Space debris management as trigger for data-driven, servitized, and circular in-space manufacturing in low Earth orbit

Claudio Sassanelli[1](✉), Angioletta R. Catalano[2], Paolo C. Priarone [2], Luca Settineri[2], Brendan P. Sullivan[3], Salvatore Digiesi[1], and Sergio Terzi[3]

[1] *Department of Mechanics, Mathematics and Management, Politecnico di Bari, Via E. Orabona 4, Bari, 70125, Italy*
[2] *Department of Management and Production Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy*
[3] *Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133, Milano, Italy*

Abstract

In Low Earth Orbit (LEO), human activities have increased the amount of orbital debris alongside naturally orbiting micrometeoroids, significantly impacting this environment. This poses a significant threat to long-term space structures and human space operations, as high-speed collisions with debris and meteoroids can result in serious consequences. Addressing this challenge falls within the domain of On-orbit Servicing, Assembly, and Manufacturing (OSAM), which includes activities such as debris detection, docking, mooring, and collision avoidance. Establishing an In-Space Manufacturing (ISM) factory in LEO, capable of using existing materials to produce components, assemblies, and services directly in space, holds promise for reducing orbital debris, extending space missions as well as spacecraft and satellite lifecycles. In addition, such a system could reduce logistical dependencies between ground-based and on-board systems. This paper reviews the implementation of ISM systems in LEO and outlines various strategies for managing space debris. The findings suggest that an ISM system equipped to detect, collect, process, and store debris, meteoroids, and decommissioned spacecraft is consistent with the principles of digital servitization, Industry 4.0, and data-driven circular manufacturing.

Keywords

In-space manufacturing, Space debris, Circular economy, Digital servitization

1. Introduction

The space environment surrounding the Earth is conventionally divided into three bands, depending on the altitude: (*i*) Low Earth Orbit (LEO) from 415 to 2,000 km, (*ii*) Medium Earth Orbit (MEO) from 2,000 to 35,876 km and (*iii*) Geostationary Earth Orbit (GEO) beyond. In over 60 years, mankind has been able to explore most of them, revealing and defining their inner characteristics. However, the area that humans have most influenced is LEO, along with the lunar surface. As human activity in LEO has increased, the presence of space debris has also increased. This is in addition to the micrometeoroids that are already naturally in orbit in this space. Taken together, they represent a significant problem that needs to be addressed [1]. In this context, long-lived space structures and manned space activities face the potential threat of high-velocity collisions with debris and meteoroids, leading to the Kessler syndrome. This phenomenon, characterized by a cascading effect

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claudio.sassanelli@poliba.it (C. Sassanelli); angioletta.catalano@polito.it (A. R. Catalano); paoloclaudio.priarone@polito.it (P. C. Priarone); luca.settineri@polito.it (L. Settineri); brendan.sullivan@polimi.it (B. P. Sullivan); salvatore.digiesi@poliba.it (S. Digiesi); sergio.terzi@polimi.it (S. Terzi)
ORCID: 000-0003-3603-9735 (C. Sassanelli); 0000-0003-3345-4829 (A. R. Catalano); 0000-0003-4226-7697 (P. C. Priarone); 0000-0002-5816-170X (L. Settineri); 0000-0001-8678-4771 (S. Digiesi); 0000-0003-0438-6185 (S. Terzi)

