacenews.com/amazons-kuiper-constellation-gets-fcc-approval/.

Hovi, J., Skodvin, T., & Aakre, S. (2013). Can Climate Change Negotiations Succeed?. *Politics and Governance, 1*(2), 138-150. https://doi.org/10.12924/pag2013.01020138.

Huang, S., Colombo, C., Gonzalo, J. L., Masserini, A., Nugnes, M., Vallini, L., & Petit, M. (2020). *Preliminary Mission Analysis of Active Debris Removal Service for Large Constellations.* 71st International Astronautical Congress, the CyberSpace Edition. IAC-20, A6, VP, 14, x60342. Retrieved February 4, 2021, from https://re.public.polimi.it/retrieve/handle/11311/1149719/549901/HUANS02-20.pdf.

Ikpaya, I. O., Onuh, S. O., Achem, C. U., Madalla, F. Y. (2016). *Quest of Nigeria into Space for Sustainable Development*. SpaceOps Conference: 14th International Conference on Space Operations. 16-20 May 2016, Daejeon, Korea. https://doi.org/10.2514/6.2016-2345.

Iliopoulos, N., & Estebanb, M. (2020). Sustainable space exploration and its relevance to the privatization of space ventures. *Acta Astronautica*, *167*, 85-92. ISSN 0094-5765. https://doi.org/10.1016/j.actaastro.2019.09.037.

Inter-Agency Space Debris Coordination Committee (IADC). (2005). *Report of the Inter-Agency Space Debris Coordination Committee Activities on IADC Space Debris Mitigation Guidelines & Supporting Document.* Presented to the 42nd Session of the Scientific and Technical Subcommittee United Nations Committee on the Peaceful Uses of Outer Space. Retrieved January 8, 2021, from https://www.iadc-home.org/documents_public/file_down/id/4112.

Inter-Agency Space Debris Coordination Committee (IADC). (2007). *IADC Space Debris Mitigation Guidelines*. Issued by Steering Group and Working Group 4. IADC Action Item number 22.4. IADC-02-01. Retrieved January 8, 2021, from https://www.unoosa.org/documents/pdf/spacelaw/sd/IADC-2002-01-IADC-Space_Debris-Guidelines-Revision1.pdf.

International Organization for Standardization (ISO). (2019). ISO 24113:2019 Space systems — Space debris mitigation requirements. Retrieved January 8, 2021, from https://www.iso.org/standard/72383.html.

International Telecommunication Union (ITU). (2010). S.1003-2 (12/2010) Environmental protection of the geostationary-satellite orbit. Retrieved January 8, 2021, from https://www.itu.int/rec/R-REC-S.1003/en.

Jacklin, S. A. (2019). *Small-Satellite Mission Failure Rates*. Document ID 20190002705. NASA Ames Research Center. Retrieved January 8, 2021, from https://ntrs.nasa.gov/citations/20190002705.

Jakhu, R. S., Nyampong, Y. O. M., & Sgobba, T. (2017). Regulatory framework and organization for space debris removal and on orbit servicing of satellites. *Journal of Space Safety Engineering*, *4*(3–4), 129–137. https://doi.org/10.1016/j.jsse.2017.10.002.

Kelly, P. W., Bevilacqua, R., Mazal, L., & Erwin, R. S. (2018). TugSat: Removing Space Debris from Geostationary Orbits Using Solar Sails. *Journal of Spacecraft and Rockets, 55*(2). https://doi.org/10.2514/1.A33872.

Kessler, D. J. & Cour-Palais, B. G. (1978). Collision frequency of artificial satellites: The creation of a debris belt. *Journal of Geophysical Research: Space Physics, 83*(A6). https://doi.org/10.1029/JA083iA06p02637.

Kitamura, S., Hayakawam, Y., & Kawamoto, S. (2014). A reorbiter for large GEO debris objects using ion beam irradiation. *Acta Astronautica, 94*(2), 725-735. https://doi.org/10.1016/j.actaastro.2013.07.037.

Klima, R., Bloembergen, D., Savani, R., Tuyls, K., Wittig, A., Sapera, A., & Izzo, D. (2018). Space Debris Removal: Learning to Cooperate and the Price of Anarchy. *Frontiers in Robotics and A.I.*, *5*. https://doi.org/10.3389/frobt.2018.00054.

Ledkov, A. S. & Aslanov, V. S. (2018). Attitude motion of space debris during its removal by ion beam taking into account atmospheric disturbance. *Journal of Physics: Conference Series, 1050*(1). https://doi.org/10.1088/1742-6596/1050/1/012041.

Liou, J. C. & Johnson, N. L. (2006). Risks in Space from Orbiting Debris. *Science, 311*(5759), 340-341. https://doi.org/10.1126/science.1121337.

Liou, J. C., Johnson, N. L. & Hill, N. M. (2010). Controlling the growth of future LEO debris populations with active debris removal. *Acta Astronautica, 66*(5-6), 648-653. https://doi.org/10.1016/j.actaastro.2009.08.005.

