Evaluating Active Space Debris Capturing Methods

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Introduction

Forming since the age of space exploration, space debris comprises millions of artificial objects in the Earth’s orbit. Both substantial and microscopic pieces of debris contribute to collisions and accidents, resulting in sizeable damage to active satellites. Additional space debris is formed in this process which poses risks to ongoing and future space missions. Large-scale debris creates additional microscopic fragments which are a major threat due to their great velocities and impact upon collisions. While the concept of launching artificially created objects into space roots back to the launch of Sputnik on October 4, 1957, the issue of space debris has only been apparent in 1996 when a French military reconnaissance satellite accidentally collided with space debris. While there have been additional verified cases of accidental collisions of space debris, because the issue of space debris is not widely publicized and the capturing method of technology is still at the development stage, it is fundamental to progress capturing methods. This research will focus on active capturing methods – which require energy from the satellite source – to combat the space debris surge. The optimal solution would ideally capture varied sizes of debris – both macro and micro – that is reusable and can be deployed at a greater distance.

Project Significance

Recently, the topic of space has become a progressively more popular topic with SpaceX being the first to successfully launch and return a reusable rocket. With the idea of potentially being able to travel to Mars and the huge impacts of satellite use in the modern world, space has become even more important to humanity. The use of satellites in space exploration is extremely important as they are able to view distant objects in space much better than down on Earth. Satellites are also useful in various research performed on the International Space Station and through satellite imagery of the Earth’s surface. Apart from scientific advancements, satellites also play an integral role in modern human society. Whether it is for beaming TV signals and phone calls around the world, determining the position of a person for their GPS, or predicting the weather, satellites are a necessity for all of these tasks. Without satellites, a large part of the functions that modern technology performs would no longer be possible. Both satellite systems and all future space missions have been put in danger due to space debris.

Space debris, or space junk, refers to man-made objects that orbit the Earth, but no longer serve a useful function. This debris includes nonfunctional satellites, abandoned launch vehicle stages, lost objects, and fragments of other debris. There are currently more than 27,000 pieces of debris that are currently being tracked in Earth’s orbit and many more that are unable to be tracked [1]. The problem is, this debris travels at an extremely high speed that could damage or destroy important satellites and rockets if they were to collide. This puts all satellites currently in Earth’s orbit in danger of collisions and becoming space junk themselves. It also puts in danger any future rockets as they will also need to arrive at or go through Earth’s orbit and risk being hit by a stray piece of space debris. What makes things even worse is that if two pieces of debris collide with each other, they would shatter and create even more debris. In addition to this, space debris is not just a hazard for things in space, it can also be dangerous to those on Earth’s surface. Over time a portion of space debris will slowly lose altitude and reenter Earth’s atmosphere. Smaller debris will burn up completely upon reentry. However, larger debris can occasionally impact the Earth [2].

The issue of space debris first surfaced when a French satellite collided with debris from an inactive, exploded French rocket in 1996. This was reported as the first verified case of unintentional space collision. Since then, there have been additional threatening accidental space collisions. Most notably on February 10, 2009, satellite Iridium 33 collided with inactive Russian military communication satellite Kosmos-2251, which generated thousands of hazardous fragments of debris. Similar events eluded the augmenting issue of space debris and the quintessence of space situational awareness, collision prevention, and debris mitigation. While measures have been taken to reduce the probability of such incidents, there still lacks a concrete solution that has been utilized beyond the developmental and testing stage [3].

There are a few ways of tackling the problem of space debris. One way is to prevent further space debris from accumulating in orbit by maintaining useful satellites and having built-in systems to remove satellites at the end of their life [4]. Proper maintenance of satellites will extend their lifespan which removes the need for a replacement satellite. Space debris avoidance is also important to extend the lifespan of satellites in order to avoid further damage and the creation of more space debris due to the collision. End-of-life disposal of satellites ensures that satellites that are no longer in use are removed from orbit so they do not become space debris themselves. Both these methods require the update of current satellites or built-in systems on new satellites. While these systems will be necessary for preventing more space debris, it does not do anything about the space debris already in orbit that is posing a threat to satellites.

Space debris removal methods fall into two categories, active and passive. Passive methods refer to systems that require no additional power from the spacecraft in order to remove the debris; passive methods. For example, a drag sail slows a decommissioned satellite using atmospheric friction until it re-enters Earth’s atmosphere. In this case, the drag sail does not use any additional energy from the satellite to slow the satellite down. Contrastly, active methods utilize additional energy to relocate or remove a piece of debris. The advantage of active methods is that it allows for targeting specific debris and is faster than passive methods. This project proposal will focus on three active debris removal methods, claw capture, net and harpoon, and electroadhesion.

