Factory in Space – Constraints of Manufacturing in Low Earth Orbit

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Abstract
Ever since its operation in the 2000s, the International Space Station (ISS) has provided mankind with an important vantage point in Low Earth Orbit (LEO), not only allowing a peak at the extraordinary view of the Earth below but also allowing for the study of orbital effects. As humanity continues to venture deeper into space, it is paramount to explore the possibility of unique space-based manufacturing as part of the next industrial revolution. While several efforts have increased the accessibility to space, there remain several hurdles, as high cost associated with extraterrestrial activities and the scarcity of resources on orbit, to the actualization of a Factory in Space (FIS). To achieve the future potential of commercial and scientific research such as manufacturing activities in LEO, it is paramount to develop new space systems with additional launch capacity at a fraction of the cost available today. Furthermore, several operational, business, and legal challenges must be tackled to make on-orbital activities such as manufacturing viable at scale for commercial players. In this paper, the constraints (grouped in technical, economic, and regulatory) hindering the progress of FIS in LEO are discussed, also providing some possible countermeasures.

Keywords
Factory in space, In-Space manufacturing, satellites, space debris, on-orbit manufacturing.

1. Introduction

Extraterrestrial activities have continued to gain significance ever since the space race in the early 1970s culminated with the decentralization of the space economy. The collaboration between private and public entities has increased the accessibility to space with an accentuated number of launches and a significant decrease in associated costs (thanks to groundbreaking innovations such as reusable rockets by SpaceX [4] and multipurpose CubeSats [1]). This renewed interest in extraterrestrial activities demands even more scrutiny of the associated safety considerations (of crew members, cargo, and space systems) [2], [5], [6]. Ensuring their survival needs detailed planning and provision of required equipment and supplies as well as of logistics associated with the transport of these resources [7]. The supply and provision of necessary equipment are heavily influenced by constraints tied to launch capacity, associated cost, volume, and mass. The efficiency and robustness of space missions have been further enhanced by the advancement in science and technology through the advent of composite materials and Additive Manufacturing (AM). Another solution that promises to address the challenge of transporting large-single component structures during extended space missions is the concept of Factory in Space (FIS), also known as In-Space Manufacturing (ISM) [8]. FIS is the manufacturing, assembly, recycling, refurbishing, and repairing of components/equipment/supply outside of the earth's atmosphere, thus bypassing the logistical constraints [2]. