Assessment of Active Space Debris Removal Methods Using the Weighted Sum Model (WSM)

Kareem Mesrega[1,2](✉), O. M. Shalabiea[2,3], Dalia Elfiky[4], Wesam Elmahy[2], and Haitham Elshimy[3]

[1] Menofia University, Gamal Abdel Nasser Street, Shebin El-Kom 32511, Egypt
kareemmesrega@science.menofia.edu.eg
[2] Cairo University, Gamaa Street 1, Giza 12613, Egypt
[3] Beni-Suef University, Beni-Suef 2731070, Egypt
[4] National Authority for Remote Sensing and Space Sciences, Jozif Tito Street 23, Cairo 11769, Egypt

Abstract. With the recent growth in space exploration, the problem of space debris is becoming increasingly important. This debris could endanger active spacecraft. So, many methods are suggested to clear space debris. The best and most efficient removal method must be selected from these available options. This is our main objective. In this study, we suggest using the Weighted Sum Model (WSM) to order the chosen removal methods according to a set of deciding criteria. WSM is one of the most common Multi-Criteria Decision Analysis (MCDA) techniques. Based on how widely applicable they are, we selected five active removal methods. Thirteen decision criteria were chosen carefully. The Relative Frequency approach was used to determine the weight of these criteria. The WSM equation was used in the final stage. According to our major findings, Tethered-Deployed Nets, with a performance score of 78.9%, is comparatively the best method among the selected methods. More in-depth research on this approach is recommended for future work. To obtain more accurate results for our future research, we will use more decision criteria.

Keywords: Space Debris · Active Removal Methods · Multi-Criteria Decision Analysis · Weighted Sum Model

1 Introduction

European Space Agency (ESA) defines space debris as any man-made objects such as fragments and other related elements that are no longer functional and currently present in Earth's orbit [1]. Around the Earth in different orbits, there is a large number of space debris with different sizes and shapes.

The estimated number of space debris objects orbiting the Earth, categorized by size as follows: over 29,000 objects larger than 10 cm, more than 670,000 objects larger than 1 cm, and over 170 million objects larger than 1 mm. These objects can pose a threat to operational spacecraft and satellites [2]. It has been discovered that an increase in

H. M. K. Al Naimiy et al. (Eds.): AUASS-CONF 2023, SPPHY 420, pp. 83–97, 2025.
https://doi.org/10.1007/978-981-96-3276-3_8

uncontrolled objects in Low Earth Orbit (LEO) might cause a series of collisions and a persistent buildup of orbital debris, which would cause environmental instability. The "Kessler Syndrome" is the name for this cascading effect [3].

Several methods or systems have been suggested over the years to clear space debris. These methods could be passive removal methods like Electrodynamic tethers or active ones like Tethered-deployed nets [4]. Each of these removal methods has benefits and drawbacks. So, selecting the most effective method among these options becomes a problem that must be tackled.

An example of conducting a comparative analysis between the removal methods is found in Hakima and Emami in their study [5]. They have made a quantitative analysis using the Analytical Hierarchy Process (AHP). They evaluate different active debris removal methods for clearing large objects in LEO. The comparison was done between the net method, on-orbit laser, electro-dynamic tether, ion beam shepherd, and robotic arm. They found that net methods are the most effective overall, with on-orbit lasers and robotic arms being close contenders.

As seen in Hakima and Emami's research, they used AHP which is one of the Multi-Criteria Decision Analysis (MCDA) techniques. MCDA concentrates on problems with discrete decision spaces. In these problems, the set of decision alternatives has been predetermined to choose the best between them based on preselected decision criteria. There are many techniques used in MCDA such as the Weighted Product Model (WPM), WSM, and AHP. One of the most popular MCDA techniques used today is WSM [6].

In this study, we attempt to find the most efficient and the most suitable method for removing space debris using WSM. WSM has never been used in this field previously. Therefore, the scientific question that we are asking is, "According to WSM, which of the proposed methods is the best for removing space debris?".

