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Space Debris Disposal: A Review of Feasibility and Effectiveness

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ABSTRACT

Orbital debris - or manmade objects that are no longer in use and are orbiting the Earth - is beginning to become a concern for the longevity of space exploration and satellite infrastructure. This article will describe different methods of debris removal, compare and contrast the methods, and their individual applicability on a large scale. This paper demonstrates that there is no singular method for the retrieval and disposal of space debris. Rather, in order to tackle this problem, we should look at it holistically, and combine multiple systems in conjunction with each other for the best results in dealing with this ever-growing issue.

Introduction

After the pristine environment surrounding the Earth was disturbed one October evening of 1957, when the first satellite - Sputnik 1 - was launched, humans added over 14,000 satellites into Earth's orbit. Among those, about 9,700 are still in space and only around 6,900 are still functioning. (European Space Agency, 2023) As humankind's curiosity for discovery beyond its home planet has increased, more and more spacecraft have been launched, and satellites and space stations orbiting the Earth have increased. In conjunction, the number of pieces of orbital debris has also increased. As seen in Figure 1, the number of new satellites in Earth's orbit has increased, taking the form of a roughly exponential increase starting from the year 2016. (NASA, 2018) This sharp increase is concerning, and if not kept in check, would jeopardize the future of space exploration and the launching of critical satellites and spacecraft, as well as the systems currently in place in Earth's orbit. The Canadian Space Agency, for example, uses satellites to monitor the health of Canada's vast forests and to detect oil pollution in Canadian waters (Canadian Space Agency, 2022). Likewise, services such as GPS and long-distance communications would be impossible without the thousands of satellites in our orbit. Space debris poses a direct threat to these satellites. In doing so, it threatens to exacerbate the problems we face here on Earth. If more and more extraneous pieces of equipment are in Earth's orbit, the likelihood of impacts with other pieces of debris and functioning spacecraft increases. Even without further space exploration, the amount of space debris will likely increase. This would eventually lead to a chain reaction known as the Kessler Syndrome, an effect described by NASA scientist Donald J. Kessler – a domino effect occurring where one collision creates more space debris, which in turn creates even more collisions between objects in space.

Just as fossil fuel–burning machines have polluted the atmosphere, the space race and now the commercialization of space travel have slowly polluted the environment around our planet. Various government space agencies and private companies have devised plans to remove space debris, none of which have been used to the needed scale.

There is a misconception that the term space debris only encompasses large pieces - rocket stages, fairings, and broken satellites. In fact, however, the term actually describes all man-made objects that do not serve any purpose which are in Earth's orbit, whether that be a Saturn 5 third stage or an explosive bolt. Small pieces of debris are also dangerous because they cannot be individually tracked, and are among the largest number of space debris in Earth's orbit. Based on statistical models, there are over 131 million pieces of debris the size of a grain of sand to the size of an apple in Earth's orbit, and with the advent of commercial space travel and the return of both manned and unmanned missions to the Moon and Mars, these numbers will only rise (European Space Agency, 2023). Despite their size, small pieces of debris can also do significant damage to mission-critical equipment, as was seen when chips of paint damaged the International Space Station (ISS) and NASA's Space Shuttle (NASA, 2021; Lewis, 2021).

This paper will primarily focus on comparing different methods of space debris removal, specifically those targeting debris over 10 cm in size. Given the different sizes and materials of the existing debris, it is challenging to design a one-size-fits-all spacecraft to retrieve space debris. We focus on this type of debris because they are the only type that can be tracked and thus have the highest chance of being recovered and disposed of. Furthermore, they are the most at risk of generating more pieces of debris if struck by other debris. Even though this paper focuses on removing large pieces of debris, the challenge of removing small pieces of debris is briefly discussed in the conclusion section. As mentioned previously, many plans for debris removal have been hypothesized to be effective, however very few have been tested in space, and none have been implemented on the needed scale.

Types of Disposal Methods

Robotic Manipulators

In theory, this is the simplest means of disposal. As a result, the use of single and multiple robotic manipulators as means of space debris retrieval has been under development by multiple organizations. However, this method is only effective when retrieving objects that are able to be tracked, and preferably very large, such as rocket fairings, defunct satellites and rocket stages. The smaller the debris, the more difficult it will be to dispose of the debris using robotic manipulators, as a greater accuracy of both the manipulators and guidance/tracking system is required.

