Factory in space – shaping the scenario

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Abstract: Interest in long-term space exploration has continued to gain interest over the past decade. This increasing interest demands a shift in the designing and manufacturing of space equipment. Currently, several space structures depend on many constraints mainly linked to the launch systems, affecting cost, volume, and mass. The factory in space is a concept that proposes the manufacturing & assembly of parts directly in space rather than on Earth. The capability to launch single components of a large structure to build and assemble in space robotically would allow for more flexible missions with onsite repair and recycling capabilities of large space infrastructures, including habitats, giant telescopes, and mission platforms. Factory in space leads to cost reduction due to initial take-off weight decrease and the decline in the dependence on spare parts. This paper employs a narrative literature review to understand the research efforts to integrate manufacturing systems in space exploration. Waste management is recognized as a critical factor in the efforts to achieve the factory-in-space concept. Implementing the 3Rs (Reduce, Reuse, and Recycle) can help manage and reduce space waste. Finally, areas of further research are highlighted to understand further and advance the possibilities of factory-in-space.

Keywords: Factory in space, Waste management, Manufacturing, Recycling

I. INTRODUCTION

Space exploration has always embodied humanity's boundless ambition for expansion and discovery. From the historic Moon landings of the late 1960s and early 1970s to recent endeavors in Low Earth Orbit (LEO), human spaceflight has captivated society. However, the significant costs and immediate impact on daily life associated with space travel have sparked debates [1]. The fatal tragedy of the Soyuz 11 and Columbia spacecraft serves as a reminder of how hostile and dangerous extraterrestrial exploration is. However, Amid these debates, the potential for scientific breakthroughs in space remains undeniably promising [2]. The satellites, which were designed to test initial capabilities in Earth's Orbit, offered vital breakthroughs in communication, global positioning, and weather forecast [3]. Long-term space exploration has gained increasing interest, evident through the work of both governing bodies and private entities, such as the manufacturing and continuous development of the International Space Station (ISS) by NASA and ESA, several human spaceflights by Blue Origin, and the groundbreaking advent of reusable rockets by SpaceX [4] to mention a few. Yet, realizing its success requires a deeper understanding of safety considerations.

The well-being and safety of space travelers, particularly the crew members, are paramount during space missions [2], [5], [6]. Ensuring their survival entails meticulous planning and provisioning of necessary equipment and supplies. Equally important is the effective management and transportation of these resources [7]. The logistical challenges of supplying and maintaining equipment and supplies in space are heavily influenced by constraints tied to launch systems, impacting cost, volume, and mass [8]. To address these challenges and enhance the efficiency of space missions, advancements in materials, such as composite materials, and manufacturing techniques like Additive Manufacturing (AM) have played a pivotal role. Additionally, the introduction of reusable launchers has significantly reduced costs and increased accessibility to space.

One promising solution that addresses the challenges of transporting large single-component structures during extended space missions is the concept of Factory in Space (FIS) [8]. FIS advocates for performing manufacturing and assembly processes directly in space, circumventing logistical obstacles. An essential aspect of the FIS concept revolves around waste management in space. As space exploration progresses, waste, including biological waste, clothing, packaging, and solid structures, poses a pressing issue that requires careful disposal strategies [9]. The conventional practice of disposing waste by burning it up in the Earth's atmosphere using empty supply vehicles becomes impractical for missions conducted far from Earth. Thus, alternative waste management methods aligned with the objectives of space travel need to be explored.

In this regard, the reduce, reuse, and recycle (3Rs) design, rooted in the principles of the traditional circular economy (CE), emerges as a promising approach [10], [11]. The 3Rs concept aims to minimize resource consumption and maximize resource utilization in space, creating a closed-loop system that aligns with the sustainable development goal of "responsible production and consumption" and enables the establishment of a self-sustaining factory ecosystem [12]. The limitation of resources in isolated colonies, such as space stations, necessitates finding ways to prolong the use of materials and goods, creating multiple product lifecycles. As space exploration expands its horizons, establishing a closed loop that emphasizes recycling and reuse not only reduces reliance on Earth for resupply but also addresses ethical concerns regarding space waste generation and the preservation of extraterrestrial ecosystems [13].

To fully grasp the implications and potential of integrating manufacturing systems in space exploration, an overview of the materials typically involved in space missions is needed. It is worth noting that apart from the waste generated in the core module, there is also waste resulting from the launch and entry of man-made objects into outer space, commonly known as space debris or "space junk" [14]. Space debris, as defined by NASA [15], can be natural materials and man-made debris that are in the Earth's Orbit. Orbital debris is a class of space debris that only includes artificial items that have been launched into space [16]. Murtaza et al. [17] reported on the threat posed by the accumulation of orbital debris by concluding that the threat of a catastrophic occurrence increases if the population of orbital debris is not reduced. Moreover, Clormann et al. [18] argue that space debris is anything but a distant outer space phenomenon; rather, it is a subject of responsibility and sustainability. For simplicity, the current work focuses on the waste generated in the core module during space missions.

This paper explores waste disposal methods and techniques employed during space explorations, drawing insights from existing literature. Understanding the materials and waste generated during space exploration serves as a foundation for examining space manufacturing trends and possibilities. Finally, the paper delves into the space economy and investigates the adoption of a circular economy within this context. By synthesizing current knowledge and exploring future prospects, this review contributes to a better understanding of the feasibility of sustainable space travel.

II. SPACE MISSION WASTE MATERIALS

A. *Waste material*

Understanding and shaping the scenario of a FIS requires a comprehensive understanding of the fundamental aspects and requirements of space flights. However, obtaining detailed information about inventories for space missions or items on the ISS has proven to be a challenge due to proprietary considerations [19]. Nonetheless, there have been several reports on the waste generated during space exploration, which can provide valuable insights for understanding the requirements and shaping the scenario of FIS.

In the context of this research, it is crucial to comprehend the architecture of a space mission in order to define the concept of a FIS. NASA researchers have reported on the Gateway mission, which involves a vehicle and its crew stationed at the Earth-moon L2 liberation point for a scientific study of the moon [9]. The core module of the mission accommodates a crew of four and relies on solar electricity and large solar arrays for power at the L2 point. Another module, such as ORION, is responsible for transporting the crew and necessary supplies. The weight of the core module varies depending on the mission's duration, ranging from approximately 28,500 kg for missions lasting less than 90 days to around 45,570 kg for missions lasting between 90 and 180 days. Additionally, a logistics module delivers approximately 2700 kg of supply cargo.

To evaluate the type of waste generated during these missions, two mission scenarios were considered: the Gateway mission and a Mars exploration mission. The Gateway mission was further divided into phase I (24 to 90-day trip) and phase II (90 to 180-day journey). A detailed waste model for space exploration was developed, categorizing the generated waste types, as presented in Table 1.

Table 1. Mission waste summary [9]

	Gateway Mission		**Mars 1-way Transit**
Waste Type	**P-I (Kg)**	**P-II (Kg)**	**Mars DRA 5.0 (KG)**
Clothing	15-18	58-115	58-115
Paper/Office Supply	1-2	2-5	7
Wipe/Tissue	13-49	49-99	148
Towel and Hygiene	9-35	35-71	106
Packaging Foam	4-14	14-29	43
Other crew supply	4-13	13-27	40
Food and Packaging	24-127	127-253	380
EVA supplies	1-4	4-7	11
Human Waste	43-162	162-324	485
Waste Mgt Sys	16-58	59-116	174
Total	139-523	523-1046	1569

B. Waste management techniques

Researchers to date have evaluated two primary methods for waste disposal. The first method involves mechanically disposing of raw waste through an airlock. The waste is packaged as individual nodules called "trash footballs" and then ejected using either high-velocity or low-velocity impact [9], [20]. However, it has been reported that the high-velocity disposal method is not feasible due to issues such as mass, size, power, and cost. On the other hand, there has been an assessment of processing waste into gases that can serve as propellants [9]. For short missions, the propellant derived from processed waste could easily fulfill the spacecraft's yearly station-keeping requirements. Additionally, for smaller spacecraft like a robotic mini lander used for lunar studies, the waste-derived propellant could enable the landing of a 200kg payload on the lunar surface annually. However, it has been noted that there is no significant benefit for large spacecraft, such as those involved in a Mars mission.

Apart from waste management and recycling, researchers have also investigated the behavior of various polymers in space with the intention of utilizing them as raw materials for manufacturing. Studies conducted by NASA, such as the Long Duration Exposure Facility (LDEF) study, have shown that ultraviolet radiation can induce cross-linking in polymers. The Materials International Space Station Experiment (MISSE) has demonstrated that polymers are susceptible to erosion when exposed to atomic oxygen [21]. Additionally, MISSE has revealed a significant decrease in the mechanical properties of polymer materials exposed to the space environment. It should be noted that these materials were placed on the exterior of the ISS, thus experiencing some of the harshest conditions. Polymers in space environments are also sensitive to the outgassing of low molecular weight residues and additives due to the high vacuum of space [22]. Outgassing typically leads to an increase in the free volume of the polymer, reducing its rigidity and facilitating the spread of pro-degradants within the material [23].

During the initial 3D printing experiments onboard the ISS in 2014 and 2016, no chemical degradation or significant alteration of the polymer material was observed when comparing the flight feedstock to the ground feedstock [24]. The flight feedstock was stored in a designated container onboard the ISS for the entire duration of the study, with the feedstock for phase I stored for six months and for phase II an additional 18 months, totaling 24 months of exposure within the ISS environment. Although a slight difference in spectral analysis between the feedstocks was observed, it was not considered significant enough to conclude that the material had degraded adversely. These findings suggest that the internal environment of the ISS is more favorable to polymers compared to the exterior environment, particularly when the material is stored properly.

In addition to the behavior of polymers in space, the potential of recyclable polymers has also been explored [19]. Synthetic polymer-based crew clothing could be recycled into feedstock for AM instead of being incinerated in Earth's atmosphere. However, from an energy perspective, reusing the clothing itself may be more beneficial than recycling the fibers for AM applications [25]. Several polymer materials have been investigated in the literature for potential recycling in space. Furthermore, NASA launched a space system called the recycler in 2019, primarily designed for processing polymers into 3D filaments for their AM units [26]. The advancements in material science aboard the ISS, along with the associated architecture, equipment, and logistics, have made the prospect of building FIS more feasible [27].

III. Manufacturing in Space

As humans continue to venture deeper into space, it becomes more challenging to foresee and prepare for all possible component failures and accidents that could occur [27]. A promising solution would be the integration of maintenance and manufacturing systems into space missions. FIS is a concept that includes processing involving fabrication, assembly, integration, and maintenance of goods outside of the Earth's atmosphere [28]. Figure 1 illustrates the concept of FIS and the major companies manufacturing space equipment. For a fast and reliable response, the flexibility of AM provides ready-to-use parts directly from filament or powder [29].

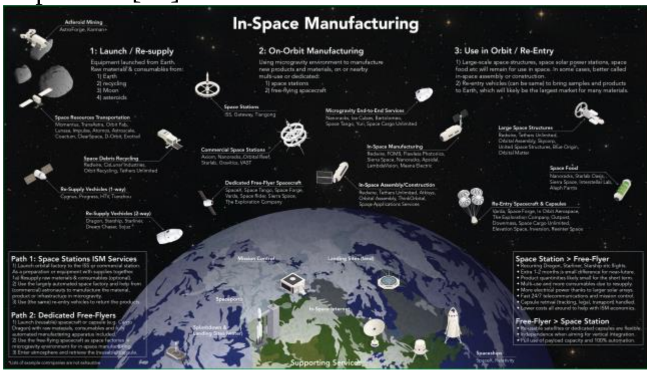

Figure 1. In-space manufacturing [28].

NASA launched an initiative known as "AM in Space" [26]. In 2014 they installed the first AM system in the ISS under the 3D Printing in Zero-G project. Furthermore, an Additive Manufacturing Facility (AMF) was installed in 2016. Later, using the AMF, they developed a metal printing system on the ISS. On the other hand, the European Union (EU), as part of its strategic agenda for AM in the aerospace industry, is developing a concept of manufacturing in space [30]. While the European Space Agency (ESA) is focused on the development of spare parts for the ISS, the primary focus of the EU is on technology and engineering that lead to sustainability/circular economy. Between 2013 and 2017, the EU launched the AM Zero Waste and Efficient Production of High-Tech Metal Products (AMAZE) project. This project employed AM techniques developed in the US to perform in situ manufacturing on planetary habitats such as the Moon and Asteroids. Similarly, several researchers[27], [29], [31]–[34] have reported on various AM techniques for in-space manufacturing.

A report from the ISS national lab [35] concluded that, as compared to conventional manufacturing on Earth, manufacturing in space is more of a systems engineering issue. Due to the non-trivial nature of the infrastructure and environment in space, there is greater reliance on reusing, recycling, and remanufacturing of rare resources. For this reason, circular economy (CE) plays a vital role in developing manufacturing systems in space.

IV. Adoption of Circular Economy in Space

Ever since the advent of the space race, the valuation and interest in the economy of space have continued to grow. The space economy - broadly defined as the activities in outer space that benefit human beings – has always been of value to humanity, mostly through communication and satellite activities [36]. The decentralization of the space economy by NASA has led to the emergence of several innovative setups such as SpaceX, Blue Origin, Virgin Galactic, and Made In Space. This has led to an increase in the revenue of the space sector from about $200 billion in 2005 [4] to about $500 billion in recent years [36].