Competing Solutions

The following solutions were evaluated and compared:

1. Claw Capture
2. Net and Harpoon
3. Electroadhesion

There are many active space debris removal techniques that are either methods of capture, deorbiting, or both in one. All of the mentioned solutions are capture methods to ensure they are adequately comparable. Lastly, all methods have data from various studies which were conducted in the development of each concept. These similarities among the methods are useful when comparing them and determining their feasibility.

Analytical Criteria

The following criteria will be focused on in the evaluation of each method:

1. Total Mass Capacity of Debris per Use
2. Total Quantity of Debris Capture per Use
3. Reusability
4. Proximity to Target

The criteria to be evaluated for each method are the mass capacity, the total quantity of debris possible, the reusability of the system, and proximity to the target mass required for function. There exists millions of space debris ranging from micro to kilo scales in size. Currently, the Department of Defense Space Surveillance Network has released estimates for the amount of space debris in lower earth orbit. Due to high velocities, it is easier to track larger space debris which also has a higher risk of collision. Therefore, a mechanism that can capture large masses of debris is ideal. In recommending a space debris capture method, mitigating the creation of debris is important. In addition to mass capabilities, the optimal function of the mechanism would include capturing multiple space debris pieces in a single try. Being able to capture multiple pieces of debris in a single use will preserve the satellites limited amount of energy and increase its efficiency. Aside from single-use functions, reusability is an advantage when estimating the total cost for removing a mass of space debris and complies with space debris mitigation. In this proposal, reusability will be defined as being able to continuously go and grab more debris in a single mission. Lastly, the proximity to the target is important because it is better to have a wider area range of application when targeting space debris because there is less effort from the spacecraft. This can also reduce costs and is more accessible.

| **Criteria** | **Metric** | **Constraints** |
| --- | --- | --- |
| Total Mass Capacity of Debris per Use | [g] | The ability to capture larger objects or denser objects is preferred due to their great impact on reducing debris population and collisions. |
| Total Quantity of Debris Capture per Use | # of Pieces | The ability to capture smaller objects or a greater amount of objects is preferred as smaller objects are more abundant and greater in quantity. |
| Reusability | # of times used | High reusability rate is favorable because it mitigates the creation of debris and optimizes the function of the mechanism. |
| Proximity to Target for Application | [m] | The mechanism is most useful with a greater range for capturing debris. |

Literature Review

*Claw Capture*

There are a few companies attempting to utilize the concept of claw capture to remove space debris, but the most prominent one is ClearSpace. ClearSpace is a Swiss startup that has partnered up with multiple companies and government agencies, including contracts with the UK Space Agency (UKSA) and European Space Agency (ESA), to accomplish their first space debris removal mission between 2025 to 2026 named ClearSpace-1. Their claw capture concept is in itself pretty simple, the satellite will act as a claw with a four-armed pincer mechanism used to grab space debris or other satellites [5] . It is similar to the claw of a crane game. Once latched on, the satellite can perform a number of tasks, refueling, repairing, relocation, or reentry [6]. By refueling and repairing other satellites, those satellites can stay in operation for much longer instead of becoming space debris. Relocating pieces of space debris will avoid having to move working satellites to avoid crashes with space debris. Reentry will be to make the debris reenter the earth's atmosphere by either being pushed in or pulled in together with the satellite and burned up on reentry. As the focus of this proposal is specifically on the capture of space debris, the main focus will be on the reentry and relocation of space debris.

Since the development of the satellite that will perform the ClearSpace-1 mission is not complete, there is no concrete data for what the satellite will be capable of. However, proof of concept and simulations conducted by the ClearSpace team demonstrates the capabilities of the claw capture method. The article “Europe plans space claw to capture orbiting junk” by Daniel Clery describes the process the ClearSpace satellite will use to grab a piece of debris. The satellite will need to be precise and adaptable in order to account for the size, shape, speed, and how the object is spinning. Once the satellite has autonomously adjusted to these conditions it will be able to move in and grab onto the debris. This means the ClearSpace satellite is designed to target one piece of debris at a time. Although precision and adaptability are necessary, the advantage of claw capture is the ability to reattempt to grab onto the debris if it were to fail the first time. The ClearSpace-1 mission is targeting the payload adapter of the Vega rocket which was used by the ESA to launch two satellites in 2013. This payload adapter weighs 112 kilograms and will be brought back into Earth’s atmosphere to burn up. The payload adapter gives an approximate weight of how much the ClearSpace-1 satellite will be able to carry [7].