Clearspace, a Swiss company funded and commissioned by the European Space Agency (ESA), is working on developing a spacecraft, *ClearSpace1*, that is capable of using 4 robotic arms to retrieve one of the ESA's payload adaptors, *Vespa 1,* and maneuver it to a de-orbit trajectory. Even though *Vespa 1* is currently orbiting Earth in a stable, non-rotational trajectory, many pieces of debris exhibit rotational motion from separation with their primary craft.

As a large number of debris are created during fairing and stage separation, where pieces of spacecraft are ejected via pyrotechnics, oftentimes a net torque due to said pyrotechnic separation will be exerted on the ejected piece. This net torque creates a rotational motion in the debris. Such rotation makes it impossible for manipulators to capture the debris. When a manipulator attempts to retrieve the debris, the debris' angular momentum is transferred to the capture device, sending the cohesive amalgamation into rotation.

To counteract this, the Japanese Aerospace Exploration Agency (JAXA) developed prototypes of brush contactors - robotic manipulators with a soft, toothbrush-like head - to keep the targeted debris' from rotating, exerting a coulomb frictional force parallel to the surface of the debris, counteracting the original torque from the separation and returning the debris to a static position (Nishida et al. 2009). In the case of *Clearspace1*, as its manipulators do not have the capability to exert a counter-torque on a piece of debris, it is only able to retrieve static debris.

Finally, the rigidity in the dimensions of current robotic manipulators as a means of retrieval, means that even though a piece of debris may be static, it could be too big/small to fit within the parameters of the manipulators. There would be no one-size-fits-all version of the robotic manipulator that could retrieve all large pieces of debris. In addition, once the manipulators retrieve the debris, the de-orbiting process requires the whole system to be burnt up, therefore making it a one-time use system.

Magnets

At first glance, one may think that magnets are an intuitive answer to the space debris problem. However, the main concern with the idea of using magnets to retrieve debris is what to do with debris that is not comprised of magnetic materials - paint chips, glass, plastic, and carbon fibre - just to name a few. However, new advancements in magnet-based disposal point in the direction of using omnimagnets, magnets that manipulate objects ferromagnetically. Traditionally, if the object itself has no external magnetic field, it cannot be manipulated by other magnets. This ferromagnetic technique can manipulate objects regardless if they have magnetic properties. Although theoretically, this could be an effective way of retrieving the debris, the researchers have only written about the usage of omnimagnets to stop the rotation of the objects due to the external torque mentioned before (Pham et al, 2021). Thus, another device needs to be used in order to retrieve the debris, as using solely the magnets, retrieval is not likely. However, if magnets are combined with devices such as rigid robotic manipulators, the cohesive device would be appropriate and feasible for debris removal. AstroScale, a company based in Japan, is the first to test active debris removal, and the first to do so using magnets. However, the scope of their test was conducted on a level that only demonstrated the magnet's ability to attract and attach to a predesigned piece of "debris", with a connection point that matched that of the device (Blackerby et al, 2019). The real world presents challenges as debris can have damage, uneven protuberances and other anomalies on their surfaces making seamless attachment of flat magnets difficult. This test has yet to be performed within the reality of the realm of orbital debris, where most debris are dissimilar and non-cooperative.

Laser-Based Systems

Some have rejected mechanical-based systems in favour of pulsed laser ablation, some ground-based, and some placed in orbit alongside the debris, as a method of disposal. The main advantage of these systems is they are more flexible: they target all sizes of debris, and they can be used on static and rotating debris and debris of different masses. Researchers across many organizations in the United States and China have investigated the theoretical applicability of both space and ground-based lasers in regard to debris removal. As early as 1996, NASA researchers concluded that the possibility of using a laser-based debris disposal system is "feasible in the near term" (Bekey, 1996).

The laser system works on the principle of laser irradiation, a common method used in healthcare to remove unwanted cells and tumours. The ground or space-based system pulses a high-energy laser at a specific energy and frequency. For both ground and space based systems, pieces of debris that are very small (<10cm) eventually are ablated and disintegrated into plasma. To remove larger pieces of debris with a ground-based laser, the laser is pulsed and the ablative plasma byproduct is ejected downwards, causing an unequal force pair, thus pushing the debris upwards. This is to be done when the debris reaches about its apogee, lowering the debris' perigee. In this case, the debris moving into a higher orbit actually has the opposite effect, slowing the debris' speed in orbit and eventually de-orbiting it. For space-based systems, the same process is carried out, but instead of the object moving to a higher orbit, it is moved to the Earth's upper atmosphere, where it incinerates due to aerodynamic drag. The lasers are pulsed instead of constant to avoid the effect of continuous plasma shielding the debris from the laser. The research has pointed to the laser pulsing at around 100 hertz, a balance between effective disintegration rates and energy consumption (Shuangyan et al, 2014). An advantage of a laser-based system is that there is no need to first stop the residual rotation of the debris, and thus a large portion of the debris removal process can be avoided.

