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Managing space debris: Risks, mitigation measures, and sustainability challenges

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ABSTRACT

Space debris consists of non-functional, human-made objects remaining in Earth's orbit or entering the atmosphere, creating significant challenges for space operations. Current surveillance systems track nearly 40,000 larger debris fragments, yet it is estimated that hundreds of thousands of smaller pieces and millions of tiny, untracked particles further contribute to the risk of high-velocity collisions. These objects threaten spacecraft integrity, satellite functionality, and the long-term sustainability of space activities. This review article investigates the hazards posed by space debris, providing an overview of its impact on satellite operations, crewed space missions, and orbital stability. It examines risk mitigation strategies, including the enforcement of stricter disposal regulations, advancements in satellite design for controlled re-entry or deorbiting, and the active removal of large debris objects. A structured approach to space debris mitigation is also explored, outlining a proposed four-step strategy: designing spacecraft for impact resistance, implementing advanced remote tracking and monitoring systems, integrating onboard detection and avoidance mechanisms, and developing impact mitigation strategies to minimize damage. Additionally, the importance of enhanced tracking technologies and international cooperation is underscored, as collective efforts are necessary to address this escalating issue. Increasing awareness of the growing risks and exploring practical mitigation strategies strengthens ongoing efforts to safeguard space activities and ensure the long-term viability of Earth's orbital environment.

1. Introduction

The low-Earth orbit (LEO) environment is increasingly congested with debris, consisting of discarded human-made objects such as dead satellites, spent rocket stages, and fragments resulting from collisions with micrometeoroids and other orbital debris [1]. Space debris was not a significant concern half a century ago; however, advancements in technology and the growing number of space missions have intensified the risks posed by existing debris [2]. As of 2024, the European Space Agency (ESA) tracked over 45,300 debris objects larger than 10 cm, about 1 million fragments ranging from 1 to 10 cm, and around 130 million pieces smaller than 1 cm currently orbiting Earth [3]. Without remediation, space debris is estimated to cause negative damage of approximately 1.95 % of global Gross Domestic Product in the long term [4].

According to ESA, a key challenge lies in the continuous dispersion of space debris, making the issue increasingly complex and risky to space travels. Additionally, while some debris is too small for detection, it remains large enough to interfere with spacecraft operations, particularly in near-Earth space [5]. The travel speed of debris plays a crucial role in the extent of damage sustained upon impact, regardless of its size [6]. For instance, the Cupola windows of the International Space Station (ISS), installed in 2010, have sustained minor damage due to collisions with millimetre-sized particles [7]. Since 1999, the ISS has performed 30

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collision avoidance manoeuvres to prevent impacts. The ESA reports that orbital collisions produce a range of effects: particle-sized debris can puncture spacecraft surfaces, debris of approximately 10 cm can severely impair spacecraft operations, and hypervelocity impacts can generate extreme stress, leading to fractures and structural failure [8]. While larger debris can be monitored and avoided, smaller undetectable objects present a persistent danger, necessitating improved tracking and mitigation strategies [9,10]. Fig. 1 illustrates space debris presently round the Earth.

Table 1 presents key statistics on space debris, emphasising the increasing risks posed to space missions and operational spacecraft. The continued accumulation of dead satellites as well as spent rocket stages and fragmentation debris in Earth's orbit necessitates mitigation strategies. The rise in space activity, with over 6380 rocket launches since 1957, has contributed to a growing population of objects in orbit, with approximately 10,290 satellites still in space, of which 7800 remain functional [12]. However, the persistent presence of non-operational satellites and other debris increases the probability of collisions, which could further exacerbate the problem. Space Surveillance Networks actively track and catalogue over 33,640 debris objects, but many smaller fragments remain undetected. These untracked particles, despite their size, pose a significant risk due to their high velocities [13]. The estimated 640+ break-ups, explosions, and collisions in orbit highlight the growing fragmentation of space debris, necessitating improved monitoring and mitigation efforts. The total mass of space objects in Earth's orbit now exceeds 10,800 tonnes, reflecting the increasing material congestion in both LEO and geostationary orbit (GEO).

To address these challenges, space agencies such as the European Space Agency (ESA) and the National Oceanic and Atmospheric Administration (NOAA) have intensified their efforts to develop advanced tracking systems, collision avoidance manoeuvres, and debris removal technologies [15]. Similarly, several scientific conferences are being held, international associations are being created, and efforts are being made to modify national standards to predict the development of the orbital environment and combat the threat of space debris [16]. Future missions increasingly focus on better spacecraft shielding, enhanced de-orbiting strategies, and improved sensor technologies to detect and track smaller debris fragments [17]. The development of international guidelines and policies plays a crucial role in ensuring the long-term sustainability of space activities and reducing the potential hazards posed by space debris.

Additionally, all spacecraft components must be optimised to minimise the risk of orbital impacts. Specifically, a more comprehensive integration of measures focused on protection, mitigation, and regulation is essential [18]. Other considerations include careful selection of materials for spacecraft construction, as well as advancements in energy, power, and propulsion systems to enhance sustainability and safety. However, these efforts often lack environmental sustainability and can be prohibitively expensive [19]. Current initiatives have largely failed to address the infrastructural challenge of space debris, as noted by Clormann and Klimburg-Witjes [20]. Considering these concerns, this study examines recent trends related to space debris, outlining the scope of the problem, the necessity of mitigation measures, and a proposed strategy for reducing debris-related risks.