In an interview with Rory Holmes, ClearSpace UK’s managing director, it was stated that their satellite will remove multiple pieces of debris on each mission. After grabbing onto the first piece of debris, the satellite will pull it down into Earth’s atmosphere or safely move it out of the way before proceeding towards the next piece to do the same [8]. It is currently unknown how many times this process can be repeated in a single mission, but it does mean that the ClearSpace satellite does have some reusability. However, considering that the ClearSpace-1 mission is only planning to remove a single object and the objects that ClearSpace is targeting are large, it is likely that the ClearSpace satellite will not be able to repeat this process too many times.

The sources provided details on the concept and future plans of how the ClearSpace satellite will perform. The first source is from ClearSpace describing the ClearSpace-1 mission, the second source is a video from ClearSpace describing their plans and the concept of their satellite, the third source is an article that provided an overview of ClearSpace and includes statements from ClearSpace staff, and the fourth source is an interview of Rory Holmes conducted by The Sun. These sources showed that the claw capture method is able to remove large pieces of debris, but can only target a single piece of debris at a time, which requires close proximity, and high levels of precision. The satellite will have some reusability, but the amount of times is inconclusive.

*Net and Harpoon Capture*

Net capture is an active technique that utilizes a tethered net to apprehend pieces of space debris from a distance. This method is beneficial because it presents a flexible tethered connection between the object and the harpoon net system. The nets are designed with a “reinforced perimeter” and “internal threads” attached to the tethered nets in order to pull in the captured target. The secondary threads are smaller in diameter for mobility purposes like moving through the process of restriction or friction it encounters. This method of capture includes a closing mechanism. At the mouth of the design – an interlaced section of thread on the perimeter of the net, the closing mechanism is initiated by a change in velocity or impact on the net. Additionally, there are a total of eight bullets located on the perimeter of the mouth in order to close the net upon capturing its target. While the closing mechanism and the net capturing process have proven to be successful in the testing stage, more simulations and tests are needed to confirm and finalize its functionality in space. Furthermore, the drawback of this design is its ability to accurately categorize space debris from other objects as the design recognizes and responds to changing velocities sensed by the net [9].

The experimentation of net capturing using tethered nets conducted by the engineers of the Department of Aerospace and Science and Technologies engineers in Milano, Italy characterizes the dynamics, models, and closing mechanisms of the tethered net capture system. Flexible nets and towable tethered have been found to be preferred compared to other space debris active capture methodologies. To measure various synthetic fiber ropes for Active Debris Removal (ADR) systems on tautness and durability, the tethered net capture system is simulated in a multibody dynamic environment at PoliMi-DAER. A harpoon system for capturing space debris is another active technique that aims to minimize damage and attaches to a target using a chemical propulsion system. The design of a harpoon system consists of barbs that maintain a grip on the target, a “crushable section” that soaks up the energy, and a tether that is connected to the capturing system. The harpoon is a promising method because it is small in size and low in mass, meaning it can be hosted conveniently on spacecraft. Because of its simplistic design, it is low in cost and developmental risks, leading to high reliability and ease of testing on the ground with similar circumstances as those experienced in space. Furthermore, because the harpoon has the ability to fire at a high speed, it can match objects with higher spinning rates. With these functionalities in mind, the harpoon system is ideal to target objects with high mass and collision possibilities. This includes objects that are 2.4 m - 4 m in diameter, 3.8 m - 12 m in length, and 1400 kg - 8000 kg in dry mass. Additionally, the harpoon system itself contains a barbed tip to ensure that it is secure after the initial impact, a crushable shaft, and a stabilizer for testing the system on the ground. The current system utilizes compressed nitrogen which allows the firing energy to vary depending on the location of the target, quintessentially allowing for multiple harpoonsto be fired simultaneously (as needed). This method of active capture has the potential to accurately deorbit or capture debris that is over 10m in distance and up to 9000 kg in mass. With its lightweight and compact design, it could also be placed in many spacecraft and used as many times as “50 firings in a day”. Furthermore, while this method has been tested for 90% accuracy, further experimentation and verification of a high probability are necessary before full implementation [9], [10].

