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Revisiting the Outer Space Treaty in the Age of Artificial Intelligence and Autonomous Debris Removal Systems

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Abstract:
The Outer Space Treaty (OST), established in 1967, serves as the cornerstone of international space law, setting broad guidelines for the responsible exploration and use of outer space. However, as space activities evolve, particularly with the advent of Artificial Intelligence (AI) and autonomous debris removal technologies, the current legal framework is facing significant challenges. While the OST addresses some fundamental aspects of space exploration and liability, it lacks the specificity and adaptability required to regulate new technologies in space, such as AI-driven systems designed to address the mounting issue of space debris. The growing proliferation of satellites, particularly small satellites like CubeSats, has exacerbated the space debris problem, with debris colliding into operational spacecraft posing severe risks to both space infrastructure and Earth's environment. This paper revisits the OST in light of these technological advancements, analyzing how its general provisions need to be updated to incorporate AI and autonomous systems. It further explores potential amendments or new legal instruments that could provide a comprehensive regulatory framework for debris removal, focusing on accountability, liability, and international cooperation. The paper calls for international consensus on defining legal norms for AI-driven debris removal systems and ensuring their integration into space law, so as to safeguard the sustainability of space activities while balancing technological progress with environmental responsibility.

Keywords: Outer Space Treaty, Artificial Intelligence, Autonomous Systems, Space Debris, Space Law, International Cooperation.

1. Lack of Legal Frameworks for Emerging Technologies in Debris Removal

When it comes to outer space concerns, Outer Space Treaty, 1967 was the first treaty which introduced norms which tends to regulate human activities and behaviour in outer space. The foremost purpose of this treaty is to protect the outer space environment. Even if the treaty raise concerns about the liability for the maintenance of outer space, it lacks while providing a standardized definition for liability and fails to differentiate between terms like space object and debris. But it has been a long time since it was implemented and hence it fails to accomplish the issues which are being faced in current situation due to the advancement of technology and tools like AI. The Liability Convention, 1972 whose major concern of implementation is to establish the accountability and liability framework of nations who are involved in debris removal and management work one or another way. It also stated that even if the damage is caused due to the commercial agencies of the nation, the government only will be held liable for the same but the compensation can only be claimed when interest of any human agency's interest is involved. It is very easy to establish that whether the damage is caused to any property on earth or to one space object through any other space object it will directly or indirectly harm the environment of the earth. As of now there are not any such treaties that deal with the protection of outer space environment.

The imbalancement of the legal framework during the evolution of technologies such as Anti-Satellites (ASAT) is a big concern contributing to unsafe & unsecure environment and also increasing trust challenges between nations. Since 1968 there 15 ASAT tests by four major developed and developing economies. It has been established by Union of Concerned Scientists that just the destruction of single 10 ton satellite can generate enormous amount of debris in outer space. China's ASAT test in 2007 destroyed FenYun 1C weather forecast satellite, it is considered as the far most destructive satellite collision in the history till now. It was the first direct ascent ASAT satellite test since 1985 which created over 3400 pieces of tracked debris.

The exploration of outer space is being done on the global level through various private and state owned organisations and is fragmented in various sectors therefore it makes it more difficult to establish a harmonised framework to regulate the activities related to space debris management. This fragmentation results into inconsistent compliance with debris mitigation practices and hinder harmonized global approach. Now, because there is absence of legal binding norms the leading players of space exploration prioritize profit over environmental responsibility and disincentive for debris removal plays a role of catalyst for undermining their responsibilities.

2. Legal Implications of Micro and Nano-Satellite Proliferation

In recent years, there has been a significant surge in the application of nano-satellites and CubeSats, owing to the democratization of space activities. Previously, satellite missions were largely conducted by these major private companies with government backing, primarily focusing on security or environmental monitoring. The size of these satellites can be compared to that of multistoried buildings, costing the companies hundreds of millions to develop and launch them.

The structure of nano-satellites and CubeSats, as the name suggests, is cubic, with dimensions measuring approximately 10 x 10 x 10 cm and a mass ranging between 1 and 1.33 kg. As per the recent data, over 1,000 CubeSats have been launched since the early 2000's, with these figures expected to grow astronomically in the coming years due to mega-constellation projects and increased commercialization.

