Context Note: This is a literature review for NASAs Orbital Debris Program Office (ODPO). NASA is currently looking for solutions for the orbital debris problem; I have synthesized a few papers that have proposed active removal technologies. NASA is sponsoring the first ever Orbital Debris Conference in December 2019, where I plan to present my findings.The conference is meant to highlight orbital debris research activities and encourage collaboration with the international community.

- ADR - Active Debris Removal
- ESA - European Space Agency
- GEO - Geostationary Orbit
- Kessler Syndrome - Scenario in which debris density grows exponentially
- LEO - Low Earth Orbit
- ROGER - Robotic Geostationary Orbit Restorer
- TRL - Technology Readiness Level (Ranges from 1-9, 1 being an idea and 9 being fully ready)

Methods for Mitigation of Space Debris: A Literature Review

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Abstract: Space debris presents a threat to current and future space missions. Solutions for debris removal have been proposed and tested in recent years, but a single piece of debris has yet to be removed. To promote the development of active removal technology, this literature review analyzes a few proposed methods for the capture and removal of space debris, comparing the technologies and describing their advantages and drawbacks. While no single method proposed would be able to remove all types of debris, it is only necessary to remove a few of the highest-risk objects. The papers in this review show promise for a technology that could remove the most threatening objects and eliminate the risk of an impassable cloud.

1. Introduction

Space debris is a growing concern for operational satellites, many of which are vital for industry and life on Earth. More than 23,000 debris objects are currently tracked, with estimates ranging into the millions for objects down to 1 millimeter in size[1]. Kessler[2] states that debris impacts are likely to cause more debris and therefore more impacts, creating a growing mass of junk. Active debris removal has therefore become greatly relevant.

Environmental studies by Liou[3] have shown that LEO, specifically between 900 km and 1050 km, is the highest risk orbit for Kessler syndrome. Debris removal should focus on large (several meters) and small(5mm to 1cm) debris to mitigate risk. Removing anything outside these two size ranges would not greatly reduce risk to other satellites[3].

This paper provides a review of existing active mitigation technology and compares and contrasts specific papers to promote the development of debris removal. Benefits and drawbacks are addressed, along with debris targets and campaigns.

2. Overview of Space Debris

Recently, a few massive collisions have spurred interest in Active Debris Removal (ADR). A Chinese anti-satellite missile test in 2007 and an accidental collision between the Cosmos 2251 and Iridium 33 in 2009 have in total increased the tracked debris population by one-third[3].