Although theoretically, the laser-based system is able to de-orbit large pieces of debris, it would take years to do so via pulsed laser ablation. Thus, this system is only effective for deorbiting small pieces of debris, less than 10 cm in size. Furthermore, there are constraints on the range of both the space and ground-based systems. The effective range for a ground-based laser system is between 350-1000km, implying the need for multiple laser stations placed around the Earth, ensuring a constant and consistent ablative process. For space-based systems, most small debris de-orbit in a few days if the maximum perigee the debris reaches during the irradiation process is under 200km (Shuangyan et al, 2014). Another obstacle that cannot be overlooked is the political challenges of using such a system to de-orbit debris. International cooperation must occur in order for this system to be effective, and there must be a certain amount of trust between cooperating nations that this technology is not used in a malicious manner.

Net-Based Removal

Net-based removal has also been proposed as an innovation to tackle space debris retrieval. *RemoveDebris*, another company testing out different types of debris removal, has already tested a net-based removal system. In their design, there are 6 cylindrical masses that are shot outwards from the launcher system, opening the net and dragging it using the inertia of the masses outwards toward the debris (Aglietti et al, 2019). *RemoveDebris* was tested in September 2018 and was successfully deployed from the International Space Station. The capture of a small CubeSat using the star-shaped net was successful and demonstrated that such a system is feasible for debris retrieval (Aglietti et al, 2019). Subsequently, researchers from China's Tsinghua University and Jiaotong University have used computer simulations to simulate the dynamics of both the net and the debris. These simulations have shown that the net capture method puts very little strain on the net in terms of tensile force. The maximum tension experienced by the net during the capture, when the debris contacts and stretches the net outwards, is hundreds of times less than the maximum threshold the net can withstand (Ru et al, 2022). Crucially, these simulations proved that net capture decreases the rotational motion of the debris to effectively nothing and proved the feasibility of net-based space debris retrieval and the viability of a reusable net controlled by thrust-enabled actuators. This broadens the scope that the net-based removal system can be used, as a controllable net eliminates the need for a de-orbiting device such as a drag sail to be used to de-orbit the debris.

Net-based removal has advantages in the sense that such a system would be very flexible in the different shapes and sizes of the debris it can capture. It also has the advantage of being among the few removal techniques that have already been tested in space. However, further research needs to be done on an effective way of taking the captured debris and actually de-orbiting it so that it burns up in the Earth's atmosphere. Such methods of de-orbiting include drag sails - thin membranes that catch on air particles in the Earth's upper atmosphere, aiding in the de-orbit process. This method has been tested before, with companies such as DragNet and Cranfield Aerospace systems in the process of deorbiting testing in space (NASA, 2023). MMA Design LLC, a company that has already patented its dragnet deorbiting system, has also already conducted orbital tests (NASA, 2023). Their system successfully deorbited the upper stage of Orbital Sciences Corporation(OSC) Minotaur, taking 2.1 years. Pairing the net capture system in conjunction with a drag sail de-orbiting system would be an effective means of disposing of moderately large to large space debris.

Another possible method of de-orbiting is the Global Aerospace Corporation's *Gossamer Orbit Lowering Device* (GOLD). Like the drag sail, it exploits the molecules of air still present in space and the uppermost part of Earth's atmosphere. Unlike the drag sail, GOLD is an inflatable kapton balloon, enclosed in a 24-inch diameter by 7-inch tall cylinder (Nock et al, 2010).

Harpoon

This removal system involves a metal harpoon that is launched from a satellite toward a target piece of debris. The harpoon would make contact with the debris and be stuck inside, where the host and its captured debris would maneuver themselves to a de-orbit trajectory. This method is in development at the European Space Agency and has already been tested in orbit by an ESA-backed company, RemoveDebris. This test showed that it was possible for a harpoon to retrieve a 10 cm x 10cm small aluminum square from a 1.5m distance (Aglietti et al, 2019). The concern with this method is the applicability across the debris of different materials, as they all possess different characteristics. It would be short-sighted to use the harpoon on material that is prone to shattering, thus doing more harm than good to the space debris problem.

