Autonomous Satellite System to Address Space Debris

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Introduction

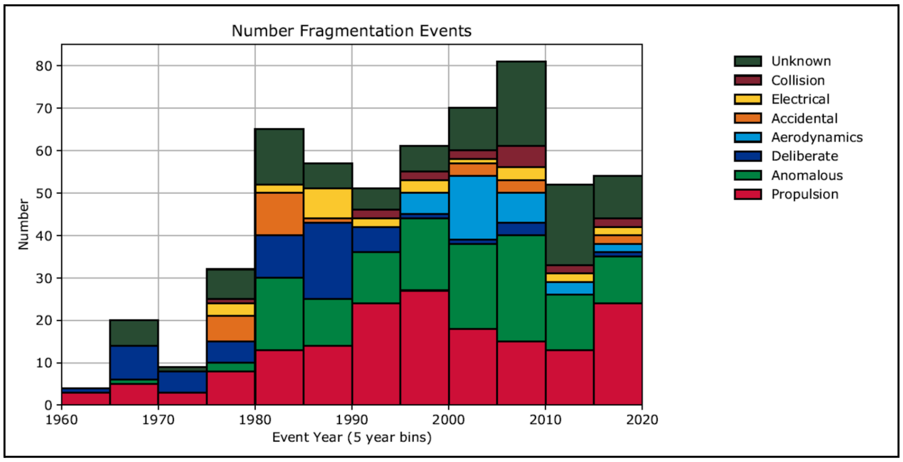
Space junk, also known as space debris or orbital debris, refers to any non-functional or discarded human-made objects in space. This includes defunct satellites, spent rocket stages, fragments from previous collisions, and even tiny paint flecks.

Most pieces of space junk reach speeds of approximately 18,000 miles per hour (27,000 kilometers per hour), nearly seven times faster than a bullet *(NASA, 2023).* While there are about 2,000 active satellites orbiting Earth at the moment, there are also 3,000 dead ones polluting the Lower Earth Orbit (LEO). Furthermore, around 34,000 pieces of space junk larger than 10 centimeters, along with millions of smaller fragments, pose a serious risk of catastrophic collisions with functioning satellites and spacecraft *(Natural History Museum, 2019).*

There are many reasons why LEO has grown into an orbital graveyard. All space junk is the result of humans launching objects from Earth, and it remains in orbit until it re-enters the atmosphere. Some objects in lower orbits of a few hundred kilometers can return quickly. They often re-enter the atmosphere after a few years and mostly burn up so that they don't reach the ground. However, debris or satellites left at higher altitudes, around 36,000 kilometers—where communication and weather satellites often reside in geostationary orbit—can remain in space for hundreds or even thousands of years.

For instance, in 2007, China deliberately destroyed its Fengyun-1C spacecraft using a hypervelocity collision with a ballistic object. This event produced the most significant artificial debris cloud in Earth's orbit since the dawn of space exploration. The U.S. Space Surveillance Network has since identified over 2,000 fragments measuring 10 centimeters or larger *(NASA, 2007)*.

Another example is the collision between an inactive Russian communications satellite, Cosmos 2251, and an active commercial satellite operated by U.S.-based Iridium Satellite LLC. The incident took place about 800 kilometers (497 miles) above Siberia and resulted in nearly 2,000 pieces of debris larger than 10 centimeters, along with thousands of smaller fragments. It marked the first recorded collision between two satellites in orbit *(Secure World Foundation, 2010).*



As shown in Figure 1.1, the number of space debris fragments, their combined mass, and the total area they take up has been increasing continuously since the beginning of the space age. This is further fuelled by a large number of in-orbit-break-ups of spacecraft and rocket stages. Over the last two decades, 12 accidental 'fragmentations' have occurred in space on average per year *(ESA, 2020).*

The number of active satellites in space is increasing at a rapid rate. This growth has allowed millions of people in remote and non-remote areas to access the internet and communicate. It has also powered technological innovations like smart cars. Because of improved and more Earth observation satellites, we are also able to monitor and understand climate change better.