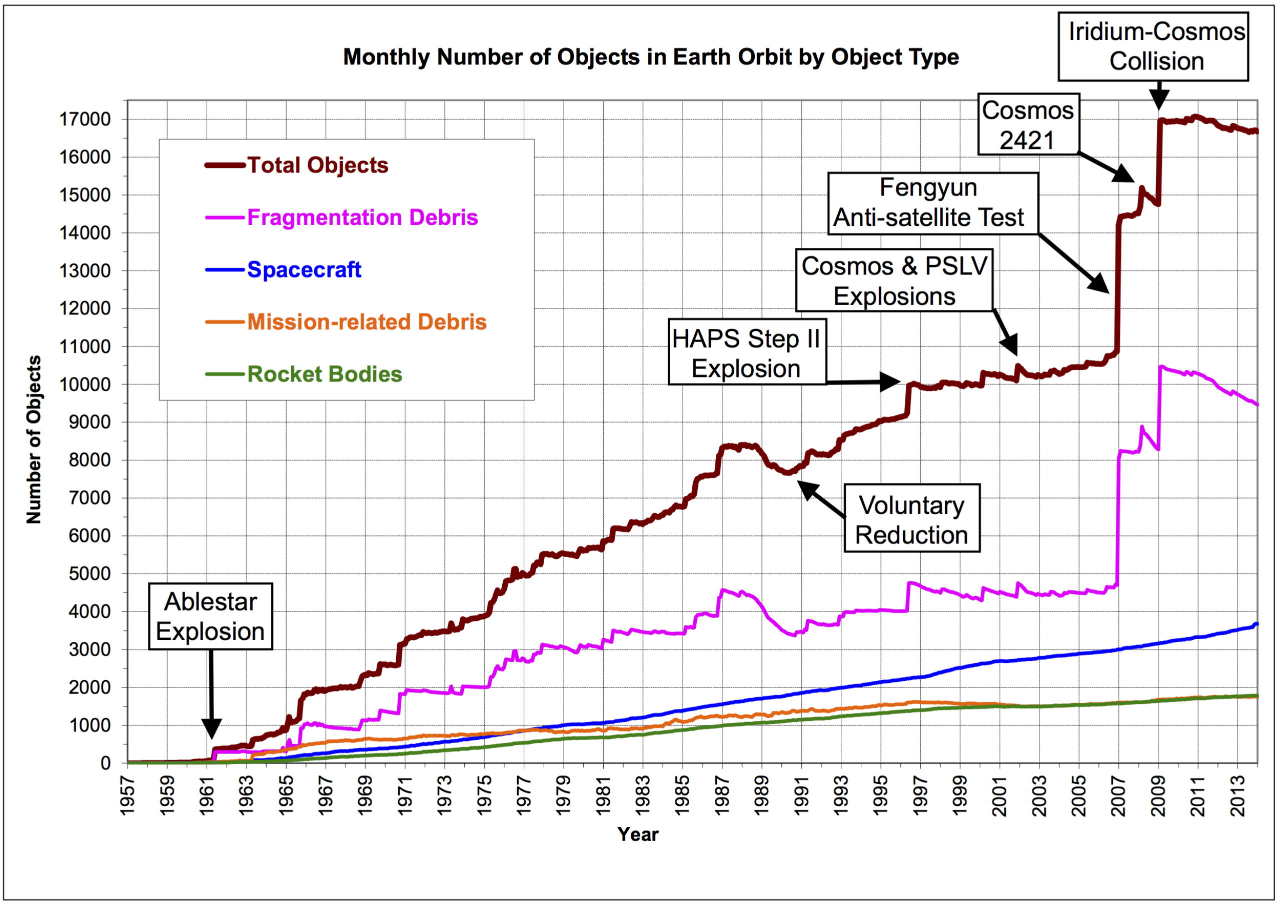

Figure 1: Graph of Space Debris, NASA

Several debris objects have been targeted for removal based on their high mass and collision probabilities[1]. These include satellites such as Envisat (8000kg) and Cosmos spacecraft (1300 to 2800kg). More attention is given to objects that are likely to collide and leave behind debris: therefore, ADR should deal in crowded orbits up to 1600km.

3. Active Debris Removal

A successful removal device has a few important criteria: it must be able to remove high-risk debris objects, it must be cost-effective, and it must not cause any extra debris. In the short term, ADR will need to focus on small debris. More massive debris becomes a risk in the long-term as it breaks up. A study by NASAs Orbital Debris Program Office (ODPO) [3] showed that the removal of 5-10 debris objects per year would stabilize the growth of debris. Physical capture and removal is challenging for a number of reasons:

- Contact with debris is difficult because the exact velocity and dimensions are usually not known.
- Debris may rotate or break apart during capture, damaging the capturing device.
- Approach, capture, and movement cost significant amounts of fuel, limiting the lifespan of chaser satellites.

4. Space Debris Mitigation Approaches

A variety of methods are reviewed below, from tentacle capture to laser orbit alteration. As such, the proposals have been divided into two sections: physical removal and non-physical removal. Physical removal involves contact with the object and in some cases would mean that the capture device burns up with the debris. Non-physical devices could be multi-use and therefore cheaper but generally have a lower TRL and are less efficient.

4.1. Physical Methods

4.1.1. Tentacle Capturing

At the 3rd European Workshop on Space Debris Modeling and Remediation, Meyer *et al* [4] presented their proposal for a tentacles with belts concept. The device would first grab hold of a single point with a robotic arm, then secure the rest of the debris with soft arms. Simulations showed that capture could be successful without a robotic arm, but this requires more precision and would allow the debris to bounce around.

The authors ran simulations on a few variations of the tentacle concept, settling on a double boom and two tentacles with two degrees of freedom each. The tip of each tentacle has a leaf spring for flexible contact. This was found to be the best combination of high performance with low cost and low risk. The method is still quite complex and risky, requiring more ground testing to raise the TRL.

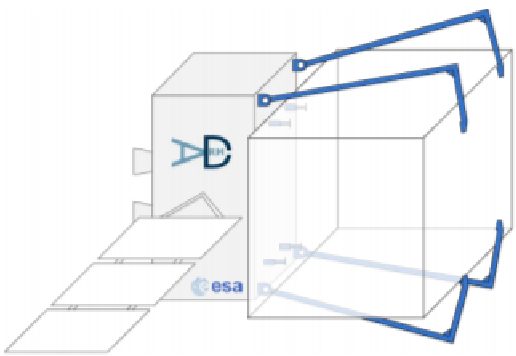

Figure 2: Tentacle Capturing Mechanism, ESA

4.1.2. Net Capturing

ESA recently sponsored the Robotic Geostationary Orbit Restorer (ROGER), a capture mechanism that fires a net at debris and attempts to reel in back in [5]. The net is fired from a canister with four weights in each corner, which provide inertia and spread apart the net. In this particular study, a 16x16m net was baselined, made out of Dyneema®. Simulations were performed to address concerns over using nets in space: whether the net would ensnare the target, if it would slip off, and the force with which the net would strike the target. While it was shown that the weights can passively wrap the net around a target, the authors note that winches could also be used to close the net. The net can be used without knowing the mass, inertia, or shape of the debris. Ground tests have been done, raising the TRL of this method. The ESA determined that the study was "quite detailed" and nets are "a very promising capture mechanism"[5]