Table 1
Significant facts on space debris (Source: Adapted from [14]).

Number of rockets launched since the start of the space age in 1957.	About 6380 (excluding failures)
Number of satellites these rocket launches have placed into Earth orbit.	About 15,430
Number of these still in space	About 10,290
Number of these still functioning	About 7800
Number of debris objects regularly tracked by Space Surveillance Networks and maintained in their catalogue.	About 33,640
Estimated number of break-ups, explosions, collisions, or anomalous events resulting in fragmentation	>640
Total mass of all space objects in Earth orbit	>10,800 tonnes
Key space agencies monitoring space debris	National Oceanic and Atmospheric Administration (NOAA) and the European Space Agency (ESA)

2. Types of orbital space debris

Space debris consists of non-functional human-made objects orbiting the Earth or re-entering the atmosphere with the potential of disastrous high-speed collision with aircraft or satellites, recognized by the United Nations Debris Mitigation Resolution as a severe threat to aerospace safety [21]. Since the beginning of the space age in the early 1960s, there has been more space debris, such as discarded launch vehicles, dead and abandoned satellites, parts of a spacecraft, and rocket fragments, than operational satellites [22]. Over 6000 satellites and rockets weighing over 30,000 tonnes have been launched into orbit in the past six decades [23]. Although most non-functional devices have plunged

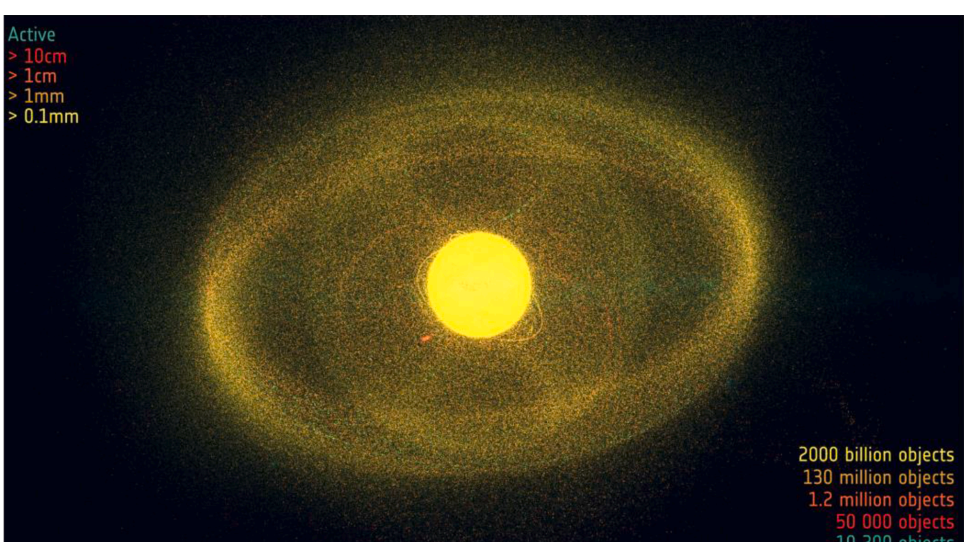

Fig. 1. Overview of space debris distribution around the Earth (Source: [11]).

into the atmosphere and burned out, more than 8000 tonnes of debris are still left in Earth's orbit. Also, the direct-ascent anti-satellite (ASAT) test undertaken by the Russian Federation on 15 November 2021 targeted Cosmos 1408, a derelict Electronic and Signals Intelligence (ELINT) Tselina-D-class spacecraft, released over 1500 pieces of large, trackable fragments. The global Space Surveillance Network (SSN) of the U.S. Space Force expects more Cosmos 1408 fragments to be added to the U.S. Satellite catalogue in the coming weeks and months [24].

Space debris is also associated with the "Kessler effect" [25], which involves serial collisions. Therefore, it could be blamed for the failure of spacecraft to launch into orbit, making orbital space economically unprofitable for commercial exploration [26]. Space debris may also interfere with astronomical observations [27] and make it difficult to accurately assess space conditions or manage space traffic [28]. As space activities are increasing with the deployment of at least 20,000 new satellites in LEO as part of new large-scale constellations and the rising number of space actors, these problems may exacerbate as these satellites should be replaced once every 5–10 years [28]. As such, the USA and several countries in the European Union have begun implementing measures, such as debris removal, to mitigate risks and safety concerns related to space debris [29].

NASA runs the Orbital Debris Program, based at the Johnson Space Center. It is recognized worldwide for its initiative in addressing orbital debris. The United States Government Orbital Debris Mitigation Standard Practices (ODMSP) was established in 2001 to address the increase in orbital debris in the near-Earth space environment. The ODMSP aims to limit generating new, long-lived debris by controlling their release during normal operations and accidental explosions and selecting a safe flight profile and operational configuration to minimize accidental collisions and post-mission disposal of space structures [7].