However, orbital debris hinders this progress. There are approximately 1 million pieces 1 centimeter and larger *(World Economic Forum, 2023)* and they travel several times faster than a bullet. A collision between the debris or with active satellites have devastating consequences, destroying space missions or creating large new debris fields.

Furthermore, hypothetical but potential situations, such as the Kessler Syndrome, arise. The concept was first proposed by NASA scientist Donald J. Kessler in 1978. The Kessler Syndrome is a theoretical scenario in which the density of objects in LEO becomes so high that collisions between objects cause a cascade effect, generating more debris and increasing the likelihood of further collisions. This chain reaction could lead to certain orbital regions unusable for satellites and spacecraft, making space activities increasingly hazardous. In essence, the increasing accumulation of debris could one day render certain orbital regions unusable, significantly limiting human access to space.

To address this critical issue, this paper proposes a solution which is a dedicated satellite equipped with artificial intelligence (AI) to actively identify, capture, and manage orbital debris. Operating like a mobile cleanup station in Earth's orbit, this autonomous satellite would detect debris using onboard AI systems, adjust its speed for interception, and physically retrieve junk using mechanical arms or nets. Based on the object's size, usefulness, and risk level, the satellite would then either de-orbit the debris safely back to Earth's atmosphere or send it further out of orbit. This solution aims to reduce the risk of future collisions and contribute to long-term space sustainability.

Background Research
In response to the growing threat of space debris, several international organizations, government agencies, and private companies have begun developing and testing debris mitigation and removal strategies. These include both preventive measures, such as designing satellites to de-orbit at the end of their mission life, and active debris removal (ADR) technologies, aimed at clearing existing junk from orbit. For example, the European Space Agency's (ESA) ClearSpace-1 mission and Japan's space agency JAXA in partnership with Astroscale are leading examples of ADR initiatives. NASA also follows strict guidelines for passivation and post-mission disposal. While these efforts represent critical steps forward, most remain in early experimental stages and have not yet scaled to match the growing volume of debris in orbit.

A prominent mission is the European Space Agency's (ESA) ClearSpace-1, set to launch in 2028. The satellite in question to be removed by the mission is ESA's 95 kilogram PROBA-1 satellite which was launched in 2001. It will be removed from its low Earth orbit to prevent potential space debris issues. ClearSpace-1 aims to be the first mission to demonstrate active debris removal by targeting and deorbiting the PROBA-1 satellite. The mission will rendezvous with the defunct satellite, capture it, and guide it safely into Earth's atmosphere for controlled reentry—marking a significant step toward what space experts refer to as Active Debris Removal (ADR).

Another notable effort in ADR comes from a collaboration between Japan's space agency, JAXA, and the private space sustainability company, Astroscale. Their joint mission is called Commercial Removal of Debris Demonstration (CRD2) and it aims to tackle the growing problem of orbital debris through a two-phase approach: first locating and characterizing a large piece of debris, and then removing it from orbit. Astroscale's ELSA-d mission, launched in 2021, successfully demonstrated an important technology: a magnetic capture mechanism that can attach to and de-orbit space junk. These missions showcase growing global efforts to develop autonomous, scalable solutions for orbital debris cleanup (JAXA, 2020; Astroscale, 2021; ESA, 2022).

While these missions like ClearSpace-1 (ESA), CRD2 (JAXA), and ELSA-d (Astroscale) represent major milestones in active debris removal, they face significant limitations. One major constraint is cost—these missions are extremely expensive, with ClearSpace-1 alone estimated to cost over €100 million ($112.2 million) for removing a single object. Secondly, scalability remains an issue. Most missions are designed to capture one piece of debris at a time, making them inefficient for addressing the thousands of fragments currently in LEO. Furthermore, technical limitations such as targeting accuracy, docking reliability, and energy usage restrict their long-term viability. Many also rely on pre-installed docking plates or magnetic targets, which do not exist on most older debris. Lastly, legal and regulatory challenges—like determining ownership of space debris and obtaining permissions—complicate mission planning and international collaboration. (ESA, 2021; Astroscale, 2021; Secure World Foundation, 2022).

As the limitations of current debris removal missions become increasingly evident, it is clear that more advanced and scalable approaches are needed. A promising area of innovation is the integration of Artificial Intelligence (AI) into space missions. AI is becoming a vital tool in addressing the growing challenge of orbital debris. One key application is in collision prediction and avoidance, where AI algorithms analyze the trajectories of thousands of space objects to forecast potential collisions and issue early warnings. For example, ESA employs machine learning models to automate conjunction assessments and reduce false alarms (ESA, 2022). AI is also used in debris detection and tracking, where deep learning techniques process satellite imagery and radar data to identify new or fast-moving debris fragments (Zhang et al., 2021). Additionally, AI enables autonomous navigation and maneuvering for satellites and cleanup spacecraft, allowing them to adjust their orbits, match speeds with debris, and optimize fuel consumption during capture missions (NASA, 2020). In missions like Astroscale's ELSA-d, AI helps control robotic arms and docking systems during in-orbit servicing operations,

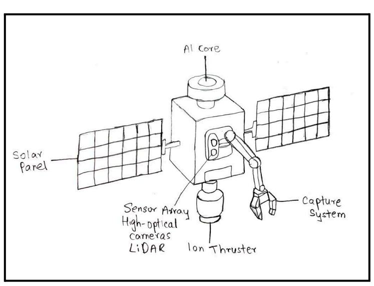
Beyond removal operations, AI is being explored for damage detection from micrometeoroids and orbital debris (MMOD). Traditionally, MMOD inspection relied on astronauts or ground personnel manually analyzing spacecraft images—a process sensitive to lighting, material type, and imaging conditions. NASA's recent research has leveraged deep learning (DL) models, using tools like the fast.ai library, to automatically identify MMOD damage on spacecraft surfaces. This "fast AI" approach significantly reduces the expertise and time required to locate damage. What previously took years and teams of analysts can now be accomplished in minutes by a single person. These AI tools support autonomous decision-making, allowing spacecraft to detect and respond to damage in real-time—representing a breakthrough in scalable, reliable inspection (NASA, n.d.).

Overall, AI enhances the speed, accuracy, and autonomy of space debris management systems. By reducing human workload, improving detection, and enabling adaptive navigation, it brings us closer to practical, large-scale orbital debris cleanup.

Proposed Solution

To address the limitations of current debris removal missions and the growing urgency of orbital cleanup, this project proposed a multifunctional, AI-powered satellite designed specifically for autonomous detection, tracking, and removal of space debris. Unlike existing missions that focus on one-time operations targeting a single object, this satellite aims to offer a scalable and intelligent solution capable of handling a wide range of debris types in LEO. Equipped with advanced sensors, robotic capture systems, and real-time AI decision-making, the satellite will identify hazardous debris, match their velocities, and execute precision retrievals—marking a step toward long-term, automated debris management in space.

Structure and Function of the Satellite

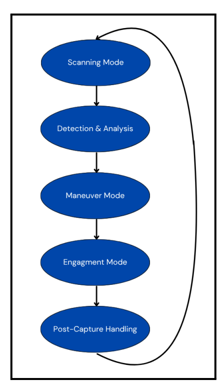


The satellite will operate in Low Earth Orbit (LEO), which was strategically chosen due to its high concentration of orbital debris—greater than in orbits like the Geostationary Orbit (GEO). This makes LEO a primary focus for debris removal efforts. Its proximity to Earth allows for easier access, maneuverability, and more efficient capture and removal operations. Additionally, debris in LEO—particularly below 600 km—experiences natural decay from atmospheric drag, enabling faster reentry and disintegration in the atmosphere (Houston Chronicle, 2024). This natural decay process can be leveraged to enhance debris mitigation. Furthermore, LEO's altitude allows for more effective monitoring and tracking using ground-based radar and optical systems, which are essential for detecting and characterizing debris targets.

To perform advanced debris removal with integrated AI and robotic systems, the satellite is estimated to weigh between 300 to 500 kilograms, aligning with active debris removal missions like ESA's ClearSpace-1 and Astroscale's ELSA-d (European Space Agency, 2023; Astroscale, 2024).The satellite's dimensions are projected to be around 1.5 meters × 1.5 meters × 2 meters, compact enough for efficient launch yet spacious enough to house robotic arms, AI computing modules, and propulsion systems. This configuration allows the satellite to effectively capture and deorbit medium-sized debris ranging from 50 to 100 kilograms.

The satellite's main source of power will be solar energy. It will use extensive solar panels to convert sunlight into electricity, which will then power various systems. For propulsion, ion thrusters will be used in the satellite. Its high fuel efficiency allows the satellite to operate for extended periods without the need for large amounts of propellant, enabling longer and more cost-effective missions (NASA, 2019). The precise control provided by ion thrusters is crucial for carefully matching the varying speeds and trajectories of different pieces of debris, ensuring accurate maneuvering in a crowded orbital environment. Additionally, the efficient fuel usage reduces the overall weight of the satellite, allowing space for more instruments or reducing launch costs. Although ion propulsion generates lower thrust compared to chemical rockets, its ability to provide continuous, gradual acceleration enables smooth and controlled orbit adjustments, which is essential for safely capturing and redirecting debris. Overall, these advantages make ion propulsion highly suitable for active debris removal operations.

The satellite is composed of four primary modules that work in tandem to identify, capture, and dispose of orbital debris. The AI core serves as the brain of the system, using machine learning algorithms to autonomously detect, track, and classify debris based on sensor data. The sensor array—including high-resolution optical cameras, radar, and LIDAR—provides continuous 3D imaging and motion tracking of the surrounding space environment (NASA Goddard, 2018). Once a target is identified, the capture system is activated, equipped with either multi-jointed robotic arms for large, stable debris or a deployable net for smaller or tumbling fragments. After successful capture, the containment and disposal system stores the debris in a secure onboard chamber, directs it for atmospheric reentry, or sends it to a designated junkyard orbit. These modules work in sync to enable autonomous, repeated debris removal missions with high precision and minimal human intervention.



The satellite follows a fully autonomous, repeatable operational cycle. It begins in Scanning Mode, using its sensor array to monitor nearby orbital space and feed real-time data to the onboard AI. In Detection and Analysis, the AI core processes this data to identify hazardous debris, classify it by size and risk level, and determine the optimal trajectory for interception. The satellite then enters Maneuver Mode, using its electric propulsion system—ideally ion thrusters for precision and efficiency—to align with the target object. In Engagement Mode, the capture system is deployed: robotic arms grasp larger objects while nets are used for smaller or erratic pieces. Once the debris is secured, the satellite shifts to Post-Capture Handling, storing the object in a containment unit, performing a controlled deorbit, or transferring it to a junkyard orbit. The satellite then resets and re-enters Scanning Mode to repeat the cycle, enabling continuous space cleanup operations.

Central to the satellite's effectiveness is its onboard artificial intelligence, which enables it to operate with minimal human oversight. While the satellite's structure provides the necessary hardware to locate, capture, and store debris, it is the AI system that gives it autonomy, adaptability, and precision. From interpreting sensor data to making real-time decisions about which debris to target and how to approach it, AI plays a crucial role in navigating the complex environment of Low Earth Orbit. The following section explores how this AI-driven system enables detection, tracking, and classification of debris with speed and accuracy far beyond manual ground-based operations.

AI's Role in Detection, Tracking, and Classification

To navigate the complex and fast-paced environment of LEO, the satellite relies heavily on advanced AI. The AI system is central to the satellite's autonomy and accuracy, enabling it to detect, track, and classify debris in real time, even despite constantly changing orbital conditions. This intelligent structure makes it possible for the satellite to act independently—without relying on continuous instructions from Earth—making debris removal faster, more efficient, and scalable.