Long, J. (2017). Ideas for Development of Long-Term Sustainability of Outer Space Activities: From the Perspective of Active Space Debris Removal. *IISL Proceedings, 145*.

Mark, C. P., & Kamath, S. (2019). Review of Active Space Debris Removal Methods. *Space Policy*, *47*, 194–206. https://doi.org/10.1016/j.spacepol.2018.12.005.

McFall-Johnsen, M. (2020). *A dead Soviet satellite and a discarded Chinese rocket body just avoided colliding in space and exploding into dangerous debris*. Insider Inc. Retrieved February 4, 2021, from https://www.businessinsider.com/soviet-satellite-chinese-rocket-might-crash-in-space-2020-10.

Merino, M., Ahedo, E., Bombardelli, C., Urrutxua, H., & Pelaez, J. (2013). Ion beam shepherd satellite for space debris removal. *Progress in Propulsion Physics, 4*, 789-802. https://doi.org/10.1051/eucass/201304789.

Microsoft Schweiz. (2020). *Swiss startup ClearSpace gets support from Microsoft to clean up space.* Microsoft Schweiz. Retrieved November 14, 2020, from https://news.microsoft.com/de-ch/2020/06/22/clearspace/.

Moorhead, A. V. & Matney, M. (2021). The ratio of hazardous meteoroids to orbital debris in near-Earth space. *Advances in Space Research*, *67*(1), 384-392. https://doi.org/10.1016/j.asr.2020.09.015.

Murtaza, A., Pirzada, S. J. H., Xu, T., & Jianwei, A. L. (2020). Orbital Debris Threat for Space Sustainability and Way Forward (Review Article). *IEEE Access, 8*, 61000-61019. https://doi.org/10.1109/ACCESS.2020.2979505.

National Aeronautics and Space Administration (NASA). (2009). *The Collision of Iridium 33 and Cosmos 2251: The Shape of Things to Come*. Document ID 20100002023. Publication Date, October 16, 2009. 60th International Astronautical Congress. Retrieved January 7, 2021, from https://ntrs.nasa.gov/citations/20100002023.

National Aeronautics and Space Administration (NASA). (n.d.). *Evolutionary Models LEGEND*. NASA. Retrieved January 14, 2021, from https://www.orbitaldebris.jsc.nasa.gov/modeling/evolmodeling.html.

Nishida, S., Kawamoto, S., Okawa, Y., Terui, F., & Kitamura, S. (2009). Space debris removal system using a small satellite. *Acta Astronautica, 65*(1–2), 95-102. https://doi.org/10.1016/j.actaastro.2009.01.041.

Obama, B. H. (2010). *National Space Policy of the United States of America*. Retrieved January 14, 2021, from https://history.nasa.gov/national_space_policy_6-28-10.pdf.

OneWeb. (n.d.). *Our Vision & Values*. ONEWEB.WORLD. Retrieved February 4, 2021, from https://www.oneweb.world/our-vision-values.

Paikowsky, D. (2017). What Is New Space? The Changing Ecosystem of Global Space Activity. *New Space 5*(2), 84-88. https://doi.org/10.1089/space.2016.0027.

Phipps, C. (2012). Clearing space debris with lasers. *SPIE Newsroom*. https://doi.org/10.1117/2.1201112.004076.

Rao, A., Burgess, M. G., & Kaffine, D. (2020). Orbital-use fees could more than quadruple the value of the space industry. *Proceedings of the National Academy of Sciences of the United States of America (PNAS), 117*(23), 12756–12762. https://doi.org/10.1073/pnas.1921260117.

Rovira, L. (2020). *SpaceX Starship as a trash collector in Earth orbit?.* EarthSky Communications Inc. Retrieved February 4, 2021, from https://earthsky.org/space/spacex-starship-clean-up-space-junk.

Ruggiero, A., Pergola, P., & Andrenucci, M. (2015). Small Electric Propulsion Platform for Active Space Debris Removal. *IEEE Transactions on Plasma Science, 43*(12), 4200-4209. https://doi.org/10.1109/TPS.2015.2491649.

Sanmartin, J. R., Martinez-Sanchez, M., & Ahedo, E. (1993). Bare wire anodes for electrodynamic tethers. *Journal of Propulsion and Power, 9*(3), 353-360, https://doi.org/10.2514/3.23629.

Schaub, H. & Sternovsky, Z. (2014). Active space debris charging for contactless electrostatic disposal maneuvers. *Advances in Space Research, 53*(1), 110-118. https://doi.org/10.1016/j.asr.2013.10.003.

Schmitz, M., Fasoulas, S., & Utzmann, J. (2015). Performance model for space-based laser debris sweepers. *Acta Astronautica, 115*, 376-383. https://doi.org/10.1016/j.actaastro.2015.05.032.