Electrodynamic Tether

The benefit of this system is that it requires virtually no energy from the spacecraft, and is mechanically very simple, using basic principles of physics. However, a drawback of this system is that it is only effective when implemented on spacecraft that have yet to be launched, as a means of future mitigation of the spacecraft becoming a piece of debris. Additionally, due to the nature of the tether, it would only be truly effective if used in certain lower altitudes of orbit. If implemented, a long tether made of conductive material is released from the spacecraft that needs to be deorbited. Since the spacecraft is in the lower orbital altitudes, where the magnetic field generated by the Earth is relatively strong, a Lorentz force is generated due to the interactions between a current in the tether and the Earth's magnetic field (Ledkov and Aslanov, 2022). This Lorentz force slows down the spacecraft until it incinerates in Earth's atmosphere.

Discussion

The aforementioned disposal methods are analyzed and compared in Table 1.

Table 1. Review of merits and demerits of aforementioned disposal methods

Disposal Methods	Merits	Demerits
Robotic Manipulator	• Can stop residual rotation and make debris easier to retrieve and dispose of • Orbital tests have been successfully conducted	• Only able to retrieve very large pieces of debris • One-size-fits-all manipulators are difficult to devise • Uneconomical as it is a one-use system.
Ablative Laser	• Able to de-orbit both small and moderate-sized pieces. • Effective for debris of various materials	• Deorbiting large debris is ineffective • Testing is still pending
Magnets	• Can stop residual rotation and make debris easier to retrieve and dispose of • Effective for debris of various materials • Orbital tests have been successfully conducted	• Not viable as a stand-alone retrieval system; requires auxiliary systems • Past tests do not reflect real-world environments
Net	• Effective for debris of various materials	• Unable to capture small pieces of debris due to

	• Orbital tests have been successfully conducted	physical characteristics of the net. • Not viable as a stand-alone retrieval system; requires auxiliary systems to de-orbit
Harpoon	• Orbital tests have been conducted • Effective for moderate to very large debris	• Ineffective for small debris • Certain debris may not be able to be targeted due to their material • Uneconomical as it is a one-use system.
Electrodynamic Tether	• Virtually no excess energy is required • Can be implemented on various future launch vehicles as a form of mitigation	• Testing is still pending • Only effective in certain orbital regions

As the table illustrates, each disposal method offers its own advantages and has its own limitations. It is difficult to come to a conclusion as to which method is the most effective, as many methods await physical testing. However, there are some methodologies which demonstrate effectiveness in the retrieval of specific types of debris.

For smaller debris less than 10 cm in size, but sizeable enough to be tracked, ablative lasers emerge as the optimal choice. They require no launch of devices in order to function, and do not discriminate between debris of different materials. Additionally, lasers also avoid the need to stop the residual rotation of the debris from when it first entered Earth's orbit. Thus, many logistical challenges associated with debris removal are mitigated through the use of laser ablation.

For large debris removal, it is clear that a singular solution that encompasses the broad area of the space debris problem is elusive. It is only through a combination of the discussed retrieval and disposal methods that the problem can be solved. For large debris, it is advantageous to use a net combined with a drag sail to retrieve and dispose of space debris. Both the retrieval and disposal systems have already been proven to be successful both mathematically through computer simulations, and through orbital tests. Net-based retrieval is the most viable as it is easy to implement, although not the most simple mechanically, it is still more simple than the ablative laser or magnet system. Furthermore, nets allow a large degree of flexibility in the types of debris it can capture, with it being able to capture debris made of any material, and of most sizes. This would prevent the need to design multiple net-capture devices to fit each specific mission, rather it would allow multiple of the same device to be used to target all large pieces of debris. However, this still leaves the smaller pieces of debris in orbit.

Conclusion

This paper elaborated on proposed space debris disposal techniques, while also comparing the merits and demerits of each technique. It is important to test extensively the referenced debris disposal methods before coming to a definite conclusion on which one is best suited for large-scale debris collection and disposal. Theoretically, the net-capture method is the most effective, but one cannot be sure until this method is tested on a larger scale. As more and more spacecraft are launched into orbit each year, it should also be noted that more emphasis should be placed on allowing current spacecraft to de-orbit themselves, hence stopping the space debris problem before it has a chance to take place. Considering that many critical technologies for human survival and convenience are rooted in the thousands of devices in Earth's orbit, it is important that as we develop and launch new spacecraft we have this problem in the back of our minds, and have a means of cleaning up after ourselves.

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