In our research, we will select five active removal methods that have the highest chance for practical implementation. The decision-making process will consider thirteen relevant criteria. These decision criteria are based on the characteristics of space debris and space debris removal missions. The weight of these criteria will be calculated by using the Relative Frequency Approach. Finally, the performance scores for the chosen methods will be calculated by WSM. This will supply the decision maker with suggested options.

This paper is structured as follows: Sect. 2 describes the methodology used in this research. The results are given in Sect. 3. Section 4 represents the discussion. Section 5 provides the conclusions and suggestions for future work.

2 Methodology

In this section, we will review more details about the WSM that we will follow in this research.

2.1 Problem Definition

The problem here is choosing the most appropriate method for removing space debris.

2.2 Identification of Decision Alternative and the Decision Criteria.

The decision alternatives are the removal methods which we will choose the best of them. In this research, we selected five active removal methods. For the decision criteria, thirteen criteria represent a combination of standard space mission criteria such as the power consumed during operation, those specific to debris removal missions such as reusability, and criteria related to space debris characteristics such as the size of debris. Each criterion was described. Through this description, a conversion scale was developed for each criterion to obtain all performance values for all methods within the context of the selected criteria.

2.3 Definition of Weights

We used the Relative Frequency Approach to determine the relative weight of each criterion which helped to find out their importance.

Relative frequencies indicate the ratio or percentage of occurrences of a particular event or observation in comparison to the total number of events or observations. They are commonly employed to illustrate the frequency with which a specific category is present in a dataset [7].

So, criteria that have higher relative frequencies will be assigned higher weights because they are considered more influential in the decision.

To implement the Relative Frequency Approach, we chose 41 scientific papers that delve into these methods. We combed through these papers to identify the selected criteria. When a criterion was found discussed or mentioned in a paper, it received a score of 1; otherwise, it received a score of zero. We tallied these scores to determine how many times each criterion was mentioned or discussed within the 41 scientific papers. Consequently, if a criterion appeared frequently, it was assigned greater significance. By the relative frequencies approach, the weight of each criterion (W_m) was computed using Eq. (1) by dividing the number of mentions of m^{th} criterion (NC) by total number of mentions of all criteria (TC) in the 41 papers:

$$W_m = \frac{NC}{TC} \tag{1}$$

2.4 Data Collection and Performance Values

Qualitative and quantitative data related to the selected criteria were collected for each method. Various sources were used to collect this data, including scientific papers, books, review papers, and websites. All gathered data is entered into the decision matrix and transformed into performance values (P) through the application of a conversion scale.

2.5 Normalization of Performance Values

To make all criteria comparable, we conduct a normalization process on the performance values for each criterion. This involves dividing the score of the performance value of n^{th}

method in m^{th} criterion (X_{nm}) by the maximum value of m^{th} criterion (X_m^{Max}). This type of normalization is referred to as linear normalization. So, we can obtain the normalized performance value ($\overline{X}_{nm}$) using Eq. (2):

$$\overline{X}_{nm} = \frac{X_{nm}}{X_m^{Max}} * 100 \tag{2}$$

2.6 Weighted Normalized Decision Matrix and Performance Score

We applied the WSM equation, Eq. (3), in two steps. The first step is to calculate the weighted normalized performance values by multiplying the normalized performance values of each method by the corresponding criterion weights ($W_m\overline{X}_{nm}$). W_m is the weight of m^{th} criterion. The weighted normalized decision matrix will contain all the weighted normalized performance values. The second step is to add all weighted normalized performance values of n^{th} method to get the performance score for n^{th} method (A_n^{WSM}) [6]:

$$A_n^{WSM} = \sum_{m=1}^{k} \left(W_m\overline{X}_{nm}\right) for\, n = 1, 2, .., l \tag{3}$$

3 Results

This section will involve a review of the chosen removal methods and decision criteria. Additionally, it will present all the results derived from both the Relative Frequency approach and the WSM.

3.1 The Identified Debris Removal Methods

Within this subsection, we will provide a concise overview of the chosen removal methods.