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of debris collisions, could hamper space exploration and satellite utilization [2]. Since the beginning of space travel, dedicated missions and experiments have been designed to explore the LEO environment and to sample, catalog and manage the satellites, spacecraft, debris, and meteoroids orbiting there. In particular, debris detection, tracking, docking and mooring, together with collision avoidance and orbit prediction, are some of the actions and strategies aimed at controlling the increasingly complex traffic in the LEO environment. These fall under the domain of On-orbit Servicing, Assembly, and Manufacturing (OSAM). Besides adopting the so-called 'sufficiency attitude' (i.e., prioritizing essential needs over excess consumption, promoting sustainability within planetary boundaries by minimizing waste and resource usage), a solution could be to establish a factory in space that can use resources sourced directly from LEO, thereby eliminating the need for regular resupply missions from Earth for spare parts and consumables. This could also facilitate the production and delivery of goods and services in space, which could become a strategic measure to mitigate the accumulation of debris in near-Earth orbit. An In-Space Manufacturing (ISM) system equipped to detect, collect, manage, process, and store debris and meteoroids, as well as obsolete and derelict spacecraft or satellites and their components, could contribute (*i*) to extend the duration of space missions by reducing reliance on component durability and the need for crew return in case of emergency, but also (*ii*) to reduce the impact of spacecraft and satellites during their life cycle by avoiding logistics between on-ground and on-board systems, thereby limiting the number of Earth-to-space missions that would cause further generation of space debris. This should be in line with the key principles of Circular Manufacturing (CM) and Industry 4.0, in particular through the implementation of Digital Servitization (DS) and data-driven paradigms. Via OSAM strategies, ISM systems have the potential to promote not only remediation efforts but also mitigation measures for the phenomenon of space debris increase. Therefore, In-Space Manufacturing (ISM) can bring advantages against the traditional 'Earth-build-and-launch approach' from different environmental, economic, and logistic perspectives [3]. This paper aims at grounding the setting of an ISM system operating in LEO, proposing all the types of activities that could be implemented to manage space debris. Section 2 provides an overview of the research context, offering insights into the background and scope of the study. Section 3 presents the main discussion and Section 4 concludes the paper by highlighting the main findings, discussing limitations, and outlining further developments.

2. Satellites and debris in LEO: OSAM potential implications

Satellites are artificial objects placed in orbit around the Earth to perform various functions, including telecommunications, Earth observation, and scientific research. In particular, small satellites (also referred to as 'smallsats') are an emerging class of spacecraft that incorporate the latest software and hardware improvements at lower dimensions. More than 26,000 smallsats (weighing less than 500 kg) are expected to be launched between 2023 and 2032 (equivalent to about 543 ton/year), compared to less than 700 launched between 2006 and 2015 [4]. Behrens and Lal [5], while exploring the trends and drivers that may influence the future of the global smallsats ecosystem with respect to the development and use of small satellites, identified four potential scenarios that illustrate different possible outcomes for the small satellite sector over the 2027-to-2032 timeframe. Such scenarios are not to be intended as predictions, but rather as tools to examine the implications of various factors and uncertainties:

- *Scenario 1 - "Two or more large smallsat constellations in Low Earth Orbit"*: commercial smallsat constellations provide affordable broadband Internet and optical imagery services, driven by high demand, low cost, and technological innovation.
- *Scenario 2 - "Smallsats achieve near-parity with larger satellites in remote sensing"*: small satellites perform most of the functions of larger satellites, particularly in remote sensing, with comparable quality and reliability, facilitated by miniaturization, standardization, and diversification.
- *Scenario 3 - "Unsafe for satellite operations in Low Earth Orbit"*: the proliferation of smallsats and debris in LEO creates hazardous conditions that threaten space activities due to a lack of regulation, coordination, and debris mitigation.

- *Scenario 4 - "On-orbit servicing, assembly, and manufacturing of spacecraft a reality"*: smallsats serve as components for larger spacecraft that are built and maintained in orbit, driven by advances in robotics, automation, and additive manufacturing.