Shan, M., Guo, J., & Gill, E. (2016). Review and comparison of active space debris capturing and removal methods. *Progress in Aerospace Sciences*, *80*, 18–32. https://doi.org/10.1016/j.paerosci.2015.11.001.

Shan, M., Guo, J., & Gill, E. (2017). Deployment dynamics of tethered-net for space debris removal. *Acta Astronautica, 132*, 293-302. https://doi.org/10.1016/j.actaastro.2017.01.001.

Sharf, I., Thomsen, B., Botta, E. M., & Misra, A. K. (2017). Experiments and simulation of a net closing mechanism for tether-net capture of space debris. *Acta Astronautica, 139*, 332-343. https://doi.org/10.1016/j.actaastro.2017.07.026.

Shuangyan, S., Xing, J., & Hao, C. (2014). Cleaning space debris with a space-based laser system. *Chinese Journal of Aeronautics, 27*(4), 805-811. https://doi.org/10.1016/j.cja.2014.05.002.

Shuvalov, V. A., Gorev, N. B., Tokmak, N. A., & Kochubei, G. S. (2017). Physical simulation of the long-term dynamic action of a plasma beam on a space debris object. *Acta Austronautica, 132*, 97-102. https://doi.org/10.1016/j.actaastro.2016.11.039.

Smith, M. S. (2011). President Obama's National Space Policy: A change in tone and a focus on space sustainability. *Space Policy, 27*(1), 20-23. https://doi.org/10.1016/j.spacepol.2010.12.010.

Soulard, R., Quinn, M. N., Tajima, T., & Mourou, G. (2014). ICAN: A novel laser architecture for space debris removal. *Acta Astronautica, 105*(1), 192-200. https://doi.org/10.1016/j.actaastro.2014.09.004.

South Asia Monitor. (2020). *India and Nigeria to have space cooperation*. South Asia Monitor. Retrieved January 24, 2021, from https://southasiamonitor.org/india/india-and-nigeria-have-space-cooperation.

Starlink. (n.d.). *High Speed Internet Access Across the Globe*. SpaceX. Retrieved January 24, 2021, from https://www.starlink.com/.

Trump, D. J. (2020). *National Space Policy of the United States of America*. Retrieved January 14, 2021, from https://www.whitehouse.gov/wp-content/uploads/2020/12/National-Space-Policy.pdf.

UN COPUOS. (n.d.). *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies.* UN COPOUS. Retrieved December 5, 2020, from https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html.

UN COPUOS. (2018a). *Guidelines for the Long-term Sustainability of Outer Space Activities*. Conference room paper by the Chair of the Working Group on the Long-term Sustainability of Outer Space Activities. Vienna, 20–29 June 2018. A/AC.105/2018/CRP.20. Retrieved November 14, 2020, from https://www.unoosa.org/res/oosadoc/data/documents/2018/aac_1052018crp/aac_1052018crp_20_0_html/AC105_2018_CRP20E.pdf.

UN COPUOS. (2018b). *Compendium on Space Debris Mitigation Standards Adopted by States and International Organizations*. Retrieved January 8, 2021, from https://www.unoosa.org/documents/pdf/spacelaw/sd/Space_Debris_Compendium_COPUOS_26-Jan-2018.pdf.

UN COPUOS. (2019). *Compendium of Space Debris Mitigation Standards Adopted by States and International Organizations*. Retrieved November 14, 2020, from https://www.unoosa.org/documents/pdf/spacelaw/sd/Space_Debris_Compendium_COPUOS_25_Feb_2019p.pdf.

United Nations (UN). (1999). *Technical Report on Space Debris*. Text of the Report adopted by the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful uses of Outer Space. Sales No. E.99.I.17. ISBN 92-1-100813-1. Retrieved January 8, 2021, from https://www.orbitaldebris.jsc.nasa.gov/library/un_report_on_space_debris99.pdf.

United Nations (UN). (n.d.). *Outer Space Objects Index*. UN. Retrieved January 7, 2021, from https://www.unoosa.org/oosa/osoindex/search-ng.jspx?lf_id=.

United Nations Office for Outer Space Affairs (UN OOSA). (2010). *Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space*. UN OOSA. Retrieved January 8, 2021, from https://www.unoosa.org/pdf/publications/st_space_49E.pdf.

United Nations Office for Outer Space Affairs (UN OOSA). (n.d.) *Space Law Treaties and Principles*. UN OOSA. Retrieved January 8, 2021, from https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties.html.

University of Surrey. (n.d.a). About our Centre. The University of Surrey. Retrieved February 2, 2021, from https://www.surrey.ac.uk/surrey-space-centre/about.

University of Surrey. (n.d.b). DEORBITSAIL. The University of Surrey. Retrieved February 2, 2021, from https://www.surrey.ac.uk/surrey-space-centre/missions/deorbitsail.

University of Surrey. (n.d.c). INFLATESAIL. The University of Surrey. Retrieved February 2, 2021, from https://www.surrey.ac.uk/surrey-space-centre/missions/inflatesail#deploytech.