Figure 3: Ejection of the net from its canister, ESA

4.1.3. Harpoon

A harpoon mechanism [6] was proposed by Jamie Reed and Simon Barraclough of Astrium. Their design uses compressed gas to fire a barbed harpoon. The key features of the design are its low mass, relative simplicity, and ease of ground testing. One of the challenges of ADR is the wide variety of targets, so a goal of the harpoon is to work universally. For satellites, the authors plan to target appendages like the solar panels and access panels. These are relatively thin and could be easily punctured by a 10N load. Rocket stages are riskier; the harpoon would puncture the tank which, if pressurized, could explode. However, almost all rocket tanks in orbit are empty or have leaked to a low pressure[6]. The harpoon mechanism would be capable of targeting debris up to 9000kg and up to a spin rate of 10 degrees per second. It is easy to test on Earth and has a TRL of 4, but runs a risk of causing more debris.

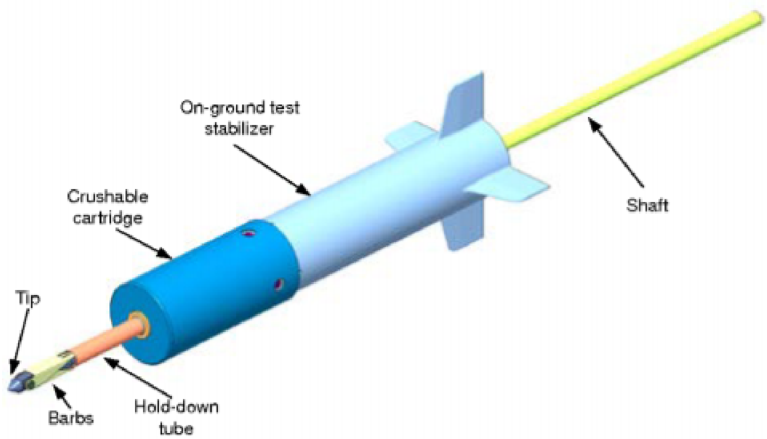

Figure 4: Harpoon concept for capturing space debris as developed by Astrium Stevenage[6]

4.2. Non-physical Methods

4.2.1. Artificial Atmosphere

A "gaseous cloud" method was patented by Boeing in 2014 [7]. The method produces a dense cloud of gas sufficient to slow down debris. The cloud would have an areal density of 10^{-3} kg/m^2 to 10^{-8} kg/m^2, a diameter of 50 km to 500 km, and a mass of 1,000 kg to 10,000 kg. Within these ranges there are tradeoffs: a more dense cloud can slow objects more but would cover a smaller area. The physical shape of the cloud depends on the properties of the gas chosen. Spheres, hemispheres, and cones are all options depending on the Prandtl-Meyer expansion of the gas. The author considered cryogenic noble gases and heavy molecular fluids like tetrafluromethane for the gas. There are again tradeoffs when choosing a gas: heavy fluids may be more expensive and difficult to work with, but would transfer more momentum to debris. The cloud would not target any specific debris, rather it would spread out to de-orbit dense patches of debris. A satellite could store multiple charges of gas, but would eventually run out and become useless.

4.2.2. Ion Beam Shepherd

The Ion Beam Shepherd concept[8] was introduced by Claudio Bombardelli *et al.* This concept uses a high-velocity ion beam to lower the orbits of debris without the need for docking. The ions travel at up to 30km/s and thus can transmit far more momentum to a target than material ablation. The key to the technology is low beam divergence (15 deg), which allows a safe distance between chaser and target. To negate the target-facing thrust, an identical ion beam fires the opposite direction.

It was found that a 100mN thruster with 70% thrust efficiency would be capable of deorbiting a 5-ton debris in less that one year.

Further study is needed for non-nominal conditions and the risk of plasma backflow. An ion beam could also cause the debris to rotate, making deorbiting difficult.