The development of nano-satellites has triggered a model shift in the space industry, from major private space organizations centering on satellite manufacturing towards NewSpace organizations. Adding to that, developing CubeSats is quite inexpensive and they can be launched in comparatively shorter periods of time, encouraging wide range of ambitious space projects. Before, space activities were only accessible to large government agencies and multinational corporations.

With the arrival of real-time navigation technologies, such as the Google Maps in 2005, and the widespread adoption of mobile phone technology, the scope of the space-related activities has expanded to include navigation, Internet of Things (IoT) connectivity, telecommunications , and more, no longer restricting itself to nation's security or environmental purposes. In accordance, start-ups and other business entities have started creating new business frameworks aimed at capitalizing on this trend.

What, then, seems to be the problem? Well, for one, the lack of regulatory mechanisms to address the untrackable debris left by these nanosatellites upon their disintegration is becoming a major issue.

The U.S. Space Surveillance Network, a ground-based radar network, has tracked approximately 40,230 artificial objects in orbit, as latest by April 2025. Nevertheless, these network systems face certain limitations, aggravating the risks posed by untrackable debris.

The current systems for tracking the space debris are limited to objects larger than 10 cm in low Earth orbit (LEO), allowing millions of sub-centimeter fragments that are produced upon the disintegration of nano-satellites to go undetected. The estimates provided by the ESA suggest that over 170 million debris particles smaller than 1 mm exist. Due to limited reflectivity and orbital velocity variations, LiDAR systems are unable to track sub-centimeter objects in orbit. The NASA's Orbital Debris Program Office has noted that debris smaller than 3mm quite often evades detection and is not accounted for until the post-mission analysis of returned spacecraft surfaces. These nano-sized satellites can fragment into 5000 particles upon collision, with over 90% smaller than 1 cm and each fragment capable of evading detection yet retaining destructive potential.

The foundational treaties, like the Outer Space Treaty (OST), 1967 and the Liability Convention 1972, lack the binding provisions to mandate the tracking of debris generated by nano-satellites as these were drafted before the era of small satellites expansion, leaving the modern debris challenges unaddressed. While the Article VIII of OST establishes the State jurisdiction over registered space objects, it does not contain provisions for post-launch tracking obligations, debris monitoring or technical standards for detectability. The absence of such provisions becomes critical as the sub-centimeter fragments produced on disintegration of non-satellites and CubeSats allows them to go undetected by existing radar networks, yet they retain potential to damage operational spacecraft at orbital velocities exceeding 7.8 km/s.

Adding to the issue, Article II of the Liability Convention establishes absolute liability for damage caused by identifiable space objects. However, this provision falters when applied to untrackable debris. The launching states are held responsible for damage caused by their space objects under Article II, but this rests on the ability to attribute debris to specific sources, a nigh impossible task when 89% risk of collisions in LEO involve particles smaller than 10 cm. Also, the Registration Convention of 1975 mandates only basic orbital data to be submitted at launch, but does not require to update positional information. It is also silent on tracking debris fragments left upon collision of nano-satellites. About 37% of CubeSats launched over past decade lacked appropriate registration, leaving their debris unaccounted for within international legal frameworks.

Another major concern regarding the CubeSats is deciding who will be responsible in the event these satellites generate space debris, which is quite confusing in itself as CubeSats and small satellites are built often through teamwork between universities, private companies, and groups from different countries. The provisions of the Outer Space Treaty 1967 hold the countries responsible for all the space activities that come from their territory or involve their citizens, even if private groups or universities are involved. However, that gets quite complicated in CubeSat projects, as usually there are multiple parties involved in the completion of such projects. A university in one country might design the satellite, a private company in another country might launch it, and the rocket might take off from some other country. The law, in such cases, imposes responsibility on all these countries if something goes awry, but it does not clearly determine how the responsibility should be divided or who is liable to pay if debris causes damage. This sense of confusion is further aggravated when CubeSats are launched as extra payloads alongside bigger satellites. It becomes quite difficult to establish accountability if debris is created as the primary mission operator and the CubeSat team may have no contractual relationship between them. The findings of 2024 study of 200 CubeSat missions suggest that around 65% of these missions involved stakeholders from three or more countries, but only 12% had clear agreements dividing the responsibility for problems. These unclear rules encourages risk-shifting, with the organizations trying to avoid responsibility. The private companies launch their CubeSats as part of government sponsored missions to leverage state immunity clauses, while the universities exploit special educations programs that do not require much insurance. In an event a CubeSat collides with an operational satellite of another country, it would be quite difficult to establish liability because of insufficient data to prove whose debris caused the problem. The outdated space treaties and the lack of clarity of international rules in establishing responsibility for space debris discourages proactive debris mitigation, as no single party is compelled to address the long- term orbital risks.