Scenarios 1 and *2* illustrate the evolutionary developments within the current dynamics of LEO, with the expansion of existing capabilities through the use of commercial smallsat constellations. *Scenarios 3* and *4*, instead, address much higher concerns for the sustainability of satellite operations in LEO due to debris proliferation and pioneering developments in OSAM. The latter could have a very high impact on long-duration human spaceflight and *in-situ* resource utilization (ISRU), a pivotal shift for more complex autonomous space infrastructure. According to *Scenario 3*, the proliferation of small satellites and debris in LEO increases the risk of collision for satellites in the 500-1200 km range, potentially hindering the commercialization of LEO without government support. In addition, if higher orbits must be reached, smallsats would require higher operating costs and bulkier spacecraft to function, due to the increased radiation to which they are subjected to and to the higher power requirements, resulting in greater launch and maintenance costs. In *Scenario 4*, governments and the commercial sector would utilize permanent platforms in LEO and GEO for OSAM. Small satellites would still be necessary but launching them from Earth would be less necessary due to such on-orbit capabilities. Hosted payload platforms would be common, enabling economic competitiveness for large satellites and tailored solutions for specific applications. The key drivers for enabling *Scenarios 3* and *4* include the demand for (*i*) OSAM systems, (*ii*) government funding and regulatory frameworks for on-orbit activities, (*iii*) technologies such as robotics and automation, (*iv*) modularity and standardization, and (*v*) Space Situational Awareness systems (SSA) tailored to OSAM needs. The realization of OSAM within the next decade is unlikely due to its early stage. However, substantial funding from public and private sectors to support OSAM platforms capable of human or robotic operation in LEO [1] would advance eventual fruition of *Scenario 4*. This paradigm may further shift if In-Situ Manufacturing (ISM) via OSAM becomes a more cost-effective solution for future space activities, potentially influencing both remediation and mitigation approaches in space debris management. Overall, as the small satellite sector continues to grow rapidly, the adoption of innovative technologies and risk mitigation strategies is essential to ensure their success and long-term sustainability. Particularly, effective management of space debris and the ability to operate safely in orbit are crucial for the future of small satellites.

3. Digitalization and Circular Manufacturing for space debris management

The 'twin transition' of digitalization and environmental sustainability has significantly impacted manufacturing on Earth. Industry 4.0 (I4.0) introduces the concept of the Smart Factory, leveraging nine key technologies to revolutionize production systems and products. These technologies also serve as enablers of Circular Economy (CE) in manufacturing, promoting resource cycling and efficiency [6, 7]. Acerbi et al. [8] proposed the notion of data-driven Circular Manufacturing (CM), emphasizing the role of technologies and evaluation methods in implementing CM strategies (such as circular design, remanufacture, and cleaner production). By classifying data into various categories and employing Digital Servitization (DS) [9], manufacturers can effectively adopt and manage CM strategies, influencing business models and supporting the transition towards sustainability in manufacturing [10]. The transformation of manufacturing on Earth, driven by digitalization and environmental sustainability, can be mirrored in the management challenges posed by space debris.

Buchs and Bernauer [11] conducted a literature review on the challenges associated with (*i*) managing space debris, proposing also market-based policy interventions to incentivize efforts in both space debris (*ii*) mitigation and (*iii*) remediation (Table 1).

The authors categorized two mechanisms for removing non-functional objects from orbits, i.e. atmospheric drag and direct retrieval, and grouped the technical approaches to address debris collision risk in three categories: (*a*) Space Situational Awareness (SSA), (*b*) Space Traffic Coordination or Management (STC/STM), and (*c*) Space Environment Management (SEM). SSA was highlighted as crucial for providing essential data related to the Space environment, underpinning all debris management activities.

The study emphasized the need for remediation actions to address the unsustainable expansion of the debris population, presenting three solutions: Active Debris Removal (ADR) [12], Just-in-time Collision Avoidance (JCA), and Debris Resurrection (DR). While JCA and DR are yet to be implemented, the first ADR uncrewed debris removal mission is projected for 2025 [13]. Debris mitigation actions instead are guided by the goal of reducing the causes of space debris, going even further upstream of the issue, for example by preventing explosions and boosting satellite dependability. Mitigation will probably fall short due to limited compliance with international rules and space environment modelling. For this reason, a systematization of debris management-related activities has been suggested. Indeed, LEO is affected by the commons challenges already registered for natural resources on Earth due to its accessibility and the possibility of providing resources from it [14]. Just as terrestrial resources face the risk of depletion and mismanagement due to unregulated use, LEO is similarly threatened by the accumulation of debris. This situation reflects a broader issue of communal resource management, wherein the absence of coordinated efforts and regulations can lead to the deterioration of a shared space [14], thereby posing significant risks to the operational integrity of satellites and other space endeavors. This challenge draws a critical parallel to recent efforts in terrestrial production systems, which are being redesigned to achieve net-zero levels through the integration of Industry 4.0 technologies aligned with CM and DS paradigms. Consequently, it becomes likely that ISM could require a similar redesign, underscoring the necessity for innovative and collaborative approaches to both terrestrial and extraterrestrial resource management. Furthermore, conventional satellite lifecycle concepts, encompassing design, manufacturing, assembly, and disposal, necessitate disruption, extending towards innovative concepts such as OSAM [15]. Although still in its early stages, ISM holds significant potential as a transformative technology that can revolutionize space access. Contrary to conventional Earth-build-and-launch strategies, ISM presents several advantages, particularly in eliminating launch-related complexities such as scheduling, risk, heavy loads, and vibrations [3]. Consequently, ISM may necessitate alignment with diverse manufacturing paradigms currently in use on Earth.

