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Sustainable Operation System for Space Debris Management

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ABSTRACT

Space debris poses an escalating threat to sustainable space operations due to the accumulation of junk from decades of exploration and engineering. The orbital debris management system is explored, utilizing autonomous lasers, robotics, and AI techniques for integrated debris mitigation. Emphasis is placed on the critical need for international standards for sustainable space stewardship. Repurposing commonly observed debris as an in-situ renewable energy source is suggested by collecting and reusing existing junk. A case study is explored, evaluating the potential to reduce Earth resource launches. While promising technologies are emerging, international cooperation remains imperative to ensure the longevity of the space environment through coordinated and responsible debris prevention and mitigation practices. This paper examines the proposed integrated space debris management design for renewable energy generation. It highlights the importance of dual technology and policy efforts for sustainable space operations.

Keywords: Axiomatic design, Sustainable manufacturing, Space energy

INTRODUCTION

Managing space debris correctly has become increasingly important as the space industry has experienced unprecedented growth. An attempt to resolve the problem using laser techniques has shown considerable promise. Although laser technology offers promise, it is important to consider several aspects of space interactions, including electrostatics, gravity, and physiochemistry (Rusu, 2012). Considering this, AI and machine learning become increasingly important in debris management, offering advanced wired communications to pioneer the future of debris management (Huang et al., 2022). Moreover, examining existing techniques and innovations is increasingly important as the space industry evolves. Retrofitting and equipping current space stations as orbital space debris recycling stations demonstrate the innovative transition of energy (Laino & Vasile, 2023). During the increasing knowledge about the Earth's vulnerability, exemplified by the symbolic "blue dot," it has become evident that debris management has become increasingly important in light of increasing space activities providing solutions (Dalal 2021; UNESCO MGIEP 2023). Determining whether emerging ways to clean debris are long-term important from increasing pollutants in rains is inevitable. Introducing laser cleaning into spacecraft designs raises questions about risk management and appropriate control mechanisms (Dalal 2021; Fang et al., 2031).

These guidelines offer essential principles for space debris autonomous operations to ensure effective cleansing as space operations in international space comply with the lexicon. The preventive standardization could include factors such as environmental impacts (F3218), navigation protocols (F3244), and obstacle evaluations (F3265, F3327, F3381). Safety and efficiency in in-orbit operations depend on adapting these guidelines to space-specific criteria. This framework helps space debris managers design their operations based on these standards. (ASTM International Technical Committee F45 on Robotics, Automation, and Autonomous Systems 2021.)

LITERATURE REVIEW

With the help of a scoping review, the study explores how to design a debris remover suitable for this operational example when debris removal is followed by the design. For the design study, PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Scoping Review) guidelines for review are suggested (Munn et al., 2018). By comparing findings, technology principles could be solidified. Thus, the study incorporated the PRISMA-ScR method for accurate reporting with PRISMA-P with SCR qualitative assessments (Tricco et al., 2018; Moher et al., 2015; Page et al., 2021).

Queries utilized the TITLE-ABS-KEY function, targeting the domain using terms space debris-related topics, incorporating terms of “space debris”, further benefiting exploring “debris removal”. These searches were aimed at understanding designs optimized for collecting space obstacles. A visual representation spanning a decade (2013-2023) is depicted in Figure 1, detailing the academic trajectory of aerospace (Scopus, 2023).

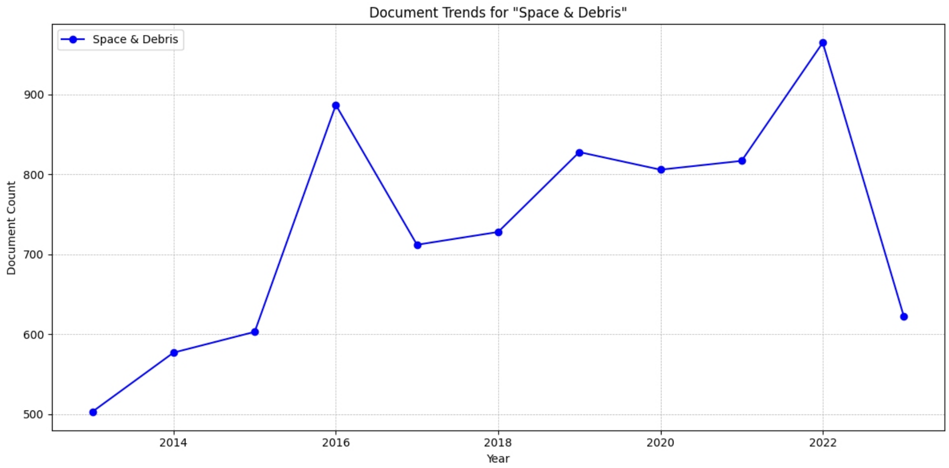

Figure 1: A The decreased surge for controlling space debris management in this study scope fills the gap well (Scopus, 2023).

Axiomatic design for space is used to assess further extension to the design parameters encompassed by the requirements to solve space debris with intelligent metasurfaces, algorithms, protocols, navigation, and collection methods. New space designs require specific functionalities such as tracking, coordination, and reliable communication in space. Exploring the technological adoption could steer the dimensionless values in physics modeling.

A SYSTEM FOR COLLECTING DEBRIS IN ORBIT

A space debris management systems engineer should have clear functional requirements (FRs) and design parameters (DPs) with sample N. FRs/FPs follow the axiomatic design theory (Suh 2007). A comprehensive approach addressing the dynamic nature of space objects is essential.

The space debris management design encompasses various functions: FR1 focuses on attaching to orbital debris safely, FR2 on maintaining a consistent towpath, FR3 on safe transit and collision avoidance in multiagent systems, and FR4 on returning debris to a predetermined function (adapted from Heilala, 2018). Design parameters (DPs) underpin functional requirements, providing the essential tools for their realization. DP1 involves mechanisms like robotic arms and magnetic latches for attachment. DP2 encompasses stabilization and thrust systems for transport. Advanced navigation tools, such as high-frequency sensors and radars, are key components of DP3, ensuring effective towing in unpredictable space conditions where angles can exceed normal (adapted from Heilala 2018). Exploring energy reuse in a circular economy is crucial for protecting electronics, with features from shifting to responsive communication(s) integration for autonomous control for safe re-entry promoted in DP4. The FR above/DPs are shown in Table 1.

Table 1. This table shows simply the functions and design related to the standardization requirement arranged by a case study (N = 4).

N	Functional Requirements (FRs)	Design Parameters (DPs)
1	Attach safely to in-orbit automotive	Robotic arms, magnetic latches
2	Maintain a stable tow with minimal deviations	Thrust and stabilization systems
3	Return debris safely to the Earth's surface	Advanced navigation; electronics' protection
4	Energy electronic protection for re-entry	Steering metasurface(s) for total control

Additionally, exploring sensing control during re-entry ensures debris safety (Lindner et al., 2022); otherwise, risks like energy loss or communication breakdown can occur as hazards. In decoupling, the effect becomes equilibrium with the DP4 feature.

Furthermore, FR5/DP5 would cover the design of robust thrust and navigation systems, with feedback and control features that contribute to making missions reliable and precise. Towing space debris, however, has its limitations and inefficiencies. By integrating advanced machine learning and fluid dynamics, this mechanism entails complex processes, including heat transfer and particle flow analysis with proper material syntheses in a proper design, which would correspond to design automation of a self-processing debris machine design. The space debris manager's algorithms, communication automation, and assemblies must be developed and innovated to converge these processes.

Table 2. This table explores the development results for parametric space debris management. The axiomatic design matrix for the one operation of the space debris management becomes functional requirement (FR) and design parameter (DP). As a synthesis, FRs include attaching safely to in-orbit debris (FR1), maintaining a stable tow with minimal deviations (FR2), and returning debris safely to the Earth's surface (FR3). It incorporates DPs such as robotic arms or magnetic latches to meet these FRs, thrust and stabilization systems to meet FPs, and advanced navigation tools to meet FPs. It features care electronics with care (like shieldings) to meet FPs.

	DP1	DP2	DP3	DP4
FR1	X			
FR2		X		
FR3			X	
FR4				X

Thrust Dynamics Axiomatic Usefulness for Space Management

Exploring the fusion of data-driven methodologies in the space operations field could demonstrate remarkable progress. Combining these methods with AI capabilities, such as neural networks, can revolutionize practices in managing space debris. As the study of dynamics advances from coupling, these data-driven strategies are incorporated, namely, the integration of aerodynamic forces and propulsions and using real-world data to refine multi-propulsion performance. Whichever number determines the coupling dynamics allows the downshifting of thrusts and the revmatching of upshifting the thrust propulsions. Additionally, simulations indicate that static magnetic fields are highly effective in distinguishing space debris. The integration of AI capabilities, especially in simulation training, could result the development of superior design. The additional understanding of the complex forces operation in space can be used to optimize space operations. A clear indication of this progress can be seen in the emergence of neural network-centric methods that allow the tracking and reconstruction of unknown objects, which can be critical in managing space debris rotational dynamics.

CONCLUSION

Several factors were explored in managing space debris, including using advanced technologies, international collaborations, and developing holistic best practices. With the ongoing growth of space exploration, it is imperative to address the challenge of space debris with proper lifecycle management.

The exploration must be paired with standardized procedures to ensure long-term sustainability. This requires technical competence and creative vision. It is essential to ensure the sustainability of space operations with realistic design by combining innovation with international cooperation and respect for the unique aspects of the space environment to become possible.

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