University of Surrey. (n.d.d). REMOVEDEBRIS. The University of Surrey. Retrieved February 2, 2021, from https://www.surrey.ac.uk/surrey-space-centre/missions/removedebris.

Visagie, L., Lappas, V., & Erb, S. (2015). Drag sails for space debris mitigation. *Acta Astronautica, 109*, 65-75. https://doi.org/10.1016/j.actaastro.2014.12.013.

Wall, M. (2015). *Wow! SpaceX Lands Orbital Rocket Successfully in Historic First*. Future US, Inc. Retrieved February 2, 2021, from https://www.space.com/31420-spacex-rocket-landing-success.html.

Wall, M. (2020). *SpaceX rocket returns to shore after historic astronaut launch (photos).* Future US, Inc. Retrieved February 2, 2021, from https://www.space.com/spacex-falcon-9-rocket-returns-shore-after-astronaut-launch.html.

Wen, Q., Yang, L., Shanghong, Z., Fang, Y., & Wang, Y. (2017). Removing small scale space debris by using a hybrid ground and space based laser system. *Optik, 141*, 105-113. https://doi.org/10.1016/j.ijleo.2017.05.075.

World Economic Forum. (n.d.). Space Sustainability Rating. World Economic Forum. Retrieved February 2, 2021, from https://www.weforum.org/projects/space-sustainability-rating.

Yang, F. Y., Nelson, B., Azizc, J., Carlinod, R., Perez A. D., Faber, N., Foster, C., Frost, C., Henze, C., Karacalıoğlu, A. G., Levit, C., Marshall, W., Mason, J., O'Toole, C., Swenson, J., Worden, S. P., & Stuple, J. (2016). LightForce photon-pressure collision avoidance: Efficiency analysis in the current debris environment and long-term simulation perspective. *Acta Astronautica, 126*, 411-423. https://doi.org/10.1016/j.actaastro.2016.04.032.

Mater’s Thesis Summary

The threat posed by space debris is hardly new. As governments and space agencies continued to release new objects into space, it became apparent that the seemingly spacious Earth’s orbits do indeed have narrow limits. With the rise in the number of nations and other actors interested in sending out their space assets into orbit, countries and international organizations started to develop debris mitigation guidelines to slow down the creation of new space debris. However, countries' and international organizations’ efforts to continue implementing useful mitigation strategies to slow down new space debris production, although valuable, are not enough. Reports have shown that ADR missions are necessary to turn back the devastating future scenarios created by the rapid multiplication of existing space debris. Scientists and researchers started to explore potential ADR technologies already in the 1980s and continue to do so today. But while researchers produce many theoretical studies about ADR’s possibilities and use, the execution of such projects lags. ADR missions are expensive and require steady long-term investment and planning, which nations and national space agencies cannot afford.

This thesis explains ADR missions' necessity, the technical and legal obstacles involved, and examples of ADR missions (organized by private actors) that managed to overcome them. Since the only existing ADR missions would not be possible without the determination of private space actors, and since outer space's environment is changing as commercial entities strive for individual space vendors' status, the current status quo faces a challenge. Governments are incapable of prudent cooperation and performing distinct space operations alone, without the involvement of commercial support. This thesis contends that countries shall instead support private actors capable of eliminating space debris from the Earth’s orbits and the private sector’s initiatives to conduct sustainable space missions. At the same time, this paper demonstrates that all space actors must work together to alter the current space norms' interpretation to reflect space's changing environment and ensure that the legal space framework accounts for ADR missions, that is currently not the case.

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Diploma thesis project

Contemporary Challenges of Space Debris Removal: Overview and Outlook

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1. Introduction to the topic

Outline of the topic to be addressed in the thesis:

Space debris, or the so-called orbital debris, refers to non-functional human-made objects that are present in the Earth's orbit. The number of uncontrollable objects grew exponentially in their numbers since the outbreak of the space arms race between the U.S. and the Soviet Union in 1957. Space debris poses a threat to any future attempt of the world civilization to reach the outer space again. While the danger that space debris poses is considerable, the question remains as to why do countries restrain from much more prudent cooperation to eliminate space debris. Furthermore, what are the reasons why counties due to the threat of space debris and the lack of consensus risk the safety of the space operations that they plan to conduct in the years and decades to come?