Traditionally, the space economy "comprises a long value-added chain, starting with research and development actors and manufacturers of space hardware (e.g., launch vehicles, satellites, ground stations) and ending with the providers of space-enabled products and services to final users" [37]. However, the space industry is going through a cycle of development. Each cycle defines new characters and stakeholders [38]. The now completed cycle 4 of this development was led by globalization and the digital revolution. In comparison, the ongoing cycle 5 (2018 - 2033) will be characterized by the ever-increasing data, global monitoring, robotic missions, and widespread adoption of CE principles. In the scope of these developments, Paladini et al. [39] proposed a framework for integrating circular economy, the space sector, and Industry 4.0. However, Industry 4.0 is at its peak when all its nine fundamental pillars [40] (i.e., Big Data & AI, Horizontal &Vertical Integration, Cloud Computing, AR, IoT, AM and 3D Printing, Autonomous Robot, Simulation, Cyber-Security) are used together [41]. Therefore, it is of great importance that cycle 5 continue to introduce a series of new characters and actors to take the sector away from its traditional definitions. Adopting incremental technologies such as data analytics, robotics, and AM has reduced material costs and production times, changing how private and public entities operate. Jackson and Joseph [30] highlighted private process innovators as the primary game changers in the sector, especially in AM, where the progress reported by EOS and Russell [42] is considered one of the cardinal points of CE applications in the industry. Space X's reusable rockets and CubeSat's revolutionary low-cost and impact satellites are further proof of the impact of private innovators.

The ESA is promoting adopting a circular economy in space by recycling, refurbishing, repurposing, and using by 2050, as illustrated in Figure 2. The definition of CE for this scenario is "ensuring long-term orbital sustainability through in-orbit servicing". A series of studies have been carried out under the umbrella of "On-Orbit Manufacture, Assembly and Recycling" (OMAR). These studies aim to help understand this new space ecosystem's advantages, such as a reduction in launch mass, reduction in raw material requirement, decrease in testing times, and manufacturing of rare materials found only in space [30].

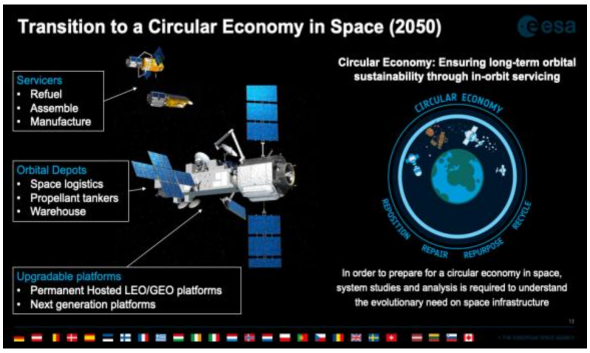

Figure 2.The transition to CE in space [30].

V. Conclusion and Discussion

The reusability of the Falcon Heavy Rocket by Space X has created a new surge of interest in both public and private entities. This renewed enthusiasm has increased the potential for innovative space applications. The space economy currently generates the most value by enabling or enhancing activities on Earth. Significant future value could arise from functions that occur entirely in Orbit, such as in-orbit servicing, research and development, and manufacturing. Super-heavy launch vehicles, such as SpaceX's Starship, could provide an avenue for companies to establish FIS.

Considering the limitation of resources in the space environment, space explorations need to be self-sufficient and regenerative by design, hence the concept of FIS. Therefore, it is paramount to implement a CE in the space economy. The ability to effectively manage waste is crucial to establish a CE in space, especially in relation to FIS. The capability to cope with waste management by implementing the 3Rs could produce long-term affordable provisions and a sustainable energy production cycle. While private innovators have been identified as critical players in the space economy, governing bodies, such as NASA and EASA, have to continue to foster the implementation of a CE in extraterrestrial activities.

On the other hand, there needs to be more definitions for CE in the context of FIS. Therefore, in the future, researchers need to identify new characters and stakeholders in the sector. Additionally, models and methods to evaluate the feasibility of FIS under CE need to be explored and evaluated.

Finally, the ability to manufacture in space could revolutionize space exploration, especially the maintenance and repair of the space vehicle, allowing for more autonomy while handling underlying failures at the space stations. This could lower launch costs and open a path for accelerated commercialization of space.

VI. Bibliography

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