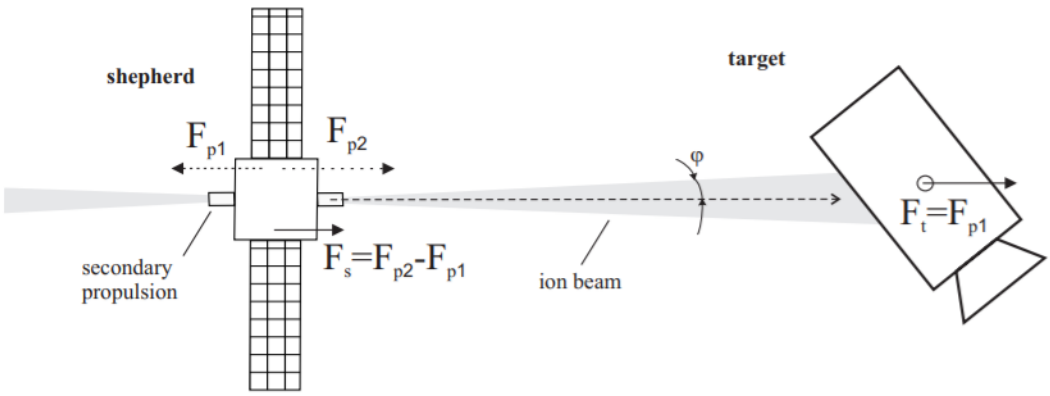

Figure 5: Ion Beam Shepherd, ESA

4.2.3. Laser

A laser system proposed by Phipps [9] is the only ground-based solution in this review. This method works very well for small debris; a NASA study[10] concluded that pulsed lasers could remove "essentially all dangerous orbital debris" in the 1-10cm range between 400 and 1100km within 2 years. Phipps also shows that, given many passes, a 13Hz, 39kJ, 1.06 µm laser could re-enter a 750kg object over a period of 44 months. Because the laser can switch between targets, this method could address multiple targets in parallel. Phipps claims that such a laser could slow down 75 large targets per day, de-orbiting 750 objects in 4 years at a cost of $4.7M each. A ground-based laser is estimated to cost 3-4 times less than a space-based mechanical solution, but there are uncertainties in both costs. Laser de-orbiting requires extremely precise tracking; this method would currently only work for targets mutiple meters across.

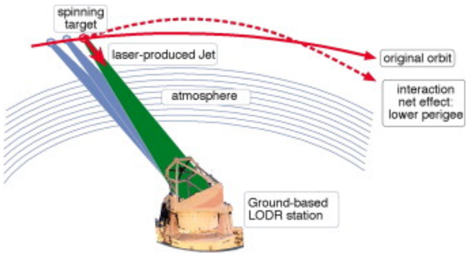

Figure 6: Laser Orbital Debris Removal (LODR)

Table 1: Overview of ADR technologies

Capture Method	**Advantages**	**Drawbacks**	**Reference**
Tentacles	High TRL, easy to test	Complex approach	[4]
Net Capture	Targets of various size	Unproven, low TRL	[5]
Harpoon	Distance from target	Risk of more debris	[6]
Artificial atmosphere	Does not have to target specific debris	Limited lifetime	[7]
Ion beam shepherd	Can deorbit very large debris	Low TRL, risk of plasma backflow	[8]
Laser	Low cost	Inefficient, requires precise tracking	[9]

In summary, harpoon and net capture approaches appear to be the most promising physical capture methods. ESA scientists chose these for their e.Deorbit project because of their high TRL and ability to work with all kinds of targets. Tentacles are complex and risky, requiring the chaser to get right up next to the debris. Lasers are promising for ADR because of their low cost and maintainability, but better tracking technology is needed before they can be used on small debris.

5. e.Deorbit

This paper would be incomplete without a discussion of the ESA's attempt to develop active debris removal technology. In 2013, they began developing a plan to remove Envisat, a satellite which failed unexpectedly in 2012[11]. Researchers investigated net capturing and harpoons as potential removal strategies. However, the decision was made to widen the scope of the mission after it was deemed too expensive for a single-case ADR. The planned project is now a multi-purpose satellite that could perform maintenance and move satellites to different orbits. ADR is still a potential application, but no longer the focus. ESA says the mission will cost around 300 million euros and would need approval by a ministerial council, but the "swiss army" satellite could be quite profitable. This is perhaps a sign of what is to come. ADR is massively expensive and has no economic incentive, so engineers and policy makers must be creative.

6. Conclusion

Methods to move and remove space debris have been developed by researchers and industry leaders. The technologies and the advantages and drawbacks have been compared in this paper. ADR is still an enormous technical challenge, especially without precise tracking data of all the millions of debris objects. As the debris grows, however, ADR becomes increasingly relevant. With one or a combination of these methods, stabilizing the Kessler syndrome is a realistic possibility.

References

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