Political/social as well as scholarly relevance:

The relevance of space debris in international politics is conspicuous. All countries rely to a varying extent on space assets to conduct many of their functions, be it military, economic, social, or other, managed on land, in the air, or on the sea. Out of all countries, the United States relies the most on its space assets for all sorts of its operations via various Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) solutions (Defense Intelligence Agency, 2019). The United States owns the most comprehensive network of communications, reconnaissance, early-warning, positioning, and weather satellites, which enable the United States to relish the position of the world's leader in outer space affairs (Ibid.). At the same time, countries such as China tries to use the window of opportunity which space has to offer and continues to develop space assets as an area yet to be discovered and fully utilized (Ibid.). Russia, although dwarfed by the presence of the United States in space, also continues to have distinct motives to engage in a race to rule the space domain (Ibid.). In addition to the United States, China, and Russia, there is India and the European Space Agency (ESA) that also increasingly engage in outer space operations to improve their strategical advantages on Earth (Ibid.). Yet, while countries aim to reach the skies and conquer all obstacles that stand in their way, achieving such ends is not deemed through cooperation. Space debris remains one of the main problems for the successful execution of space operations. Yet, countries try to overcome this issue in general on an individual basis, instead of joining forces which would save costs as well as efforts.

The thesis shall draw on a and contribute to the already existing knowledge, as reflected in academic literature, and should offer additional input into the often-undebated issue of space debris, which receives little attention in much of contemporary life.

2. Research target, research question

To answer the question and explain, why do countries restrain from much more prudent cooperation to eliminate space debris, the paper will have to answer the following several research questions. First, who are currently the main actors in space, and what is the current status of their space operations, and what are their aims in continuing to explore the outer space domain? Second, what threat does space debris pose, and what are the technical limitations of space debris removal, and how can they be mitigated? Thirdly, who should be responsible for the clean-up of space debris? And finally, what are the political obstacles to space debris removal, and what are the outlooks for any cooperation of state actors regarding space debris removal?

3. Literature review

1. Forshaw, J. L., Aglietti, G. S., Fellowes, S., Salmon, T., Retat, I., Hall, A., Chabot, T., Pisseloup, A., Tye, D., Bernal, C., Chaumette, F., Pollini, A., & Steyn, W. H.. (2020). The active space debris removal mission RemoveDebris. Part 1: From concept to launch. *Acta Astronautica*, *168*, 293–309. https://doi.org/10.1016/j.actaastro.2019.09.002.

This paper is the first out of two papers describing the outcomes and implications of the first fully executed 2018 RemoveDEBRIS mission to demonstrate possible technologies and use them to remove debris from the outer space. This mission was the first mission directly aimed to showcase current Active Debris Removal (ADR) technologies. The paper focuses on the mission's design, starting with the development of the hardware together with the operational satellites and following with subsequent delivery of the spacecraft to the launching site. This paper exhausts the ramifications of designing a full scope debris removal operation, including the planning and execution.

2. Aglietti, G. S., Taylor, B., Fellowes, S., Salmon, T., Retat, I., Hall, A., Chabot, T., Pisseloup, A., Cox, C., Zarkesh, A., Mafficini, A., Vinkoff, N., Bashford, K., Bernal, C., Chaumette, F., Pollini, A., & Steyn, W. H.. (2020). The active space debris removal mission RemoveDebris. Part 2: In orbit operations. *Acta Astronautica*, *168*, 310–322. https://doi.org/10.1016/j.actaastro.2019.09.001.

This paper is the second of two articles describing the outcomes and implications of the fully executed RemoveDEBRIS mission. While the first paper focused on the design phase of the mission and the hardware of the satellite, this paper focuses on the mission's execution and in-orbit operations. Furthermore, the article deep dives into the demonstrations of the debris removal using net capture, vision-based navigation, harpoon, and DragSail capability.

3. Dobos, B., & Prazak, J. (2019). To Clear or to Eliminate? Active Debris Removal Systems as Antisatellite Weapons. *SPACE POLICY*, *47*, 217–223. https://doi.org/10.1016/j.spacepol.2019.01.007.

In the article, the authors reflect on the problem of an overcrowded Earth's outer space, which threatens the successful outcomes of all space missions in the years and decades to come. Although there is an internationally shared understanding that space debris poses a treat and efforts to limit the amount of waste generated in outer space are necessary, problems arise when countries discuss Active Debris Removal technologies. Countries fear the development and use of Active Debris Removal technologies due to concerns that these technologies could develop into weapons. The authors in the article state that although Active Debris Removal technologies can be used to attack working satellites in space and can become weapons, their destructive capabilities are not intense, and their damaging potential is not high. While a risk exists that Active Debris Removal technologies could be misused, countries should still facilitate their space deployment. Instead of obstructing the development of Active Debris Removal technologies, states should seek to build closer relations and trust to ensure that they hold confidence in mutual space operations. Moreover, further commercialization of space industries would also contribute and expedite the attempts to remove debris from outer space.

4. Drago, S. (2019). No Man's Sky: Utilizing Maritime Law to Address the Need for Space Debris Removal Technology. *Santa Clara Law Review*, *59*(2), 389.

The article by Sandra Drago offers an analysis of the needed possible response to the removal of space debris. While Drago begins with defining the problematization of space debris, its danger, and the current methods of responding to the threat of the space waste, it then continues to explore other means of debris mitigation. The author explores the national and international responses to the problem of space debris. At the national level, the author explores the significance of NASA's efforts as well as the efforts of the U.S. Department of Defense and the implications of the U.S. orbital debris mitigation standards. At the international level, the author studies the effectiveness of the Inter-Agency Space Debris Coordination Committee, the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space, the United Nations Outer Space Treaty, the United Nations Convention on International Liability for Damage Caused by Space Objects, and the United Nations Convention on Registration of Objects Launched into Outer Space.