Moreover, the implementation of DS in ISM systems, encompassing activities like OSAM alongside additional in-space logistics, is needed. Integration with remediation-driven assets for ADRS and waste management is also essential for ISM. However, to effectively exploit collected debris in LEO, ISM must adopt mitigation- and data-driven CM strategies. This requires the incorporation of new technologies to facilitate data-driven CM practices and intelligent operational services. These advancements should encompass not only I4.0 technologies but also novel satellite and spacecraft types such as Cubesats, Smallsats, and OSAM platforms, necessitating tailored integration and interoperability measures. Conversely, modular, plug-and-play (PnP) satellite concepts and readily available commercial off-the-shelf (COTS) components will be pivotal in shaping forthcoming Space operations, facilities, and associated businesses. These resources will facilitate OSAM activities, complemented by new components of ISM systems as cutting-edge upgradable platforms intended for permanent placement in LEO. Additionally, orbital depots could serve as on-orbit warehouses to support space logistics operations.

Table 1. Space debris management activities (adapted from [11]).

Type of activity:	Description:
(*i*) *Debris collision risk technical approaches*	
Space Situational Awareness (SSA)	Detect, catalog, and predict object orbits for collision avoidance and safe space operations.
Space Traffic Coordination (STC) and Space Traffic Management (STM)	STC: Plan, coordinate, and synchronize activities in space, asking for international collaboration. Since just a tiny portion of space objects are movable, it only affects a small portion of them. STM: National licensing and monitoring of spacecraft, as a supplement to STC.
Space Environment Assessment (SEA) and Space Environment Management (SEM)	Implement mitigation and remedial procedures once SEA has assessed the degree of risk and their cost-effectiveness, to prevent the population of uncontrollable space objects from colliding, carried out by STM and SEM, respectively

(*ii*) *Debris population remediation activities*	
Active Debris Removal (ADR)	Active removal of derelict objects to decrease collision probability
Just-in-time Collision Avoidance (JCA)	External influence the trajectory of one of the two pieces of debris before collision time, to reduce collisions likelihood
Debris Resurrection (DR)	Nano-tugs use to upgrade derelict objects with collision avoidance capabilities
(*iii*) *Debris population mitigation activities*	
In Space Manufacturing (ISM)	Reduction of the sources of space debris (e.g. avoiding explosions, increasing satellite reliability); DS (OSAM); CM strategies

4. Conclusions

This paper underlines, among other technical solutions, the need of establishing an ISM system in LEO for managing space debris. The proposed ISM system should align with principles of digitalization and Industry 4.0, playing a pivotal role in both remediating and mitigating space debris. To address the Kessler syndrome, ISM systems should integrate not only remediation but also mitigation actions due to the higher costs associated with the former [11]. This necessitates disrupting conventional satellite lifecycle concepts and embracing new approaches like OSAM [15]. However, significant barriers exist, including the need for substantial financial resources, regulatory frameworks, technological innovation, and integration challenges. A systematic literature review is recommended to explore waste management strategies in ISM and trigger data-driven dynamics. Further research is required to understand infrastructure needs for ISM, including technology adoption, spacecraft development, debris management strategies, and collision risk management approaches. Demanufacturing practices and energy input requirements should be explored for ISM, ensuring feasibility and sustainability. Additionally, a conceptual data model promoting data-based collision management should be extended to ISM systems in LEO.

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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