3. Environmental Impact of Space Debris on Non-Orbital Ecosystems

In March 2021, NASA confirmed that the metal object that crashed into a Naples, Florida was part of the International Space Station (ISS). Additionally recent studies show that there are nearly 130 million pieces, the density of debris in low Earth orbit (LEO) leads to collisions, greatly amplifying the debris field. This comprehensive analysis examines the environmental impacts of space debris, drawing from recent research to illuminate the complex interactions between human space activities and the fragile orbital and atmospheric environments. It can be clearly drawn upon that space debris is hazardous for the outer space and raise a question on the approaches towards the sustainability. Not only space debris results into the adverse impact on orbital ecosystem of earth but also create a huge damage to non-orbital ecosystem.

MARINE POLLUTION

The spare parts of the space crafts that survive in the atmospheric re-entrance during their launch, highly end their journey in Earth's ocean, creating an growing concern toward the damages caused to the marine life existing there. The International Maritime Organization (IMO) has identified that "debris dumped in the ocean during the launch of spaceflight activities could potentially harm the environment." Although the dumpage of domestic waste at sea is addressed through London Convention and Protocols but it remains uncertain in terms of space debris.

According to IMO the impact from spacecraft debris include several threats to ocean ecosystem. One of the most prominent harm that rises due to the termination of space debris in earth's sea is release of toxic substance, like hazardous gases and fluids emitted. The direct physical contact with marine creatures not only cause a substantial loss like mortality, damage and displacement of the marine habitats but also have the potential to reduce essential light and oxygen needed for their survival. As the collision of meteorites impact the land surface, the collision of space debris impact the sea bed. The collisions of space debris in sea can alter the sea bed's surface and can create craters in the sea bed which disturbs the suitable ecosystem for the marine plants or corals. Even the accumulated debris can result into recurrent damages due to the movement of debris objects due to tides and waves of water body.

Coral Reefs which are traditionally identified as the mere rocks serves as the support the vibrant communities of plants, fishes and other organisms and have the highest biodiversity of any ecosystem on the planet. Reefs can be impacted by marine debris that can smother, crush, or break off pieces of coral and due to very slow recovery speed it can take a long time to regain its initial stage back. Additionally, abandoned spacecraft components can release fuel, anti-fouling paints, or other chemicals that damage or kill corals while releasing nutrients that may promote excessive algal growth, potentially disrupting ecosystem balance.

STRATOSPHERE POLLUTION

Stratosphere is a layer, which counts between 10 to 50 kilometers above the surface of the Earth. A groundbreaking 2023 study published in the Proceedings of the National Academy of Sciences demonstrated that "metals that vaporized during spacecraft reentries can be clearly measured in stratospheric sulfuric acid particles," with over 20 different elements detected at levels consistent with alloys commonly used in spacecraft construction. This research confirmed that "10% of stratospheric sulfuric acid particles larger than 120 nm in diameter contain[ing] aluminum and other elements from spacecraft re-entry."

In the generation of broadband internet connectivity, rapid proliferation of satellite mega constellations is creating a vast effect on Earth's atmosphere which directly impact and disrupt climatic cycles. New CIRES research modeling this process suggests that by 2040, there would be enough alumina in the stratosphere to alter wind speeds and temperatures at the poles and impact Earth's climate in ways scientists don't fully understand. The chemical exfoliation due to re-entry of the space debris in earth's atmosphere, at some extend also contribute to ablation.

4. Absence of Binding Agreements on Active Debris Removal (ADR)

Over 130 million fragments of debris larger than 1mm now orbit Earth, threatening the sustainability of space activities. This threat has magnified to critical levels as humanity's reliance on space infrastructure increases, spanning from telecommunications, weather monitoring to global navigation and what not. ADR, short for Active Debris Removal, is considered one of the many significant solutions for removing space debris. It refers to the deliberate process of locating, capturing and deorbiting defunct satellites, spent rocket stages, and other hazardous space debris to mitigate collision risks and preserve orbital sustainability. ADR technologies aim to address this crisis by physically removing high-risk debris, but they face technical, legal and economic hurdles in their implementation. Further, there is absence of binding international agreements that stifles the progress. By 2030, the debris density in the low Earth orbit (LEO) is going to intensify by 500% due to the increase in the number of projected 100,000+ satellites, which could jeopardize Earth observation, global communications, and scientific missions.