5. Force, M. K. (2016). Active Space Debris Removal: When Consent Is Not an Option. Air and Space Lawyer, 29(3), 9–13.

In her short article, Force restates the importance of Active Debris Removal systems as researchers caution for quite a long time about the dangers of space debris. Current international space law offers no help as to how active debris removal should take place and what are its implications for the relations among states. Necessary legal arrangements exist; however, they are very vague and leave much to interpretation. According to the author, states should adopt a recognized understanding of treaty language, which would best reflect the original intent. As such, disputed or unclear legal clauses and policies, uncovered by recent developments of Active Debris Removal systems could offer legitimate solutions due to a constructive interpretation.

Construing space law through treaty interpretation would mean no additional treaties to be agreed or amended among countries at the national and international levels, which would be very difficult and time-consuming.

6. Guerra, G., Muresan, A. C., Nordqvist, K. G., Brissaud, A., Naciri, N., & Luo, L. (2017). Active Space Debris Removal System. INCAS Bulletin, 9(2), 97–116. https://doi.org/10.13111/2066-8201.2017.9.2.8.

The authors in the article explore the possibilities of using a so-called "drag augmentation system" as a method of active space debris removal for achieving the optimal results for space clean-up. The system would use an expanded foam, which would engulf space debris and increase the area-to-mass ratio of the space waste and, as such, heighten the chances of natural atmospheric drag and solar pressure on the matter. The drag augmentation system, as described in the paper, requires a stable docking system, from which the debris would be in the final stage un-docked, and the resulting uncontrolled re-entry of the matter into space would mean a burn up of the objects together with the induced foam in the atmosphere. The authors in the paper analyze the drag augmentation system along with the so-called "electric pulsion" system. The authors state that if two dedicated satellites would exist, which would contribute to the drag augmentation system, up to five large debris bodies could be removed from the outer space within a year.

7. Jakhu, R. S., Nyampong, Y. O. M. & Sgobba, T. (2017). Regulatory framework and organization for space debris removal and on orbit servicing of satellites. *Journal of Space Safety Engineering*, *4*(3–4), 129–137. https://doi.org/10.1016/j.jsse.2017.10.002.

The authors in the article argue that while debris mitigation, active debris removal, and on-orbiting servicing of satellites is vital for safeguarding the safety of space, the operations remain daunted due to legal constraint. As a result, the authors propose an establishment of a new international intergovernmental organization to safeguard and conduct all necessary actions to remove and prevent the further uncontrollable formation of space debris. Furthermore, the authors discuss the benefits of setting up an operational, institutional, and international regulatory framework for debris removal.

8. Klima, R., Bloembergen, D., Savani, R., Tuyls, K., Wittig, A., Sapera, A., & Izzo, D. (2018). Space Debris Removal: Learning to Cooperate and the Price of Anarchy. *Frontiers in Robotics and AI*, *5*. https://doi.org/10.3389/frobt.2018.00054.

In the article, the authors explore the implications of using a decentralized approach to space debris removal and the related costs to an individualistic approach determining active debris removal strategies. The authors build on their previously defined space debris simulator to present an accurate picture of the problematization of the current space debris removal methods while evaluating single-agent and multi-agent ways of dealing with space debris. Considering the significant investments and considerable resources needed for the successful execution of each space debris removal mission and the calculated 10% increase in costs of a decentralized strategy for conducting the space mission, the authors conclude that multi-actor solutions are much more sustainable. According to the authors, space debris removal would be much more efficient if countries would coordinate their strategies at the global level, rather than organizing their missions on an individual basis.

9. Long, J. (2018). Ideas for Development of Long-Term Sustainability of Outer Space Activities: From the Perspective of Active Space Debris Removal. IISL Proceedings, 145.

Jie Long, in the article, discusses the legal aspects of space debris removal. Long argues that any recognizable space debris still ultimately belongs to the space objects by definition, as stated in the Outer Space Treaty. As such, countries who owned the space objects at the beginning of their mission do not only have the right to remove the debris of that object from outer space but should proactively aim to do so. Similarly, it should be the aim of countries that have active debris removal capabilities to remove from space debris whose owner cannot be recognized; this mainly applies to tiny pieces of space debris. Furthermore, if a bit of space debris that has an identified owner threatens another space actor, that actor should also have the right to remove the dangerous space debris from space, given that the actor can justify and show proof of the existing threat in due time.

10. Mark, C. P., & Kamath, S. (2019). Review of Active Space Debris Removal Methods. *Space Policy*, *47*, 194–206. https://doi.org/10.1016/j.spacepol.2018.12.005.