Ion Beam Shepherd (IBS). This method entails placing the IBS spacecraft into orbit, where it will track and meet a preselected target debris. The IBS will position itself adjacent to the target and use an ion beam to reduce the speed of the designated debris by applying a decelerating force. This force causes debris to deorbit into the atmosphere or reorbit to disposal orbit, all without the necessity of physically docking with debris [8].

Laser Systems. The laser-based technique uses a pulsed laser beam directed towards the target object, causing the object to decelerate and descend into the Earth's atmosphere. This laser system can be deployed either from a ground station (ground-based laser) or a space station (space-based laser). It serves the purpose of space debris removal. Laser systems can vaporize or ablate small debris [9].

Robotic Systems. Robotic systems are means of space debris removal. These systems are attached to the debris and subsequently propel the object into an orbit that will rapidly deorbit and degrade [10, 11]. These robotic systems come in various forms, including tentacles, single robotic arms, and multiple robotic arms [12].

Space Harpoon System. The procedure involves using a chaser spacecraft to launch a harpoon connected to a tether from a safe distance. The harpoon is required to pierce a predefined part of the debris and firmly secure itself. Subsequently, the chaser spacecraft deorbits the debris and transports it toward the upper atmosphere and ultimate destruction [13].

Tethered-Deployed Nets. This system functions as a capture mechanism using a flexible net in conjunction with a spacecraft. The flexible net is tethered to the spacecraft using an extended rope, and mechanical mechanisms are employed to cinch the net. Then, the spacecraft pulls the net with the debris down into the atmosphere [12].

3.2 The Identified Decision Criteria

Table 1 contains the description and the conversion scale of each criterion. The conversion scale replaced the qualitative data with quantitative data and scores to help us in applying WSM.

Table 1. The description and the conversion scale of each criterion.

The criterion	Performance values
Applied orbit	- The method can be used in one orbit (LEO or geostationary orbit (GEO)) = 1 - It can be used in both orbits (LEO or GEO) = 2
Policy and legal concerns	- The method may be used as a space weapon = 1 - It is not used as a space weapon = 2
Flight proven. A space mission was launched to test the method or to test the technology on which this method is based	- There is no space mission was launched = 1 - A space mission was launched = 2
The ability of the method to deal with different shapes of debris	- The method don't have this ability = 1 - It has this ability = 2
Size of debris which the method can deal with. The space debris has been divided into three categories according to size: Small debris (S) (< 1mm), Medium debris (M) (10 cm to 1 mm), and Large debris (L) (> 10cm) [14]	- The method can deal with one category whether small, medium, or large = 1 - It can handle two categories = 2 - It can handle three categories = 3

(*continued*)

Table 1. (*continued*)

The criterion	Performance values
Reusability. The ability of the method to remove more than one piece of debris through one system	- The method can only remove one piece of debris with the same system = 1 (one for one) - The method can remove more than one piece of debris with the same system = 2 (one for more)
Weight of the method	- The method weighs 4000 kg or more = 1 - It weighs from 3000 kg to 4000 kg = 2 - It weighs 2000 kg to 3000 kg = 3 - It weighs 1000 kg to 2000 kg = 4 - It weighs less than 1000 kg = 5
Ability to deal with tumbling debris	- The method cannot deal with tumbling debris = 1 - It cannot deal with high tumbling debris only = 2 - It can deal with and remove tumbling debris = 3
If the method needs docking or a close approximation	- The method needs a docking mechanism = 1 - It needs only a close approximation to the debris = 2 - It does not need any docking or a close approximation = 3
Technology readiness level (TRL)	- The method will be evaluated according to its TRL based on the National Aeronautics and Space Administration (NASA) classification [15]
Risk of Collision of the method with the other debris. This risk depends mainly on the cross-sectional area of the spacecraft. The risk of collision is classified into three stages, high, medium, and low risk of collision	- The method has a high risk of collision = 1 - It has a medium risk = 2 - It has a low risk = 3
Contamination of the surrounding environment	- The method can pollute the surrounding environment = 1 - It isn't polluting the surrounding environment = 2
Power used during the operation of the method	- The used power is within the limits of megawatts = 1 - The used power is within kilowatts = 2 - The power used is within the limits of watts = 3 - There is no power used = 4