Table 2 presents an overview of some of the characteristics of space debris, indicating the need for space missions and spacecraft to pay special attention to the risks from debris to prevent any incidents. Because space debris range in size from millimetres to meters and orbiting at very high speed, approximately 17,500 mph in LEO, which are too small to be tracked but large enough to be a threat [7], extra-strong materials such as carbon nanotubes will be required to intercept them [30]. The objects' geometry, size, or shape are important parameters influencing satellite shape classification through machine learning to avoid a collision, as even millimetre-sized debris represents a risk to robotic missions [31]. Weeden [32], one of the most cited authors in this respect, argues that space debris resulting from collisions can be categorized into three types, as follows: i) collisions between a spacecraft with debris greater than 10 cm in diameter, resulting in destruction and thousands of additional pieces of debris; ii) collisions with objects ranging in size from 1 to 10 cm can be fatal to a spacecraft, less likely to produce debris; and iii) collisions with objects smaller than 1 cm, and considerable debris is unlikely to result. The detection capabilities have improved, and so additional uncatalogued objects are detected.

Table 2
Key features of space debris.

Features	Implications	Reference
Varied size and composition	Space debris can vary in size, leading to smaller or larger damages to satellites and spacecraft.	ESA [3]
Varied orbital altitudes	Space debris can be found at various orbital altitudes, including LEO below 2000 km, medium-Earth orbit (MEO) between 2000 and 35,786 km, and geostationary orbit (GEO) around 35,786 km.	Johnson [33].
Varied concentrations	The density of debris is highest in the lower orbits due to increased space activities.	Pardini and Anselmo [34]
Collision risks	Debris moves at high velocities, and even small fragments can pose a significant risk due to their kinetic energy.	ESA [35]
Tracking and Cataloguing	Space agencies around the world track and catalogue space debris to monitor its movement and predict potential collisions	NASA [7]

The use of small satellites and CubeSats is often criticised, since they have shorter lifetimes, and the decay to Earth is not immediate, creating additional space debris while threatening the space environment [36]. According to Muciaccia [37], there are different sources of debris: (a) mission-related debris (spacecraft's operation), originating less debris; (b) satellite breakup debris (destructive orbital disassociation), originating the most volume of debris; and (c) anomalous events (objects detaching from the main body), representing a minor source of concern, even without additional launches, since the first satellite in 1957, more space debris continues to be generated [35,32]. Still, there is yet to be a consensus on what type of space debris is to be prioritized for removal, even though it seems reasonable to remove debris of the largest sizes [38]. As part of a space battlefield, sensor space surveillance, able to scan a vast space domain, has been gaining attention in the context of an orbit catalogue and can contribute to efficient surveillance of space debris [39,40]. Space debris removal is projected to benefit greatly from on-orbit service technologies from servicing satellites, planning missions, and safety approaches in a limited time [41,42].

In 2002, The Inter-Agency Debris Coordination Committee developed the Space Debris Mitigation Guidelines, serving as the foundation for national space policy, legislation, and technical standards [8]. The guidelines established the procedures for designing, flying, and removing spacecraft from LEO not later than 25 years after their lifespans [43]. However, unfortunately, not all countries comply with it.

3. Comprehensive strategies for mitigating space debris risk

There are numerous measures currently being deployed to mitigate the risks associated with orbital debris, particularly concerning space travel and the long-term sustainability of satellites. As space activity increases, the accumulation of space debris poses a significant hazard to operational spacecraft. To address this challenge, a comprehensive strategy must be implemented to enhance spacecraft resilience, improve debris detection and tracking, and develop impact mitigation techniques [44].

Several lines of action can help combat the space debris threat, including a careful design of spacecraft and satellites, revision of mission programs, monitoring and predicting the movement of space debris, space traffic management, active space debris removal, collision avoidance measures and impact mitigation [15]. Fig. 2 illustrates a structured approach to reducing the risks posed by space debris, dividing the mitigation strategy into four key steps:

Step 1: Spacecraft Design for Impact Resistance

The first line of defence against space debris threat is the careful design of spacecraft and satellites to minimize their susceptibility to collisions. This line of action includes:

- Using resistant materials: Employing materials capable of withstanding impacts from small debris without critical damage. This strategy is crucial in improving spacecraft and rocket designs,
- Design simplicity: Reducing the number of exposed, fragile components to decrease vulnerabilities.
- Minimizing surface area: Crafting structures with lower cross-sectional areas to reduce the probability of being struck by debris.

Beyond protecting against impacts, designing spacecraft with a focus on minimizing their contribution to the space debris problem—such as by reducing fragmentation upon decommissioning—further aids in long-term mitigation efforts [45].