The authors in the article outline the current methods of active space debris removal, which are momentarily under construction and development, or whose expedition is pending implementation. The authors delve into eight main methods of proactive space debris removal (collective, laser-based, ion-beam shepherd-based, tether-based, sail-based, satellite-based, unconventional, and dynamical systems-based). The methods vary not only in their concept and operations but also in the different space debris each method can remove from space based on the size of the space waste and its location in the outer space. The authors conclude that more information and work remains in the hands of researchers to attain the best possible ways of cleaning up space debris. For this, programs should not be supported only by international organizations and state actors through cooperation but should involve even commercial entities in the research and planning.

4. List of further relevant references:

1. Shan, M., Guo, J., & Gill, E. (2016). Review and comparison of active space debris capturing and removal methods. *Progress in Aerospace Sciences*, *80*, 18–32. https://doi.org/10.1016/j.paerosci.2015.11.001.
2. Wen, J. (2017). Analyzing Costs of Space Debris Removal in Basis of Three Kinds of Methods. *International Journal of Economics and Finance*, *8*, 151.
3. Al-Ekabi, C. (2015). European Autonomy in Space. (Cham: Springer).
4. Al-Rodhan, N.R.F. (2012). Meta-Geopolitics of Outer Space: An Analysis of Space Power, Security and Governance. (Basingstoke: Palgrave Macmillan). Chapter 3: Space Technologies and Meta-Geopolitics, pp. 44-68.
5. Anantatmula, V. (2013). U.S. Initiative to Place Weapons in Space: The Catalyst for a Space-Based Arms Race with China and Russia. *Astropolitics* 11 (3), pp. 132-155.
6. Bormann, N., Sheehan, M. (2009). Securing Outer Space. (Abingdon: Routledge).
7. Bowen, B. E. (2014). Cascading Crises: Orbital Debris and the Widening of Space Security. *Astropolitics* 12 (1), pp. 46-68.
8. Dolman, E. (1999). Geostrategy in the space age: An astropolitical analysis. *Journal of Strategic Studies* 22 (2-3), pp. 83-106.

9. Dolman, E. C. (2005). *Astropolitik: classical geopolitics in the space age.* (London: Frank Cass Publishers).

10. Fukushima, Y. (2013). Debates over the Military Value of Outer Space in the Past, Present and the Future: Drawing on Space Power Theory in the U.S., NIDS Journal of Defense and Security, http://www.nids.mod.go.jp/english/publication/kiyo/pdf/2013/bulletin_e2013_4.pdf.

11. Hays, P.L. (2011). Space and Security: A Reference Handbook. Contemporary World Issues book series.

12. Johnson-Freese, J. (2007). Space as a Strategic Asset. (New York: Columbia University Press).

13. Johnson-Freese, J. (2017). Space Warfare in the 21st Century: Arming the Heavens. (New York: Routledge).

14. Lambeth, B.S. (1999). Air power, space power and geography. *Journal of Strategic Studies* 22 (2-3), pp. 63-82.

15. McCormick, P. (2015). Space Situational Awarness in Europe: The Fractures and the Federative Aspects of European Space Efforts. *Astropolitics* 13 (1), pp. 43-64.

16. Moltz, J. C. (2014). Crowded Orbits: Conflict and Cooperation in Space. New York: Columbia University Press.

17. Paikowsky, D. (2017). What Is New Space? The Changing Ecosystem of Global Space Activity. *New Space* 5 (2), pp. 84-88.

18. Quintana, E. (2017). The New Space Age. *The RUSI Journal* 162 (3), pp. 88-109.

19. Sadeh, E. (2011). The Politics of Space: A Survey (Routledge: London)

20. Tellis, A. (2007). China´s Military Space Strategy. *Survival* 49 (3), pp. 41-72.

21. Zhang, Y. (2013). The eagle eyes the dragon in space – A critique. *Space Policy* 29 (2), pp. 113-120.

5. Conceptual and theoretical framework, research hypotheses

The advancement of both civilian and military technology has enabled the use of outer space. Acquisition of sufficiently sophisticated IT solutions has empowered states to look to the outer space and think of it as having an increasingly more mature and profound strategic importance. As such, states understand that full utilization of outer space will offer a window of opportunity for all nations to advance their strategic goals. With this belief in mind, states currently continue to develop new space assets at a persistent rate. However, with the increase in the number of space assets in outer space since the space age begun in the middle of the 20th century, problems associated with the outer space multiplied as well. Failing to understand that one actor cannot solve issues such as space debris with single resources alone, countries have led their ways to achieve their efforts to dominate the outer space blinded by reaching the ultimate high ground.

The outer space can be considered an ungoverned area as any law regulation in place is loose, to say the least, with Cold War-like treaties such as the Outer Space Treaty, which has been active since 1967 falling behind the swift advancements of states in the arena (UN, 2019). The complete lack of obligatory regulations has enabled outer space to stay in an almost state of anarchy where states area almost free to act as they best see fit. Due to its characteristics (or perhaps the lack of them), outer space is by many considered an ungovernable territory, missing, for example, traditional features such as borders and other divisions that could split the responsibilities and assign accountability to the actors that choose to operate within the domain.