AI-powered detection begins with a computer vision system that integrates input from high-resolution cameras, radar, and LIDAR sensors. These inputs are processed by deep learning models such as convolutional neural networks (CNNs), trained on extensive datasets of orbital debris imagery. Depending on the complexity of the object's motion, recurrent neural networks (RNNs) or transformers may also be employed to model sequential data like trajectory patterns. These models are capable of distinguishing debris from satellites, stars, and other space objects based on patterns in shape, motion, and reflectivity. Unlike traditional systems that may struggle with detecting small or fast-moving debris, AI systems continuously learn and adapt to new input, improving their ability to identify even previously uncatalogued objects in real time.

Once debris is detected, the AI shifts to tracking mode. Here, neural networks or reinforcement learning algorithms are used to predict the debris's future trajectory. These models take into account variables like orbital speed, altitude, Earth's gravitational field, and solar radiation pressure. They are continuously refined using reinforcement learning techniques, allowing the system to adapt its path planning based on mission outcomes and sensor feedback in real time. What sets AI-based tracking apart is its ability to adjust for real-time changes caused by unexpected events—such as micro-collisions, atmospheric drag, or satellite maneuvers—ensuring the satellite maintains an accurate lock on its target. This dynamic response is essential for planning precise and safe interception paths.

Following tracking, the AI classifies each piece of debris based on multiple criteria: size, mass, material composition, rotation speed, and relative risk level. For example, a large, tumbling fragment of an old satellite may be categorized as high-risk, while a small paint chip may be deemed lower priority. The AI uses this classification to determine not only whether the debris should be captured, but also how. It selects the appropriate capture mechanism—robotic arm or net—and plans the safest and most efficient approach. This prioritization ensures that the satellite targets debris posing the greatest threat to active missions or densely populated orbits.

Perhaps the most critical aspect of the AI system is its autonomy. Unlike traditional missions that depend on ground-based commands, this satellite is designed to operate independently for extended periods. The AI constantly learns from previous encounters—using onboard memory to store and evaluate telemetry, capture precision, and fuel efficiency data. This iterative learning improves models through updates during periods of solar charging or data syncing with ground stations, enhancing overall mission intelligence and reducing misclassification risks. With full autonomy, it can carry out continuous cleanup operations without the need for costly and time-consuming ground interventions, making it a viable solution for long-term orbital debris management.

Debris Handling

With the autonomous AI system effectively detecting, tracking, and classifying debris in real time, the next crucial stage is the satellite's ability to physically engage and remove the identified threats. This is where advanced debris handling technologies come into play. Combining robotic capture mechanisms with AI-driven decision-making, the satellite is equipped to respond dynamically to varying debris types, sizes, and motion patterns. Whether it's a slow-moving satellite fragment or a rapidly tumbling object, the satellite adapts its approach to ensure safe, precise capture and disposal. The following section outlines how the satellite handles this complex task through specialized systems like robotic arms, deployable nets, and an intelligent capture flow process.

After AI has successfully identified and classified a piece of debris, the satellite's debris handling system is activated. This system is designed to be versatile and adaptive, capable of dealing with debris of different sizes, shapes, and motion profiles through two main capture mechanisms: robotic arms and deployable nets.

For large, relatively stable pieces of debris—such as defunct satellites or intact rocket parts—the satellite deploys multi-jointed robotic arms. These arms are equipped with a variety of end-effectors, including claw-like grippers, magnetic pads, or adhesive surfaces, depending on the target debris's material and shape. The arms can operate with high precision, guided by the AI system's real-time calculations of the debris's trajectory, rotation, and relative velocity. With multiple degrees of freedom, the arms can approach the debris from optimal angles, gently stabilize it, and secure it without causing fragmentation.

For smaller or irregularly shaped debris—especially those that are spinning or tumbling rapidly—the satellite uses a deployable net system. This net is designed to expand outward from the satellite, forming a wide mesh that can envelope fast-moving fragments. Once the debris is caught, the net contracts and draws the object toward the satellite's contaminant area. This method minimizes the risk of collision damage or debris shattering and is ideal for handling fragments that are too difficult or dangerous to grab with robotic arms.