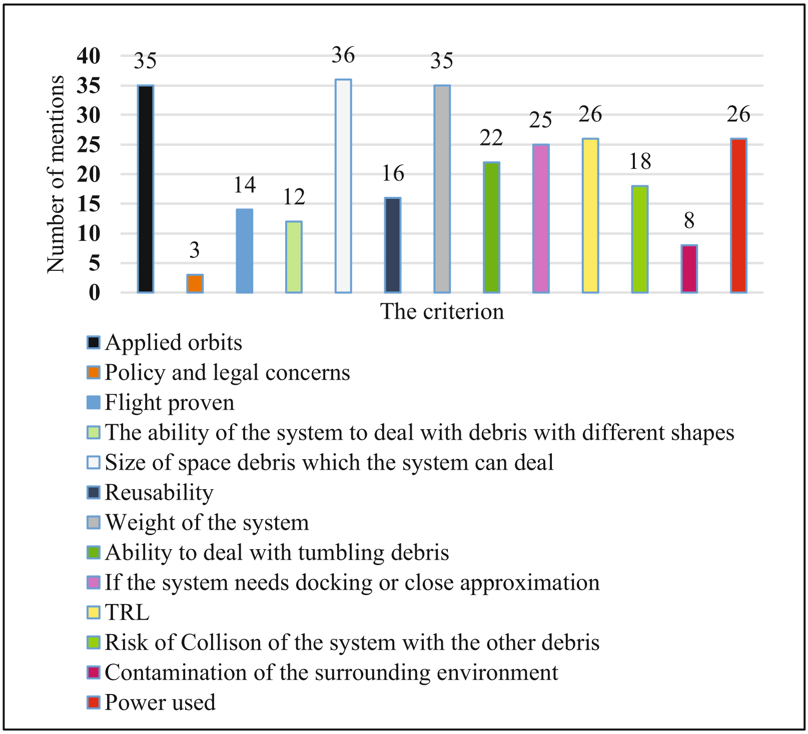

Fig. 1. Number of times each criterion was mentioned in the 41 papers. (Relative frequency histogram).

3.3 Weights of the Decision Criteria

The number of times each criterion was mentioned or discussed in the 41 papers was collected to calculate the weight. Figure 1 is a graph illustrating the frequency of mentions for each criterion within the 41 papers.

Using Eq. (1), the weight for each criterion was determined. It was observed that the criterion "size of debris which the method can deal with" holds the utmost significance, with 36 mentions in the 41 papers and the highest weight of 0.130. Conversely, "policy and legal concerns" is the least significant criterion, with only 3 mentions in the 41 papers and the lowest weight of 0.011. The order of the criteria and their respective weights are detailed in Table 2.

Based on the findings in Table 2, it becomes evident that a method capable of effectively addressing a broad range of debris sizes, functioning in multiple orbits, and being lightweight holds a significant advantage over alternative methods.

3.4 Decision Matrices

All the gathered data and the corresponding performance values have been presented in Table 3 and Table 4. Within the decision matrices, the criteria are organized in descending order based on their relative weights, from the most important to the least important one.

Table 2. The weight of the thirteen criteria.

The criterion	Weight of each criterion
1-Size of debris which the method can deal with	0.130
2-Applied orbit	0.127
3-Weight of the method	0.127
4-Power used during the operation of the method	0.094
5-TRL	0.094
6-If the method needs docking or a close approximation	0.091
7-Ability to deal with tumbling debris	0.080
8-Risk of Collision of the method with the other debris	0.065
9-Reusability	0.058
10-Flight proven	0.051
11- The ability of the method to deal with different shapes of debris	0.043
12-Contamination of the surrounding environment	0.029
13-Policy and legal concerns	0.011

Table 3. Decision matrix for active removal methods (IBS, Laser systems, and Robotic systems).