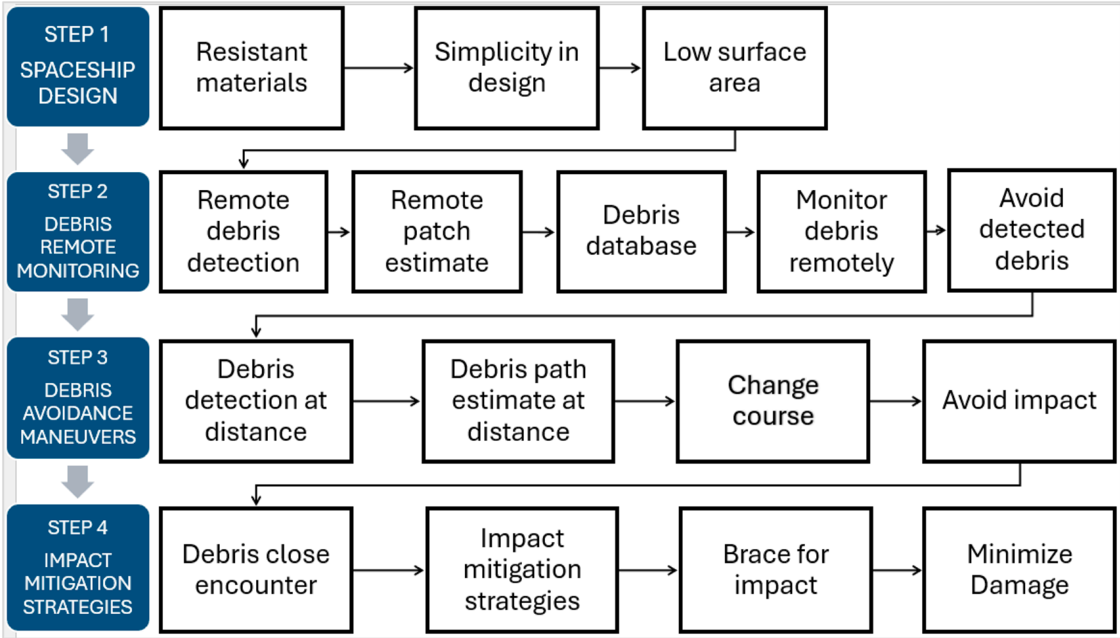

Fig. 2. Proposed strategy for minimising space debris risks (Source: Authors).

Step 2: Remote Monitoring and Tracking of Space Debris

The ability to monitor and predict the movement of space debris is crucial for risk avoidance. This step involves:

- Remote space debris detection: Identifying debris from Earth-based, orbital, or space-based observation systems.
- Estimating debris paths: Using tracking data to predict future trajectories and potential collision risks.
- Building a space debris database: Compiling detected debris data to facilitate ongoing monitoring and risk assessment.
- Continuous remote monitoring: Keeping real-time track of debris to provide timely alerts for operational spacecraft.

The integration of these measures ensures that spacecraft operators have the necessary information to proactively manage collision risks [46].

Step 3: Active Avoidance Manoeuvres

While monitoring provides critical data, spacecraft must also have the capability to actively avoid debris when necessary. This step includes:

- Onboard space debris detection: Installing sensors on spacecraft to detect potential threats in real time.
- Estimating impact trajectories: Using onboard computing to assess potential collisions and evaluate response options.
- Course correction: Adjusting the spacecraft's path to safely evade detected debris.

Implementing real-time detection and response mechanisms allows spacecraft to autonomously navigate around high-risk areas, greatly reducing the likelihood of an impact.

Step 4: Impact Mitigation Strategies

Despite the best efforts in avoidance, some encounters with space debris may be unavoidable. In these scenarios, mitigation strategies must be in place to minimize damage, including:

- Physical shielding: Deploying impact-resistant barriers or airbag-like protection systems to absorb kinetic energy.
- Active deflection: Using controlled projectiles to nudge debris off a collision course without causing fragmentation.
- Speed reduction techniques: Employing plastic nets or similar tools to decelerate debris before impact.
- Strategic spacecraft rotation: Orienting the spacecraft to ensure that debris impacts more resilient sections.

Each of these strategies plays a crucial role in protecting spacecraft from catastrophic failures while ensuring mission continuity.

The growing presence of space debris requires a multi-layered approach to risk management. Integrating resilient spacecraft design, robust tracking systems, proactive avoidance manoeuvres, and innovative impact mitigation techniques allow space missions to significantly reduce the dangers posed by orbital debris [13]. This holistic strategy enhances the safety of current missions and contributes to the sustainability of future space operations.

Implementing effective space traffic management systems can also help prevent future space debris. This involves coordinating satellite launches, managing orbital slots, and ensuring safe separation distances between satellites. Governments and international organisations should establish more strict guidelines and standards for space traffic management. As the space industry expands with increasing global participation, the challenge of managing space debris becomes more pressing. Table 3 highlights key future trends that illustrate a growing commitment to ensuring the long-term sustainability of space operations. These trends emphasize proactive removal, improved tracking, regulatory frameworks, and technological advancements to address the risks posed by space debris effectively.

One of the most significant trends is *Active Debris Removal (ADR)*, which focuses on developing technologies such as robotic arms and lasers to eliminate large debris fragments [48]. This initiative is crucial for reducing the risk of collisions and preventing the exponential growth of debris in orbit [15]. Contactless space debris removal is advantageous as there is no need to capture or dock with a space debris object, which considerably decreases the likelihood of an accident and loss of an active spacecraft [44]. Complementary to this effort are *End-of-Life Protocols*, which enforce stricter guidelines requiring satellites to deorbit safely after their operational lifespan, helping to minimize future debris

Table 3
Examples of future trends in space debris management, adopted and modified from [23,47].

Trend	Description	Potential Impact
Active Debris Removal (ADR)	Development of technologies to actively remove large pieces of debris, such as lasers or robotic arms.	Reduces collision risk, mitigates long-term debris accumulation.
End-of-Life Protocols	Implementation of stricter guidelines for deorbiting satellites at the end of their operational life.	Promotes sustainability and reduces future debris generation.
Tracking and Monitoring	Enhanced tracking systems using ground-based radars and space-based sensors to monitor debris more effectively.	Improves situational awareness and collision avoidance.
Space Traffic Management	Development of international frameworks for space traffic management to coordinate satellite operations.	Reduces the likelihood of collisions and optimizes orbital space usage.
Debris Mitigation Standards	Establishment of global standards for satellite design to minimize debris creation during launch and operation.	Encourages responsible satellite design practices.
Public-Private Partnerships	Collaborations between government agencies and private companies for debris management initiatives.	Leverages innovation and funding for debris mitigation solutions.
In-orbit Servicing	Technologies for repairing or refuelling satellites to prolong their lifespan and reduce the launch of new satellites.	Reduces the need for new satellites, thus minimizing debris.
Technological Innovation	Advancements in materials and propulsion systems aimed at making space operations less prone to debris generation.	Enhances long-term sustainability of space activities.
Education and Awareness	Programs aimed at increasing awareness and understanding of space debris issues among stakeholders.	Promotes better practices at all levels of the space industry.

generation[49]. Effective debris management also relies heavily on *Tracking and Monitoring* systems. Advances in ground-based radars and space-based sensors allow for more precise observation of space debris, improving situational awareness and enabling timely collision avoidance measures [50]. However, accurate tracking alone is not enough—*Space Traffic Management* frameworks are necessary to ensure coordinated satellite operations and prevent congestion in increasingly crowded orbital regions. The development of international policies will be essential for enforcing these protocols and maintaining safe orbital environments.

To further prevent debris accumulation, *Debris Mitigation Standards* are being established globally, encouraging responsible satellite design. By integrating debris reduction strategies during the design phase, such as modular components and controlled re-entry mechanisms, space agencies and private companies can significantly decrease the number of debris generated during launch and operation [51]. Collaboration plays a key role in space debris management. *Public-Private Partnerships* leverage the expertise and resources of both government agencies and commercial enterprises to drive innovation and funding for mitigation strategies. One such innovation is *In-Orbit Servicing*, which includes technologies for repairing, refuelling, and repurposing satellites to extend their operational life [47]. By reducing the need for new launches, these services contribute to a more sustainable orbital environment. Additionally, *Technological Innovation* in materials and propulsion systems is leading to safer and more efficient space operations. Advances in self-deorbiting materials and propulsion technologies designed to minimize debris production represent promising solutions for the future. Lastly, *Education and Awareness* initiatives aim to instil a culture of responsibility across the space industry. By educating stakeholders—including governments, private entities, and the public—on best practices for space debris mitigation, these programs help promote sustainable behaviours that benefit the global space community [52].

Together, these emerging trends signify a shift towards a more proactive and collaborative approach to space debris management. As space activity continues to increase, integrated actions combining technology, policy, and education will be essential in ensuring the long-term usability of Earth's orbital environment.

4. Concluding remarks

As this paper has shown, the growing amount of space debris poses a serious risk to satellites, spacecraft, and even human space missions. As of 2024, the ESA estimates that there are over 130 million pieces of debris orbiting Earth—ranging from more than 36,500 debris objects larger than 10 cm, around 1 million pieces between 1 and 10 cm, and 130 million fragments smaller than 1 cm orbiting Earth [3]. The U.S. Space Surveillance Network (SSN) is currently tracking approximately 45,300+ total objects, including active satellites, defunct debris, and other tiny fragments traveling at hypervelocity, which can lead to collisions that can cause catastrophic damage, leading to the Kessler Syndrome, where cascading impacts create an unsustainable orbital environment. The fact that space debris poses a real threat to space travel and space-based operations, suggests that urgent measures to address it are needed. Tracking and monitoring systems as outlined here, through Space Surveillance Networks, help predict potential collisions, allowing operators to manoeuvre satellites out of harm's way. ADR technologies, like robotic arms, nets, and harpoons, are being tested to capture and deorbit large debris. Additionally, designing satellites for end-of-life disposal—through controlled re-entry or moving to graveyard orbits—reduces future debris accumulation.

This review has provided a comprehensive assessment of the hazards posed by space debris, synthesizing existing research on mitigation strategies and technological advancements. By structuring the discussion around key risk factors and current intervention methods, this study highlights both the challenges and potential solutions necessary to ensure the long-term sustainability of space operations. Moreover, a structured approach to space debris mitigation is essential to minimizing risks and ensuring long-term sustainability. This approach involves four key proposed strategies: designing spacecraft with impact-resistant materials to withstand potential collisions, implementing advanced remote tracking and monitoring systems to improve situational awareness, integrating onboard detection and avoidance mechanisms to enable real-time responses to threats, and developing impact mitigation techniques that reduce damage from debris strikes. Incorporating these strategies strengthens spacecraft protection against debris-related hazards, enhancing mission safety and operational longevity. In the long term, parts of future spacecraft will necessarily need to be optimized to reduce possible impacts when in orbit. Specifically, greater integration of measures aimed at protecting mitigating, and regulating spacecraft is needed.

Other measures should include greater consideration of the materials used in spacecraft construction, as well as the energy, power, and propulsion systems. Such efforts are seldom environmentally friendly and can be extremely costly [17] but may increase safety in space-based operations. To prevent problems in the future, innovative ways to reduce the number of debris released need to be developed [2]. One way to reduce debris is by minimizing the number of mission-related debris released in the first place. Mission-related debris comes from three main sources: objects released from spacecraft deployment, refuse from onboard crew members, and products from rocket exhausts [28]. Such physical debris contributes significantly to the amount of space debris and is reported to have the longest orbital lifetime[53]. Regarding the physical features of the space shuttle being left behind, developers need to create more sturdy objects and methods for tethering materials so that it is not released easily or can be recovered [54].