The analysis of the states' behavior regarding space debris removal is critical, keeping in mind the anarchical nature of the outer space domain through the lens of the structural realist thought. According to Dolman (1999), the underlying logic of space geostrategy is that if a space actor can reach outer space and instates himself as the dominant controller of the lower Earth orbits, then the actor ultimately controls the whole outer space. If an actor controls the outer space, he can choose to destroy and dominate actors on Earth which have lost the battle for the ultimate high ground position. According to this analysis, Dolman argues that for the international community, it would be beneficial if the United States as a liberal hegemon were the dominant actor in outer space. On the contrary, if actors such as Russia or China were to dominate the high ground, then they would use their power only to their strategic advantage, which is threatening to all other nations.

Research hypothesis:

Based on the outlined conceptual framework and the literature presented in the literature review, the research hypothesis for this paper is as follows. Due to the anarchic characteristics of the space domain, countries will continue to refrain from conducting comprehensive cooperative operations aimed at cleaning up the outer space from space debris. Due to the lack of accountability, that is associated with the outer space and with space debris, the space debris removal operations are likely to drag on as countries will choose to execute individualistic actions with their domestic assets instead of opting for relying on other countries. On the contrary, politically independent space agencies will step in to join forces and enhance space debris removal systems.

Empirical data and analytical technique:

The paper will stand on the comparative case study research method to consolidate the similarities, differences, and other patterns across the doctrines of the main space actors, the United States, the European Space Agency, Russia, China, and India. Also, the paper will include deep dives into selected space agencies and their efforts. This comparative case study will offer a thorough understanding as to why counties, given the scale of the space debris issue, refrain from cooperating in the contemporary context on its removal.

The paper will include the following principal sources: historical, academic, as well as military documents, namely in the various specific case studies of the countries and entities conducting outer space operations.

Classified government documentation that cannot be accessed will pose limitations to this study. Furthermore, the final part of the paper will hold the formulation of the possible outlook, which will be subject to discussion. Any perspective on matters of space debris is highly debatable, and any solutions or efforts to mitigate space debris are subject to the influence of external factors such as economic, political, and societal issues and norms.

6. Planned thesis outline

1. Introduction
    - The introduction will include information about the structure of the thesis, including conceptual framework outline, research questions, and hypothesis
2. Conceptual framework including a review of relevant literature
    - Including the characteristics of the outer space domain and brief historical overview of the space domain as a strategy realm rising in importance
3. The threat of space debris
    - What threat does space debris pose?
    - What are the technical limitations of space debris removal?
    - How can they be mitigated?
4. Space debris removal
    - What is currently on the foreseeable agenda? A summary.
5. Case study: United States
    - Why is it one of the main actors in space?
    - What is the current status of its state operations?
    - What are its aims in continuing to explore the outer space domain?
    - What does the country currently do to tackle the problem of space debris, including cooperation in terms of technologies with other space actors?
6. Case study: European Space Agency
    - Why is it one of the main actors in space?
    - What is the current status of its state operations?
    - What are its aims in continuing to explore the outer space domain?

- What does the organization currently do to tackle the problem of space debris, including cooperation in terms of technologies with other space actors?

7. Case study: Russia
    - Why is it one of the main actors in space?
    - What is the current status of its state operations?
    - What are its aims in continuing to explore the outer space domain?
    - What does the country currently do to tackle the problem of space debris, including cooperation in terms of technologies with other space actors?
8. Case study: China
    - Why is it one of the main actors in space?
    - What is the current status of its state operations?
    - What are its aims in continuing to explore the outer space domain?
    - What does the country currently do to tackle the problem of space debris, including cooperation in terms of technologies with other space actors?
9. Case study: India
    - Why is it one of the main actors in space?
    - What is the current status of its state operations?
    - What are its aims in continuing to explore the outer space domain?
    - What does the country currently do to tackle the problem of space debris, including cooperation in terms of technologies with other space actors?
10. Political obstacles to space debris removal
    - Referring to attempts at international cooperation of state actors
    - Also looking at non-state space agencies and their efforts to tackle space debris

11. Outlook

    - What are the outlooks for any cooperation of state actors regarding space debris removal?

12. Conclusion

7. References

Defense Intelligence Agency. (2019). *Challenges to Security in Space.* Retrieved March 30, 2020, from https://www.dia.mil/Portals/27/Documents/News/Military%20Power%20Publications/Space_Threat_V14_020119_sm.pdf.

Dolman, E. (1999). Geostrategy in the space age: An astropolitical analysis. Journal of Strategic Studies 22 (2-3), pp. 83-106.

United Nations (2019), *Space Law. Office for Outer Space Affairs*, COPOUS 2019.