Criterion	Method					
	IBS	P	Laser Systems (ground and space-based)	P	Robotic Systems	P
1	L. debris [18]	1	L., M., and S. debris [9, 16, 17]	3	L. debris [18]	1
2	LEO, GEO [19, 20]	2	LEO, GEO [21, 22]	2	LEO, GEO[23, 24]	2
3 (Chaser dry mass)	About 500 kg for large debris [20, 25]	5	About 2300 kg (for space-based) [26]	3	About 700 kg for 1.5 arm length [26]	5
4	Up to 15 KW for large debris [20]	2	Some MW [27]	1	Handers of W [26]	3
5	3 [26]	3	3 [26]	3	7 [28]	7
6	Needs close approximation [19]	2	No docking or close approximation [29]	3	Needs docking [4, 30]	1
7	Can deal [20]	3	Can deal [31]	3	Cannot deal [4, 28]	1
8	Low risk [26]	3	Low risk for space-based	3	Medium risk	2
9	One for more [19]	2	One for more [22]	2	One for more [24]	2
10	No	1	No	1	ETS-VII [4]	2
11	Can deal [25]	2	Can deal [32]	2	Can't deal [33]	1
12	Yes [20]	1	Yes	1	Yes	1
13	Yes [17]	1	Yes [17]	1	Yes [11]	1

Table 4. Decision matrix for active removal methods (Space harpoon system and Tethered-deployed nets).

Criterion	Method			
	Space Harpoon System	P	Tethered-Deployed Nets	P
1	L. debris [17]	1	L. and M. debris [34–36]	2
2	LEO, GEO [26]	2	LEO, GEO [12, 37, 38]	2
3 (Chaser dry mass)	About 150 kg [26]	5	About 1300 kg [26]	4
4	Up to 20 W [39]	3	About power 12 KW [26]	2
5	9 [39]	9	9	9
6	Needs close approximation [13, 39]	2	Needs close approximation [34]	2
7	Can deal (problem with high tumbling rate) [13]	2	Can deal [38]	3
8	Medium risk	2	Medium risk	2
9	One for one [17]	1	One for one [36]	1
10	RemoveDebris [40]	2	RemoveDebris [40]	2
11	Can deal [41]	2	Can deal [36]	2
12	Yes	1	Yes	1
13	No	2	No [11]	2

3.5 Normalized Decision Matrix

By using Eq. (2) on the decision matrices for the active removal methods, we can generate the normalized decision matrix. This matrix includes the normalized performance values. Table 5 illustrates the Normalized decision matrix. Within this matrix, the criteria are organized in descending order based on their relative weights.

Table 5. Normalized decision matrix for active removal methods.

Criterion	Method				
	IBS	Laser Systems (ground and space-based)	Robotic Systems	Space Harpoon System	Tethered-Deployed Nets
1	33.3%	100%	33.3%	33.3%	66.6%
2	100%	100%	100%	100%	100%
3	100%	60%	100%	100%	80%

(*continued*)

Table 5. (*continued*)

Criterion	Method				
	IBS	Laser Systems (ground and space-based)	Robotic Systems	Space Harpoon System	Tethered-Deployed Nets
4	50%	25%	75%	75%	50%
5	33.3%	33.3%	77.7%	100%	100%
6	66.6%	100%	33.3%	66.6%	66.6%
7	100%	100%	33.3%	66.6%	100%
8	100%	100%	66.6%	66.6%	66.6%
9	100%	100%	100%	50%	50%
10	50%	50%	100%	100%	100%
11	100%	100%	50%	100%	100%
12	50%	50%	50%	50%	50%
13	50%	50%	50%	100%	100%

3.6 Weighted Normalized Decision Matrix and Performance Scores

By applying Eq. (3), we obtain a weighted normalized decision matrix, from which the performance scores for all methods are computed. Table 6 illustrates the weighted normalized decision matrix, while Fig. 2 depicts the performance scores for each removal method.

Table 6. Weighted normalized decision matrix for active removal method.