Another major contributor to space debris is material released from explosions, requiring scientists and engineers to design spacecraft and transport systems with enhanced resistance to explosions. This may be achieved by using new materials with more resistant properties or by including the passivation of rocket bodies. Furthermore, spacecraft's exterior design needs to deploy materials more resistant to surface degradation [55]. In other instances, measures must be implemented to minimize debris from collisions, requiring the adoption of advanced protocols and techniques for collision avoidance. Similarly, objects capable of inducing collision should be removed from crowded orbital regions [56]. International cooperation is also important, as seen with guidelines from the UN Committee on the Peaceful Uses of Outer Space and the Inter-Agency Space Debris Coordination Committee. By combining improved regulations, advanced tracking, and innovative cleanup technologies, we can ensure safer and more sustainable space operations for future missions. The key lies in acting now—before the risks escalate beyond control.

Future research is required to develop active in-orbit "clean up" systems, which may gather and remove large debris, including dedicated vehicles to assist with removing objects [57]. Other options include debris removal that works by using passive debris removal satellites [47]. These decrease the kinetic energy by letting them penetrate debris particles, thus driving them into the atmosphere. In doing so, the orbital radius of the debris is reduced [58]. Also, some methods to accelerate the decay of objects that may end up as debris should be considered. This measure allows for objects to break down naturally and thus reduces the total amount of mass in a cross-sectional area and can be effective in reducing potential hazards [55]. As these initiatives are costly, potential funding options include a dedicated fund contributed by satellite operators during new launches or the imposition of fines when satellites become debris. Nations engaged in space operations must make concerted efforts to safeguard critical satellite infrastructure that supports communication, navigation, weather forecasting, and other essential services on Earth.

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CRediT authorship contribution statement

Walter Leal Filho: Writing – review & editing, Validation, Supervision, Investigation, Formal analysis, Data curation, Conceptualization. **Ismaila Rimi Abubakar:** Writing – original draft, Validation, Resources, Investigation, Formal analysis, Data curation. **Julian D. Hunt:** Writing – original draft, Resources, Investigation, Formal analysis, Data curation. **Maria Alzira Pimenta Dinis:** Writing – original draft, Resources, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors have declared that they have no financial or non-financial competing interests in the conduct of the present study. The manuscript has not been published previously (in part or completely), nor is it under consideration in another journal.

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Data availability

All data used for the research is available within the article.