The choice between robotic arms and nets is made through a structured AI-driven decision-making flow. Once the AI has classified the debris, it evaluates key parameters such as size, shape, speed, rotation, and predicted risk. If the object is stable and above a certain size threshold (e.g., > 20 cm), the AI prioritizes the use of robotic arms for direct capture. If the object is irregular, fast-moving, or too small for a firm grip, the AI selects the net system. In both cases, the satellite's AI continuously adjusts for unexpected motion, ensuring that the approach and capture are safe and controlled.

Once the debris is captured, it is either:

- Stored in an internal contaminant unit for later disposal,
- Guided into Earth's atmosphere for controlled burn-up and disintegration, or
- Transferred to a designated junkyard orbit (a stable region where inactive objects are parked to prevent interference).

All these actions are coordinated autonomously, with minimal human input, allowing the satellite to repeat the cycle for multiple debris targets across a single mission. This modular, AI-powered handling approach significantly improves the satellite's effectiveness in real-world orbital cleanup operations.

Considerations

While the proposed satellite design offers a promising and innovative approach to mitigating space debris, translating such a concept into a functioning, real-world mission requires careful evaluation of both practical limitations and broader implications. Any attempt to operate autonomously in space must be grounded in not only technical feasibility but also ethical responsibility. Therefore, this section examines the critical technical and ethical considerations that must be addressed before implementation.

Technical Considerations

Developing an autonomous, AI-enabled satellite for debris removal introduced numerous technical challenges. High-precision tracking and real-time decision-making depend on the performance of onboard AI and sensor arrays, which must function reliably in a harsh orbital environment. This requires vigorous radiation shielding, thermal control, and hardened components capable of enduring micrometeoroid impacts and space weather conditions (NASA, n.d.-a).

Ion thrusters, while highly fuel-efficient and suitable for long-term, precise maneuvering, provide low thrust levels that may not suffice in emergencies. To address this, hybrid propulsion systems could be explored—combining ion propulsion with short-burst chemical thrusters for rapid reorientation during unexpected maneuvers. This could be problematic when trying to intercept fast-moving or tumbling debris (ESA, 2021). Additionally, capture systems such as robotic arms and nets must be engineered to adapt to debris of varied shapes, mass, and spin states, with minimal risk of creating new fragments through accidental collisions.

System redundancy and fail-safes must be integrated to handle malfunctions. Furthermore, the satellite's operations need to be synchronized with international space traffic databases to avoid interfering with operational assets. Without proper space situational awareness and coordination, even well-intentioned missions could inadvertently raise risks (UNOOSA, 2010).

Ethical Considerations

The use of AI to autonomously detect and classify orbital debris raises significant concerns regarding accountability and transparency. Determining which debris is prioritized for removal—and ensuring no functioning or sensitive satellite is mistakenly targeted—requires clear governance and oversight (Crawford & Calo, 2016). Without human-in-the-loop supervision, even small algorithmic biases or errors could lead to international disputes.

Legal and geopolitical issues also come into the picture. According to the Outer Space Treaty (1967), objects launched into space remain the property of the launching state. This means that removing another nation's debris—even if defunct—without permission could be perceived as a violation of sovereignty (UNOOSA, 2010). Liability under the Liability Convention (1972) further complicates matters if a satellite unintentionally damages active infrastructure during removal efforts.

Privacy and surveillance concerns could arise as the satellite's high-resolution sensors might inadvertently gather data about operational assets. To mitigate this, onboard encryption must be implemented, and all visual data processed locally unless flagged as critical, with only metadata shared unless reviewed under international data-sharing agreements. Ethical design must include strict data handling protocols to prevent misuse or suspicion of espionage (Gleason, 2018).

Finally, environmental stewardship of space itself must be considered. The satellite, though designed to reduce debris, will add to orbital congestion during its operational life and must have a reliable deorbit plan to prevent becoming debris itself (NASA, n.d.-b).