Criterion	Method				
	IBS (%)	Laser Systems (ground and space-based) (%)	Robotic Systems (%)	Space Harpoon System (%)	Tethered-Deployed Nets (%)
1 (W = 0.130)	4.329	13	4.329	4.329	8.658
2 (W = 0.127)	12.7	12.7	12.7	12.7	12.7
3 (W = 0.127)	12.7	7.62	12.7	12.7	10.16
4 (W = 0.094)	4.7	2.35	7.05	7.05	4.7

(*continued*)

Table 6. (*continued*)

Criterion	Method				
	IBS (%)	Laser Systems (ground and space-based) (%)	Robotic Systems (%)	Space Harpoon System (%)	Tethered-Deployed Nets (%)
5 (W = 0.094)	3.13	3.13	7.30	9.4	9.4
6 (W = 0.091)	6.06	9.1	3.03	6.06	6.06
7 (W = 0.080)	8	8	2.664	5.328	8
8 (W = 0.065)	6.5	6.5	4.329	4.329	4.329
9 (W = 0.058)	5.8	5.8	5.8	2.9	2.9
10 (W = 0.051)	2.55	2.55	5.1	5.1	5.1
11 (W = 0.043)	4.3	4.3	2.15	4.3	4.3
12 (W = 0.029)	1.45	1.45	1.45	1.45	1.45
13 (W = 0.011)	0.55	0.55	0.55	1.1	1.1

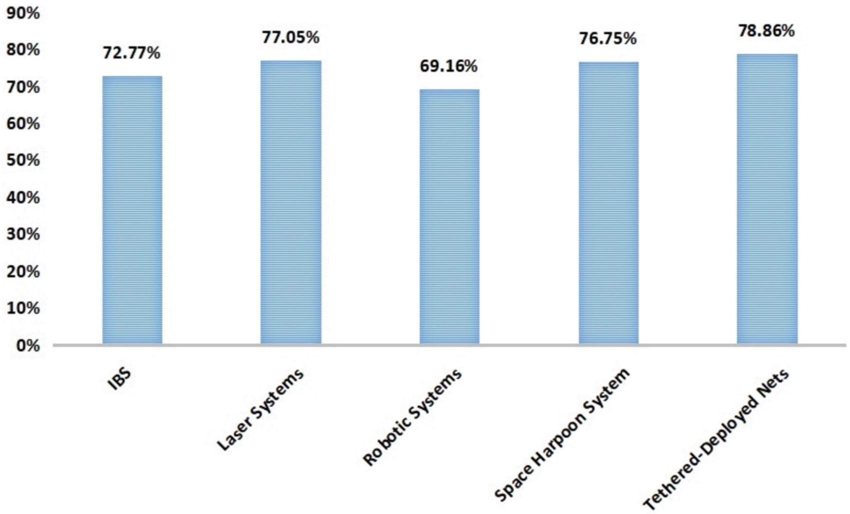

Fig. 2. Assessment of active removal methods.

4 Discussion

Through this section, we will discuss the importance of the results we obtained and the factors that can change the results. We will also explain how these results can be improved to get accurate ones.

4.1 Method ranking

Through ranking the selected methods, we offer valuable information that can assist in the selection of the most suitable method for space debris removal.

Following the application of Eq. (3) to derive the performance score for each method, these methods can be sorted in order of their performance score. The method with the highest performance score is typically regarded as the favored choice.

The research determined that the most effective method is Tether-Deployed Nets, 78.9%. However, a significant drawback is its inability to deal with small debris. Following closely behind is the laser systems, having a performance score of 77.0%, yet it necessitates a higher power supply and has policy and legal concerns. Subsequently, the space harpoon system achieved a performance score of 76.7%.

It's important to note that each method has its own set of pros and cons. Hence, the methods identified as the best are relatively most suitable when compared to the other methods.

Several factors within this study can influence the outcome and the ranking of the removal methods. Firstly, the selection of papers, which serves as the basis for calculating the weight of each criterion, is a critical factor. Altering these papers could potentially lead to changes in the weighting of each criterion. Secondly, modifying the decision criteria used in the evaluation is another influential factor. We made diligent efforts to ensure that the assessment of each method was as reliable as possible.

Enhancing the quality of these results can be achieved by expanding the sample size, which would enable more accurate weight calculations. Additionally, the possibility exists to introduce additional decision criteria and provide a more comprehensive study of the interconnections between these criteria. Such measures would lead to increased precision and confidence in the results.