References

[1] A. Bongers, J.L. Torres, Star wars: anti-satellite weapons and orbital debris, Def. Peace Econ. 35 (7) (2024) 826–845, https://doi.org/10.1080/10242694.2023.2208020.
[2] C.P. Mark, S. Kamath, Review of active space debris removal methods, Space Policy 47 (2019) 194–206, https://doi.org/10.1016/j.spacepol.2018.12.005.
[3] ESA, ESA Space Environment Report 2024, The European Space Agency, 2024. https://www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2024. Accessed: 12 April 2025.
[4] W. Nozawa, K. Kurita, T. Tamaki, S. Managi, To what extent will space debris impact the economy? Space Policy 66 (2023) 101580 https://doi.org/10.1016/j.spacepol.2023.101580.
[5] H. Klinkrad, Space debris: models and risk analysis, Springer Science & Business Media, 2006.
[6] K. Nomura, S. Rella, H. Merritt, M. Baltussen, D. Bird, A. Tjuka, D. Falk, Tipping points of space debris in low Earth orbit, Int. J. Commons 18 (1) (2024) 1–15, https://doi.org/10.5334/ijc.1275.
[7] NASA, Space Debris and Human Spacecraft, National Aeronautics and Space Administration, 2021. https://www.nasa.gov/mission_pages/station/news/orbital_debris.html. Accessed: 1 March 2024.
[8] ESA, Hypervelocity Impacts and Protecting Spacecraft, The European Space Agency, 2021. https://www.esa.int/Safety_Security/Space_Debris/Hypervelocity_impacts_and_protecting_spacecraft. Accessed: 15 February 2024.
[9] H.G. Lewis, G.G. Swinerd, R.J. Newland, The space debris environment: future evolution, Aeronaut. J. 115 (1166) (2011) 241–247, https://doi.org/10.1017/S0001924000005698.
[10] S.I. Nishida, S. Kawamoto, Y. Okawa, F. Terui, S. Kitamura, Space debris removal system using a small satellite, Acta Astronaut. 65 (1–2) (2009) 95–102, https://doi.org/10.1016/j.actaastro.2009.01.041.
[11] ESA, Model of the Distribution of Space Debris Around Earth, The European Space Agency, 2025. https://www.esa.int/ESA_Multimedia/Images/2025/04/Model_of_the_distribution_of_space_debris_around_Earth. Accessed: 21 April 2025.
[12] L. Hall, The history of space debris, in: Space traffic Management Conference, 5-6 November, Daytona Beach, Florida, USA, 2014.
[13] A.M. Bradley, L.M. Wein, Space debris: assessing risk and responsibility, Adv. Space Res. 43 (9) (2009) 1372–1390.
[14] ESA, Space Debris by the Numbers, The European Space Agency, 2023. https://www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers. Accessed: 2 December 2024.
[15] G.U.O. Jia, P.A.N.G. Zhaojun, D.U. Zhonghua, Optimal planning for a multi-debris active removal mission with a partial debris capture strategy, Chin. J. Aeronaut. 36 (6) (2023) 256–265, https://doi.org/10.1016/j.cja.2023.03.013.
[16] M. Bigdeli, R. Srivastava, M. Scaraggi, Mechanics of space debris removal: a review, Aerospace 12 (4) (2025) 277.
[17] H. Schaub, L.E. Jasper, P.V. Anderson, D.S. McKnight, Cost and risk assessment for spacecraft operation decisions caused by the space debris environment, Acta Astronaut. 113 (2015) 66–79, https://doi.org/10.1016/j.actaastro.2015.03.028s.
[18] S. Kaineg, The growing problem of space debris, Hastings Environ. Law J. 26 (2020) 277.
[19] A. Rossi, C. Colombo, K. Tsiganis, J. Beck, J.B. Rodriguez, S. Walker, F. Letterio, F. Dalla Vedova, V. Schaus, R. Popova, ReDSHIFT: a global approach to space debris mitigation, Aerospace 5 (2) (2018) 64, https://doi.org/10.3390/aerospace5020064.
[20] M. Clormann, N. Klimburg-Witjes, Troubled orbits and earthly concerns: space debris as a boundary infrastructure, Sci. Technol. Hum. Values 47 (5) (2022) 960–985, https://doi.org/10.1177/01622439211023554.
[21] NOAA, Does Space Junk Fall from the Sky? The Lethal Population of Space Debris, 2018. https://www.nesdis.noaa.gov/news/does-space-junk-fall-the-sky. Accessed: 19 April 2025.
[22] ESA, ESA's Space Environment Report 2021, The European Space Agency, 2021. https://www.esa.int/Safety_Security/Space_Debris/ESA_s_Space_Environment_Report_2021. Accessed: 15 February 2024.
[23] P. Zhao, J. Liu, C. Wu, Survey on research and development of on-orbit active debris removal methods, Sci. China Technol. Sci. 63 (11) (2020) 2188–2210, https://doi.org/10.1007/s11431-020-1661-7.
[24] NASA, Orbital Debris Quarterly, 26, NASA, Houston, 2022. March 2022, https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv26i1.pdf. Accessed: 12 March 2024.
[25] C. Bonnal, J.M. Ruault, M.C. Desjean, Active debris removal: recent progress and current trends, Acta Astronaut. 85 (2013) 51–60, https://doi.org/10.1016/j.actaastro.2012.11.009.
[26] N. Adilov, P.J. Alexander, B.M. Cunningham, The economics of orbital debris generation, accumulation, mitigation, and remediation, J. Space Saf. Eng. 7 (3) (2020) 447–450, https://doi.org/10.1016/j.jsse.2020.07.016.
[27] V.V. Adushkin, O.Y. Aksenov, S.S. Veniaminov, S.I. Kozlov, V.V. Tyurenkova, The small orbital debris population and its impact on space activities and ecological safety, Acta Astronaut. 176 (2020) 591–597, https://doi.org/10.1016/j.actaastro.2020.01.015.
[28] J.N. Pelton, A path forward to better space security: finding new solutions to space debris, space situational awareness and space traffic management, J. Space Saf. Eng. 6 (2) (2019) 92–100, https://doi.org/10.1016/j.jsse.2019.04.005.
[29] M. Undseth, C. Jolly, M. Olivari, Space sustainability: the economics of space debris in perspective. OECD Science, Technology and Industry Policy Papers, No. 87, OECD Publishing, Paris, 2020, https://doi.org/10.1787/a339de43-en.

[30] Y. Zhao, L. Miao, W. Hao, G. Zhao, J. Li, J. Li, Z. Liu, C. Sui, X. He, C. Wang, Two-dimensional carbon nanotube woven highly-stretchable film with strain-induced tunable impacting performance, Carbon 189 (2022) 539–547, https://doi.org/10.1016/j.carbon.2021.12.065.

[31] L.U. Yao, Z. Chang-yin, The basic shape classification of space debris with light curves, Chin. Astron. Astrophys. 45 (2) (2021) 190–208, https://doi.org/10.1016/j.chinastron.2021.05.005.

[32] B. Weeden, Overview of the legal and policy challenges of orbital debris removal, Space Policy 27 (1) (2011) 38–43, https://doi.org/10.1016/j.spacepol.2010.12.019.

[33] N.L. Johnson, Medium Earth orbits: is there a need for a third protected region?, in: 61st International Astronautical Congress, Prague, 2010. January 1, 2010, https://ntrs.nasa.gov/citations/20100007939. Accessed: 10 October 2024.

[34] C. Pardini, L. Anselmo, Evaluating the impact of space activities in low Earth orbit, Acta Astronaut. 184 (2021) 11–22, https://doi.org/10.1016/j.actaastro.2021.03.030.

[35] ESA, When Debris Disaster Strikes, The European Space Agency, 2021. https://www.esa.int/Space_Safety/Space_Debris/When_debris_disaster_strikes. Accessed: 19 April 2025.

[36] H.R. Hertzfeld, Unsolved issues of compliance with the registration convention, J. Space Saf. Eng. 8 (3) (2021) 238–244, https://doi.org/10.1016/j.jsse.2021.05.004.