As the urgency to address space debris intensifies, innovative solutions like AI-powered autonomous satellites present a forward-looking pathway. However, ambition must be tempered with caution. Technical reliability and performance are essential but so too are legal, ethical, and environmental responsibilities. By rigorously addressing all considerations, the space community can move toward sustainable orbital environments that protect both current and future missions. Only through collaborative, transparent development can such a solution become not just feasible—but truly impactful.

Potential Benefits

Despite the technical and ethical challenges involved in deploying an autonomous debris-removal satellite, the long-term benefits it offers are compelling. From enhancing orbital safety to promoting environmental sustainability in space, the implementation of such a system could positively transform how humanity manages its shared orbital commons. The following section outlines the key advantages this proposed solution brings to the future of space operations.

1. **Enhanced Orbital Safety**

One of the most immediate benefits of deploying AI-enabled debris removal satellites is the reduction of collision risk in space. With over 100 million pieces of debris currently orbiting Earth, even small fragments pose catastrophic risks to functioning spacecraft and satellites (NASA, n.d.-a). By actively removing the medium-sized debris, the proposed satellite would lower the likelihood of chain-reaction collisions, also known as the Kessler Syndrome, which could otherwise render entire orbits unusable (Kessler & Cour-Palais, 1978).

2. **Sustainability of Space Activities**
The satellite supports long-term space sustainability by helping maintain cleaner orbital paths. This aligns with the UN's Space Debris Mitigation Guidelines, which call for active intervention to minimize space pollution (UNOOSA, 2010). As space becomes increasingly commercialized and congested, removing debris proactively will ensure that future missions—governmental, commercial, and academic—can operate safely and sustainably.

3. **Technological Advancement**
The integration of AI, robotics, and ion propulsion in space debris mitigation can serve as a testbed for advanced technologies. Success in this domain will contribute to the evolution of autonomous satellite systems, which could eventually support planetary exploration, satellite servicing, and interplanetary navigation (ESA, 2021). Demonstrating AI's reliability in critical space tasks also builds confidence for its broader use in mission-critical operations.

4. **Economic Savings**
Collisions in space can cost millions of dollars in satellite damage, delays, and replacements. Active debris removal can prevent these losses. According to a report by the European Space Policy Institute (ESPI), reducing the probability of collisions even by a small fraction could lead to significant savings for satellite operators and insurers (ESPI, 2019). In the long run, the cost of deploying a debris-removal satellite could be far outweighed by the savings from avoided damage.

5. **International Collaboration and Leadership**
Pioneering a responsible, AI-based debris mitigation effort can establish leadership in global space governance. Countries that develop and share such technology can foster international cooperation while setting standards for orbital behavior. This builds trust and strengthens diplomatic ties around the peaceful use of outer space (Gleason, 2018).

Challenges and Limitations

While the potential benefits of an autonomous debris-removal satellite are substantial, several challenges and limitations must be acknowledged before implementation. These range from technological feasibility to international legal frameworks and financial constraints. Understanding these issues is essential for refining the design, securing stakeholder support, and ensuring the mission's long-term success.

1. **Technical Complexity**

Building an AI-powered satellite that can autonomously detect, track, and remove various types of space debris involves high levels of engineering precision. The challenges include training AI models to function accurately in unpredictable environments, ensuring reliable communication with ground control, and designing robotic capture systems that can handle different shapes, sizes, and rotational speeds of debris (Wiedemann et al., 2019). Additionally, integrating propulsion, energy systems and real-time navigation technologies within a compact satellite increases the complexity of system design.

2. **Cost and Funding Barriers**
Developing and deploying such advanced satellites is expensive. The cost of a single active debris removal mission can run into tens of millions of dollars, and recurring missions would require sustained funding (ESPI, 2019). Securing financial support—especially for a problem with no immediate economic return—remains one of the biggest hurdles. Unlike commercial satellite launches, debris removal lacks direct revenue, making public-private partnerships and governmental backing crucial.