The Outer Space Treaty contains a clause requiring the states to avoid "harmful contamination" of space under Article IX. However, it does not define quantitative debris thresholds, mandate removal of defunct satellites, or assign liability for debris-generating collisions. For example, the collision of Iridium 33 satellite with the defunct Russian military satellite Cosmos 2251 at high speed, with neither parties being held accountable or penalized, displays the limitations of the international treaties. The collision took place in 2009 at high speed, generating thousands of debris fragments.

From an economic standpoint, the implementation of ADR requires exorbitant amount of money, and usually these high costs of cleaning up orbital debris fall upon individual nations or companies. It costs between $60 million and $150 million for removing a single hazardous debris object, yet every satellite operator in that orbital region benefits from the reduced collision risks. It creates a situation where the entity funding 100% cost of debris removal only captures a fraction of the benefits, while other nations or private companies shirk away from this financial burden and enjoy the rewards of a cleaner space environment. An example of this would be the upcoming ClearSpace-1 Mission initiated by the European Space Agency, which has received €86 million in funds by 12 EU countries and aims to remove a 112 kg debris in 2026. However, leading space powers like the U.S. and China declined to contribute financially in such an endeavor, despite being responsible for over 68% debris in low Earth orbit (LEO).

Taking the above-mentioned example, the collision of Iridium 33 with the defunct Russian satellite Cosmos 2251 created at least 2300 debris fragments, increasing the risk for all operators in the orbit by 18%. With none of the parties shouldering the responsibility, the cleanup costs were disproportionately borne by third parties with the ESA funding €12 million for collision avoidance upgrades and the commercial operators putting in €220 million in uninsured losses.

The current frameworks governing the space law, like the OST 1967 and the IADC, lack the binding mechanisms to enforce debris removal. The 25-year deorbit guidelines are voluntary and lack enforcement, and about 40% of satellites in LEO exceed this limit without consequences.

5. Ethical and Equity Concerns in Orbital Space Use

All nations possess the right to explore the outer space equally. There are 195 counties in this world, but not all countries are equally liable for the management of the space debris management as the responsibility for the maintenance lies in accordance with the proportionality of the exploitation of the resources. The developed countries who are the historical explorer of the outer space should be held accountable accordingly. So that developing countries and underdeveloped countries can practise their rights freely.

The rapid exploration of space has created a complex web in terms of ethics and equality among the nations and this lies beyond the technical considerations of management of space debris. All the nations resist with equitable rights to explore the space but it being increasingly congested with both operational and defunct debris, questions fairness, responsibility and equitable access.

International Telecommunication Commission which was established under International Telegraph Convention is responsible for allocation of spectrum and register frequency assignments, orbital positions and other parameters of satellite. ITU's orbital slotting is allocated on the basis of first come first serve basis which leaves very few slots or no slots for the new entrants in the race of space exploration. This results in the unavailability of finite resources for new comers.

The most developed countries like America, China and Japan have launched several satellite for a strong telecommunication base in their country which have congested the Geostationary Earth Orbit. This congestion is particularly problematic in the geostationary Earth orbit (GEO) belt, which is critical for telecommunications and weather monitoring satellites. The scarcity of available slots in prime orbital locations means that developing nations often face the choice between accepting suboptimal positions or being excluded entirely from certain types of space activities. The World Meteorological Organization has recognized this challenge and recommends that African countries file for orbital slots as a block, as they stand a better chance of securing spectrum resources through collective action.

To establish the ethical conduct and equity for future operations it is necessary to understand the historical concept of initiation of space debris. The first satellite which was Sputnik I in 1957 was the initial step that amounted to human made space debris. This launch initiated a race between the established nations of that era and since then space has been exploited even after serious environmental and sustainability considerations. The aim of historical players was to establish their own assets in space while they completely ignored the fact that this space is a finite resource to explore.