The engineers at the 6th European Sociological Association Conference propose the development of a harpoon system for capturing space debris due to its compatibility in size and low cost for implementation. A study performed at the Australian Space Agency by Jamie Reed and Simon Barraclough, with support from the National Aeronautics, Astrium, and Space Administration (NASA) and the European Space Agency (ESA), analyzes the target properties, system design, and feasibility of this product. The authors introduce an estimated 5,900 tons of space debris orbiting the Earth, explaining that collisions from satellites, failures, rocket launches, and accidental or deliberate explosions increase the probability of additional collisions. They proceed to offer three reliable measures that can be implemented including reducing the vulnerability to micro debris, preventing accumulating new debris, and averting collisions by removing or relocating current debris. The authors highlight the key features of the harpoon system including (1) the compact size and low cost of the harpoon system allow for spacecraft to conveniently host one, (2) the high reliability and minimalistic mechanism reduce costs and risks, (3) the rapid firing speed indicate greater success against objects with higher velocities and spin rates. In this research, the researchers found that the harpoon causes only small flecks of debris upon impact, is able to accurately capture from a distance of 10m up to 6 degrees per second, and has been fired over 30 times into a single panel. Because the capture is rapid (within 0.5s), this design is promising as it primarily disregards the dynamic and orbital state of the target. The authors elaborate on the harpoon system, consisting of a barbed tip to ensure a secure penetration throughout, a crushable section to absorb surplus energy, and a tether to reel or connect to the host vehicle. Furthermore, the study showed that tethered net mechanism does not majorly alter the stability or direction of the harpoon, with the promising potential to carry up to 9000 kilograms. The study concludes by proposing several modifications to further simplify the harpoon system which includes the elimination of a host/firing spacecraft and the incorporation of thrusters. There are diagrams supporting the functionality and location of the harpoon system [10].

A study published at the ESA conference discusses the potential benefits and modifications of the harpoon-capturing system using complementary Astrium technologies. The authors explain that active removal is critical to removing larger pieces, and Astrium’s technologies are capable of enabling active capture missions such as the harpoon capture system. Due to its minimal damage, low cost, and ideal target properties for varied sizes of space debris, the study tests and explores the capabilities of this product. The target properties of the net harpoon system are designed to penetrate satellites made of honeycomb cores and aluminum skins up to 50mm and rocket bodies that are solid 2000/7000 series aluminum plates. Furthermore, as satellite bodies decay at a faster rate, the system is designed to support up to 10 degrees per second in a principal axis, pulling up to 9000 kg. The authors explain that removing larger debris has the biggest impact on the debris population. Thus, this product captures at a rate of fewer than 0.5 seconds and has the potential to be reused up to 50 times per mission or harpoon [10].

In general, net-capturing success is dependent on the ability of the host satellite to maintain control and successfully launch the system accurately to the correct positioning of the debris. Understanding the net itself and its closing mechanism is useful for comparison with other methods. Compared to the conventional active capture methods available, the net harpoon complemented by Astrium technology offers a cost-efficient solution with the capability to maximize reusability up to 50 times and hold greater mass less than equivalent to approximately 9000 kg, and distance that captures space debris of 10 meters. Additionally, there are a few promising space debris removal projects such as RemoveDEBRIS that include both the net capture and harpoon mechanism. This satellite contains a harpoon and net mechanism that pierces and captures space debris, and by 2019 of February, it was successfully captured at a rate of 20 meters per second, up to 1800 kg in mass, and 2m in size. This satellite uses a visual navigation system to track debris in orbit and holds additional functionality – drag sail – which is at its testing stage.

*Electroadhesion*

Electroadhesion(EA) is a method of attachment that has been researched and developed since the early 1900s. It was discovered that two surfaces attract when there is a voltage potential difference between them. This means that each surface has a different electrical charge. On an electroadhesive mechanism, there is an electric field applied to a non-conductive surface. When an additional surface is introduced independent of the electric field, it induces voltage potential difference which results in adhesion [11]. The electroadhesion mechanism proposed for space debris capture adheres to various insulating materials and textures. To induce the electric field across the adhesion surface, a large voltage must be applied. However, minimal current draw is necessary to achieve adhesion. An important aspect of this technology is that deadhesion, or unattachment, is possible by turning off the voltage supplied to the surface. Deadhesion shows promise of reusability which is important for lowering costs and maintenance routines required for multiple missions. However, EA has not been implemented or tested for space application. There are research and mission projects with intentions of using EA in lower earth orbit(LEO), but they are still in the development stages [12]. There exists a wide range of data and resources for EA technology on earth that validate the concept.

In the development of various EA systems, there are two key features that are ideal for potential space applications. The pad design is important in determining the capabilities of the mechanism. A symmetrical pad pattern provides more uniform EA forces while a non-symmetrical pad design concentrates the stronger EA forces in one area. The highest adhesion strength corresponds to pads with concentric and comb designs [13]. Next, the electrode placement on the pad affects the electric field created. The closer the electrodes are, the higher the adhesion. However, as the space between electrodes decreases, the increasing electric field could cause the pad material to break down [11]. Electroadhesion mechanisms have the potential to be fabricated for capturing very specific materials and target masses. With a customizable pad, common space-rated materials like kapton, aluminum, and mylar are more likely to be attained given the geometry and construction of the EA surface.

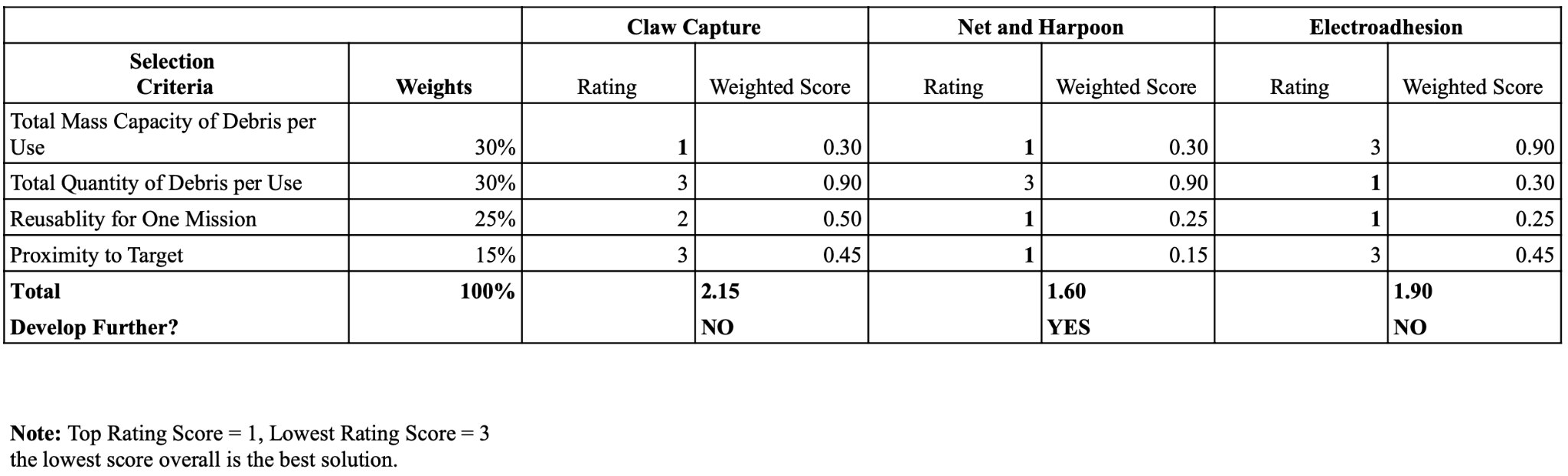
In 2010, SRI International partnered with NASA to study the implementation of electroadhesion as a space debris capture method. A series of space rated testing procedures occurred to qualify the method for space. For common space materials like kapton, mylar, and anodized bare aluminum, there were successful demonstrations of space-rated electroadhesion pads in a vacuum. It was also successful at -40°C to 150°C at 10-6 torr [12]. The results even showed better adhesion in vacuum at 5x10-5 torr which simulated the space environment. Electroadhesion in LEO plasma is yet to be determined. In 2014, terrestrial demonstrations again validated the concept and showed promise during the DARPA Phoenix Program in which electroadhesion pads were tested for sticking to different materials with a certain force value. Earth experimentation of EA mechanisms was proven to be feasible from this collective research.