3. **Legal and Regulatory Ambiguities**
International law does not clearly define who is responsible for removing space debris or who owns it. According to the Outer Space Treaty (1967), objects launched into space remain the property of the launching state, even if they are defunct or broken (UNOOSA, 1967). This makes the removal of debris from another nation's satellite legally complex. Without updated international agreements, debris removal missions risk violating sovereignty or creating diplomatic friction.

4. **Risk of Malfunctions or Collisions**
Autonomous operations in space come with inherent risks. If the satellite malfunctions or fails to capture debris correctly, it could become debris itself. Robotic arms or nets may not function as expected, particularly when dealing with high-velocity or tumbling debris, which could lead to further collisions (Liou & Johnson, 2009). Thorough testing, redundancy, and risk mitigation strategies are essential to avoid contributing to the very problem the satellite is designed to solve.

5. **AI Reliability and Ethics**
Although AI provides major advantages, there are risks of misclassification or errors in decision-making.If the system misidentifies an active satellite as debris, it could cause accidental damage or diplomatic conflict. Hence, periodic model retraining using the latest datasets, formal verification techniques for AI safety, and sandbox simulations should be standard before each mission deployment. Ensuring that AI operates within strict parameters and receives periodic updates and oversight is essential for preventing ethical and operational failures (Gleason, 2018).

Future Scope

As technology continues to advance, there is considerable potential to enhance and scale the proposed satellite system. In the future, satellites may be developed with greater autonomy, allowing them to collaboratively operate in constellations for more efficient debris collection. Improvements in miniaturization of components, energy storage, and AI computing power could make the system lighter, faster, and more cost-effective. Additionally, the integration of on-orbit servicing and repair capabilities could allow satellites to self-repair or maintain other spacecraft, adding even more value beyond debris removal (Wright, 2021).

There is also potential to extend operations beyond LEO into MEO and GEO, where debris presents unique challenges. Moreover, as materials science evolves, advanced capture mechanisms—such as electroadhesion, gecko-inspired adhesives, or cryogenic arms—could be incorporated for improved performance (Kibe et al., 2020). In the long term, such missions may even pave the way for commercial applications, such as salvaging functional components from defunct satellites or recycling materials in space, thereby creating a sustainable orbital economy.

Recommendations

To support the successful implementation and future evolution of this satellite system, the following recommendations are proposed:

1. **Policy and Legal Frameworks**: International space agencies and governments must harmonize space debris regulations, develop clear guidelines for ADR, and establish protocols for shared orbital zones to prevent disputes.
2. **Funding and Collaboration**: Greater government and private sector investment is required to fund R&D in AI, propulsion, and robotics for space applications. Collaborations between agencies like NASA, ESA, ISRO, and private firms such as Astroscale or Northrop Grumman should be encouraged (ESA, n.d.).
3. **Standardization of Satellite Design**: Implementing end-of-life deorbiting protocols and standardized docking interfaces on all new satellites can make future debris removal missions safer and more efficient (NASA, 2023).
4. **Public Awareness and Education**: Increasing awareness among the public and academia about the space debris crisis can foster innovation and lead to grassroots contributions in the form of coding, data labeling for AI, or low-cost component design.
5. **Data Sharing Platforms**: The creation of open-access databases for tracking orbital debris, training AI, and stimulating scenarios can accelerate research and collaboration across countries and institutions.

Conclusion

The growing threat of space debris demands immediate and innovative action. This paper presents a forward-looking, AI-powered satellite designed to autonomously detect, track, and remove debris from Low Earth Orbit. By integrating advanced sensors, robotic systems, and ion propulsion, the proposed solution offers a sustainable and scalable approach to orbital cleanup. While there are technical and ethical considerations—as well as clear challenges—this system holds the potential to significantly reduce the risks posed by space debris to both existing and future space operations. With the right support in policy, funding, and technological development, autonomous debris removal systems like this one could play a transformative role in ensuring the long-term sustainability and safety of Earth’s orbital environment.

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