6. Legal Challenges of Space Traffic Management (STM)

The transformation of the Earth's orbit into an extremely congested and hazardous environment due to the explosive growth of the space activities creates a critical situation. The current space environment is often likened to a crowded highway with no universally recognized traffic controller. The sheer number of objects in the Earth's orbit is staggering, with over 14,000 satellites currently in orbit, with more than 3,500 inactive and an estimated 120 million fragments of debris from past missions and collisions. This overcrowding raises the risk of accidental collisions, which could trigger chain reaction of debris, endangering not only current satellites but also the very future of space operations. Recently, the United Nations has issued a call for urgent action, warning that without coordinated management, critical orbital regions could become unusable, compromising global communications, navigation, and scientific missions.

Adding to that, the absence of a global governing body to oversee and regulate this orbital traffic create a legal hurdle. While the established international frameworks and agreements like the Outer Space Treaty, 1967 lay down basic principles such as the prohibition of nuclear weapons in space and establishing state liability for damages, they lack concrete, enforceable rules for modern space traffic management. There are no universally accepted "rules of the road" for space due to absence of binding international standards or dedicated regulatory body. As a result, nations form their own rules and procedures for licensing, liability, and satellite operations, sometimes giving priority national interests or technological advancement over international cooperation. It creates a vacuum where it is difficult to determine the liability or assign fault in the event of collision. Nations are hesitant in sharing essential information about their space activities and location of their satellites in fear that sharing such an information could jeopardise national security and their economic interests.

Another thing to consider is that the data that ensures orbital safety can expose vulnerabilities in military or commercial satellites. The Two-Line Element datasets provided by the U.S. Space Surveillance Network (SSN) to 43 nations and 130 commercial operators is the world's most advanced space-tracking system. However, these TLEs rendered themselves insufficient for precise collision avoidance as they have a positional inaccuracy of 1 kilometre. An incident involving an Indian NavIC satellite and a Starlink satellite in 2024, highlighted this limitation. These satellites had to exercise last-minute evasive maneuvers that consumed precious fuel as the outdated TLEs failed to predict a 200-meter close approach.

According to the data gathered by Secure World Foundation, nearly 30 % of active orbiters comprise of military satellites, often operating in secrecy. A similar incident occurred in 2023, when China refused to disclose the trajectory of its Shijian-21 satellite during a close approach event with an ESA craft, citing national security.

This creates a legal uncertainty as commercial organisations and private companies now play a significant role in space activities such as launching and operating satellites, often adhering to the laws of their host nations rather than international frameworks.

Conclusion:

The Outer Space Treaty (OST) laid the foundational framework for outer space governance, but its provisions, crafted in the 1960s, are increasingly inadequate in addressing modern challenges, particularly the growing issue of space debris. With the rise of Artificial Intelligence (AI) and autonomous systems, the OST's general and outdated provisions fail to provide a legal structure that accommodates the rapid advancements in space technology. Space debris, exacerbated by the proliferation of satellites and small satellite constellations, poses a significant risk to both space operations and Earth's environment. While AI-driven systems and autonomous debris removal technologies hold great promise in mitigating this issue, the absence of updated, binding legal norms leaves a regulatory void. This void creates challenges in terms of accountability, liability, and coordination among space-faring nations and commercial entities.

In conclusion, the Outer Space Treaty must undergo a comprehensive review and adaptation to incorporate emerging technologies like AI and autonomous systems. A new, specialized legal framework should be developed to address the specific challenges of debris removal, ensuring that technological advancements align with global environmental and safety standards. Failure to modernize the treaty will result in a fragmented and reactive legal environment, where space debris continues to threaten the sustainability of space activities.

Suggestions:

1. **Amend the Outer Space Treaty:** The OST should be revised to include provisions on AI and autonomous systems, focusing on space debris management, removal technologies, and liability frameworks for debris-related damage.
2. **Establish Clear Liability Standards:** New guidelines must be established to define liability for space debris, particularly when it comes to debris generated by autonomous systems and private commercial entities.
3. **Promote International Collaboration:** Global cooperation is essential for effective space debris management. International treaties should include binding agreements on space debris removal operations, ensuring that all space-faring nations contribute to maintaining a safe orbital environment.
4. **Develop Technical and Operational Standards:** Clear guidelines on debris removal systems should be developed, including technical standards for AI-driven systems, ensuring they operate within an established legal framework.
5. **Create a Regulatory Body:** A supranational space regulatory body could oversee the implementation of debris removal protocols, ensuring compliance with international laws, promoting transparency, and holding entities accountable.
6. **Encourage Research and Innovation:** Governments and private sectors should invest in research and development of sustainable and cost-effective debris removal technologies, with a focus on minimizing environmental impact.