[37] A. Muciaccia, Tesi di laurea Magistrale, Politecnico di MilPolitecnico di Milano, 2021.

[38] R. Leonard, I.D. Williams, Viability of a circular economy for space debris, Waste Manag. 155 (2023) 19–28, https://doi.org/10.1016/j.wasman.2022.10.024.

[39] A. Cavagna, M. Cencini, S. Melillo, L. Parisi, F. Piergentili, F. Santoni, A. Sozza, Stereovision for surveillance of Earth orbiting objects: two methods and their validation with synthetic data, Acta Astronaut. 190 (2022) 273–282, https://doi.org/10.1016/j.actaastro.2021.10.011.

[40] J. Huang, X. Lei, B. Li, J. Sang, H. Liu, Towards fast and reliable evaluation of detection performance of space surveillance sensors, Remote Sens. 14 (3) (2022) 483, https://doi.org/10.3390/rs14030483.

[41] Y.X. Cai, X.L. Wang, Y.Z. Luo, X.Y. Bao, Mission planning of safe approach and emergency evacuation to large slow-rotating space debris, Adv. Space Res. 69 (3) (2022) 1513–1527, https://doi.org/10.1016/j.asr.2021.12.022.

[42] M.H. Shan, J. Guo, E. Gill, Review and comparison of active space debris capturing and removal methods, Prog. Aerosp. Sci. 80 (2016) 18–32, https://doi.org/10.1016/j.paerosci.2015.11.001.

[43] United Nations Office for Outer Space Affairs, Space Debris Mitigation Guidelines of The United Nations Committee On The Peaceful Uses of Outer Space, United Nations, 2010. https://www.unoosa.org/pdf/publications/st_space_49E.pdf. Accessed: 2 February 2024.

[44] A. Ledkov, V. Aslanov, Review of contact and contactless active space debris removal approaches, Prog. Aerosp. Sci. 134 (2022) 100858, https://doi.org/10.1016/j.paerosci.2022.100858.

[45] G. Viavattene, E. Devereux, D. Snelling, N. Payne, S. Wokes, M. Ceriotti, Design of multiple space debris removal missions using machine learning, Acta Astronaut. 193 (2022) 277–286, https://doi.org/10.1016/j.actaastro.2021.12.051.

[46] A. Murtaza, S.J.H. Pirzada, T. Xu, L. Jianwei, Orbital debris threat for space sustainability and way forward, IEEE Access 8 (2020) 61000–61019, https://doi.org/10.1109/ACCESS.2020.2979505.

[47] V.V. Svotina, M.V. Cherkasova, Space debris removal–Review of technologies and techniques. Flexible or virtual connection between space debris and service spacecraft, Acta Astronaut. 204 (2023) 840–853, https://doi.org/10.1016/j.actaastro.2022.09.027.

[48] J. Guyot, S. Rouillon, Sustainable management of space activity in low Earth orbit, J. Environ. Econ. Policy 13 (2) (2024) 188–212, https://doi.org/10.1080/21606544.2023.2231402.

[49] K. Wormnes, R. Le Letty, L. Summerer, R. Schonenborg, O. Dubois-Matra, E. Luraschi, J. Delaval, ESA technologies for space debris remediation, in: 6th European Conference on Space Debris 1, ESA Communications ESTEC, Noordwijk, The Netherlands, 2013, pp. 1–8.

[50] A. Gorman, Space debris, space situational awareness and cultural heritage management in Earth orbit, in: M. de Zwart, S. Henderson (Eds.), Commercial and Military Uses of Outer Space, Springer, Singapore, 2021, https://doi.org/10.1007/978-981-15-8924-9_10. Issues in Space.

[51] C.R. Rajapaksa, J.K. Wijerathna, Adaptation to space debris mitigation guidelines and space law, Astropolitics 15 (1) (2017) 65–76, https://doi.org/10.1080/14777622.2017.1288513.

[52] M.R. Migaud, Protecting Earth's orbital environment: policy tools for combating space debris, Space Policy 52 (2020) 101361, https://doi.org/10.1016/j.spacepol.2020.101361.

[53] NOAA, Space Trash and Satellites - Science on a Sphere, 2016. https://sos.noaa.gov/catalog/datasets/space-trash-and-satellites/. Accessed: 19 April 2025.

[54] NASA, (n.d). Spacecraft to Remove Orbital Debris (MSC-TOPS-90), https://technology.nasa.gov/patent/MSC-TOPS-90 (Accessed: 12 April 2025).

[55] ESA, Mitigating Space Debris Generation, The European Space Agency, 2022. https://www.esa.int/Safety_Security/Space_Debris/Mitigating_space_debris_generation. Accessed: 2 April 2024.

[56] N. Takeichi, N. Tachibana, A tethered plate satellite as a sweeper of small space debris, Acta Astronaut. 189 (2021) 429–436, https://doi.org/10.1016/j.actaastro.2021.08.051.

[57] ESA. (n.d). Active Debris Removal. Space Safety. The European Space Agency. https://www.esa.int/Space_Safety/Space_Debris/Active_debris_removal (Accessed: 12 April 2025).

[58] M. Nitta, Y. Yoshimura, T. Hanada, Space debris mitigation by passive debris removal in large constellation, in: First International Orbital Debris Conference, Houston, Texas, 2019, pp. 1–7. https://www.hou.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6084.pdf. Accessed: 12 March 2024.