In summary, we can affirm that we have successfully responded to the scientific question posed before initiating this research.

4.2 Verification of the Results

Hakima and Emami used the AHP method, as previously discussed in the introduction, whereas we utilized the WSM in our study. The first two methods are identical between our study and theirs, with the first method being net methods and the second being on-orbit lasers [5].

5 Conclusions and Future Work

Space debris has a variety of negative effects, including the malfunction or partial loss of operating satellites. Addressing this problem demands extensive efforts from all organizations participating in the space industry. Amidst numerous proposed methods for space debris removal, we selected five active removal methods for examination in this study. These methods were ranked using the WSM, leading to the identification of Tether-Deployed Nets as the top-performing method with a performance score of 78.9%. A significant advantage of tethered deployed nets is their versatility, as they can function across various orbits, handle debris of different shapes, and even address tumbling debris. This research can contribute to the process of decision-making and can provide recommendations for further testing of the methods that have achieved high-performance scores.

In future work, we will work to increase the number of scientific papers used in the sample. Also, increasing the decision criteria will help in judging the methods and make the results more confident and realistic. The use of other MCDA techniques and comparing the results of these techniques with each other will be essential.

References

1. ESA: FAQ: Frequently asked questions. https://www.esa.int/Space_Safety/Space_Debris/FAQ_Frequently_asked_questions. Accessed Apr 2021
2. ESA: How many space debris objects are currently in orbit?. https://www.esa.int/Space_Safety/Clean_Space/How_many_space_debris_objects_are_currently_in_orbit. Accessed 2021
3. Kessler, D.J., Cour-Palais, B.G.: Collision frequency of artificial satellites: the creation of a debris belt. J. Geophys. Res. Space Phys. **83**(A6), 2637–2646 (1978)
4. Zhao, P., Liu, J., Wu, C.: Survey on research and development of on-orbit active debris removal methods. Sci. China Technol. Sci. **63**(11), 2188–2210 (2020)
5. Hakima, H., Emami, M.R.: Assessment of active methods for removal of LEO debris. Acta Astronaut. **144**, 225–243 (2018)
6. Guzman, L.M.: Multi-criteria decision Making Methods: A Compartive Study. In: Applied optimization. Evangelos Triantaphyllou, 288 p. . Kluwer Academic Publishers, Wiley, Hoboken (2001)
7. Heumann, C., Shalabh, M.S.: Introduction to Statistics and Data Analysis. Springer, Cham (2016)
8. Ahedo, E., et al.: Space debris removal with an ion beam shepherd satellite: target-plasma interaction. In: 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit (2011)
9. Choi, S.H., Pappa, R.S.: Assessment study of small space debris removal by laser satellites. Recent Patents Space Technol. **2**(2), 116–122 (2012)
10. Pelton, J.N., Ailor, W.: Space Debris and Other Threats from Outer Space. Springer, Cham (2013)
11. Pelton, J.N.: Technological approaches to debris removal or mitigation. In: Space Debris and Other Threats from Outer Space, pp. 35–44 (2013)
12. Ru, M., et al.: Capture dynamics and control of a flexible net for space debris removal. Aerospace **9**(6), 299 (2022)
13. Dudziak, R., Tuttle, S., Barraclough, S.: Harpoon technology development for the active removal of space debris. Adv. Space Res. **56**(3), 509–527 (2015)
14. Chunlai, L., et al.: Chemical classification of space debris. Acta Geologica Sinica-Engl. Ed. **78**(5), 1090–1093 (2004)
15. NASA: Technology Readiness Level. https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level. Accessed 28 Oct 2012
16. Klinkrad, H., et al.: Effects of debris mitigation measures on environment projections. In: Space Debris: Models and Risk Analysis, pp. 165–198 (2006)