In the earth's environment, electroadhesive mechanisms are widely used in manufacturing and creative applications which have provided the basis for understanding what works in EA applications. Robotic arms in industrial applications have utilized this concept to transport fragile semi-conducting materials in a manufacturing environment [11]. Specifically, in terms of this research study, micro-air vehicles(MAVs) developed by students at Stanford University proved whether EA capabilities could reduce power draw compared to MAVs in a hovering state. Ideally, the MAV could be perched on top of a tree or nearby structure using less energy than if it remained static in the air. The information from this study is useful because the attributes and behaviors of the electroadhesion pad in an Earth environment are explored that mirror its capabilities in space. The MAV remained attached to a surface via EA for ten minutes with a total power consumption of 333 mW and a mass of 23.4 grams. The purpose of this demonstration was to show the capabilities of battery design and voltage multipliers but was significant in demonstrating the capabilities of a non-ideal EA pad. In the research paper, the electroadhesive pads induced different pressure forces against various objects. For worst case scenarios, only 15.6 Pa was induced for 1kV on unfinished plywood and 2kPa for 4kV on damp concrete [14]. Additionally, data was collected showing a linear relationship between voltage and the projected force. This is ideal in any machine because actuation is easily achieved with reliable and predictable results. Additionally, the expectation for non-ideal surfaces provides insight to the limitations of EA in worst-case scenarios.

Some drawbacks in using electroadhesion technology include the high voltage necessary to maintain a large force on the pad. The force may be limited by the spacecraft power management system. Another issue is that EA is unstable in changing environments. A jolt or velocity impact may compromise the attachment to the object. Lastly, EA is possible for objects that are in close proximity to the pad. From the MAV research from Stanford University, the MAV was reliable within 1 to 3 millimeters from the desired location. Outside of this range, EA is not applicable. Aside from the improvements that are yet to be made, electroadhesion is useful for objects of different masses. Since the force is actuated by the voltage applied to the pad, an object with greater mass can be captured and held with an adjustment to the voltage by the satellite. The range of masses only includes up to 45 grams as recorded from the MAV Stanford experiment. Considering that space debris range from 1 micrometer to 3 meters, the range of debris that can be captured is small. However, smaller masses are traditionally more difficult to capture and are the most abundant form of space debris. In concept, the electroadhesion pad can capture multiple small-sized debris during its mission as long as the total debris mass falls within the mass limits [12].

Comparative Analysis and Recommendation

The weighted decision matrix shown in Table 1 evaluates three active capture methods for four selection criterias. The table shows which capture method is versatile in capturing larger space debris, the amount of debris captured, reusability, and ability to capture the target at a further distance.



**Table 1. Comparing Active Capture Methods.** Methods can either capture a greater total mass or a greater number of space debris per use.

The overall best score was achieved by the net and harpoon method as shown in Table 1. Net and harpoon methods met expectations in three out of the four criteria. The two most important criteria were the total mass and quantity capabilities. For the claw capture mechanism, the total mass capacity was large at 112 kilograms which are best for the purpose of this comparison. Similarly, the net and harpoon method has the largest pulling capability at 9000 kilograms. Unfortunately, electroadhesion was proven to support less than half a kilogram of debris in unfavorable circumstances, therefore it scored the lowest for this portion. Electroadhesion is ideal in capturing the most debris in one mission, so it received the highest score in this aspect. Depending on the size of the pad, multiple small pieces of debris can be captured. For both claw capture and net and harpoon methods, the expected mission payload is limited to one or few large objects. Next, reusability was important because it correlates with the mission cost and debris mitigation strategy proposed by NASA. This section was graded based on proof of concept. Net and harpoon and EA were theorized to be reusable based on earth-based testing. For the net and harpoon, as many as 50 firing a day were observed in the target capture simulation. In concept, EA’s ability to attach and reattach enables the spacecraft to relocate the debris before releasing it closer to earth’s atmosphere. Claw capture is focused on simply attaching to debris without current infrastructure and software for letting go and being reused. While there are plans for claw capture to capture multiple debris in a single mission, the ClearSpace-1 mission only targets a single piece of debris. This is why claw capture was not ideal in this criteria. Lastly, proximity to the target was an important factor to consider because the mechanism’s ability to reach debris without additional support from the spacecraft results in less fuel used for reaching the target and a wider range of motion in the case of any unexpected situations. Both claw capture and EA needed to be in extremely close proximity to the target. Claw capture must be touching the target to be effective and EA must be within 3 millimeters of the target to function. Meanwhile, the net and harpoon is functional from 10 meters away. Based on the criteria, the net and harpoon active capture method for space debris is optimal for minimizing the amount of space debris in lower earth orbit. Encouraging the research and development of this concept is promising given the data that exists based on terrestrial studies.

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