17. Chatterjee, J., Pelton, J.N., Allahdadi, F.: Active orbital debris removal and the sustainability of space. In: Handbook of Cosmic Hazards and Planetary Defense, pp. 921–940. Springer, Cham (2015)
18. Dubanchet, V., et al.: Modeling and control of a space robot for active debris removal. CEAS Space J. **7**(2), 203–218 (2015)
19. Bombardelli, C., Pelaez, J.: Ion beam shepherd for contactless space debris removal. J. Guid. Control. Dyn. **34**(3), 916–920 (2011)
20. Bombardelli, C.: Ion beam technology for space debris mitigation (2017)
21. Thind, M.K., Lokesh, C.: Removal of space debris using laser. Adv. Aerosp. Sci. Appl. **3**(2), 107–112 (2013)
22. Phipps, C.R., et al.: A Laser Optical System to Remove Low Earth Orbit Space Debris. Lawrence Livermore National Lab. (LLNL), Livermore, CA (USA) (2013)
23. Jankovic, M., et al.: Robotic system for active debris removal: requirements, state-of-the-art and concept architecture of the rendezvous and capture (RVC) control system. In: 5th CEAS Air and Space Conference Proceedings. CEAS, Delft, the Netherlands (2015)
24. Pelton, J.N.: New technological approaches to orbital debris remediation. In: New Solutions for the Space Debris Problem, pp. 53–68 (2015)
25. Kitamura, S., Hayakawa, Y., Kawamoto, S.: A reorbiter for GEO large space debris using ion beam irradiation. In: 32nd Electric Propulsion Conference (International). IEPC-2011-087 (2011)
26. Michal, M.: Aktivní technologie řešení kosmického odpadu, České vysoké učení technické v Praze. Vypočetní a informační centrum (2021)
27. Khanolkar, N.P., et al.: Advanced space debris removable technique and proposed laser ablation technique: a review. In: 2017 International Conference on Infocom Technologies and Unmanned Systems (Trends and Future Directions) (ICTUS). IEEE (2017)
28. Jankovic, M., Kirchner, F.: Trajectory generation method for robotic free-floating capture of a non-cooperative, tumbling target. In: Stardust Final Conference: Advances in Asteroids and Space Debris Engineering and Science. Springer, Cham (2018)
29. Shen, S., Jin, X., Hao, C.: Cleaning space debris with a space-based laser system. Chinese J. Aeronaut. **27**(4), 805–811 (2014)
30. Nishida, S.-I., et al.: Lightweight robot arm for capturing large space debris. J. Electr. Eng. **6**(5), 271–280 (2018)
31. Phipps, C.: Clearing space debris with lasers. SPIE Newsroom **20** (2012)
32. Pelton, J.N.: Examining the case for active orbital debris removal. In: New Solutions for the Space Debris Problem, pp. 39–51 (2015)
33. Vyas, S., Jankovic, M., Kirchner, F.: Momentum based classification for robotic active debris removal. J. Space Saf. Eng. **9**(4), 649–655 (2022)
34. Benvenuto, R., Lavagna, M.: Flexible capture devices for medium to large debris active removal: simulations results to drive experiments. In: 12th Symposium on Advanced Space Technologies in Automation and Robotics. ASTRA Noordwijk, The Netherlands (2013)
35. Forshaw, J.L., et al.: The active space debris removal mission RemoveDebris. Part 1: From concept to launch. Acta Astronautica **168**, 293–309 (2020)
36. Lavagna, M., et al: Debris removal mechanism based on tethered nets. In: Robotics and Automation in Space (iSAIRAS 2012) International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSAIRAS 2012) (2012)
37. Mark, C.P., Kamath, S.: Review of active space debris removal methods. Space Policy **47**, 194–206 (2019)
38. Stadny, K., Hovell, K., Brewster, L.: Space debris removal with sub-tethered net: a feasibility study and preliminary design. In: Proceedings of 8th European Conference on Space Debris (Virtual), Darmstadt, Germany (2021)

39. Reed, J., Barraclough, S.: Development of harpoon system for capturing space debris. In: 6th European Conference on Space Debris (2013)
40. AIRBUS: RemoveDEBRIS, Testing technology to clear out space junk. https://www.airbus.com/en/products-services/space/in-space-infrastructure/removedebris. Accessed 2023
41. Zhao, W., et al.: A simulation and an experimental study of space harpoon low-velocity impact, anchored debris. Materials **15**(14), 5041 (2022)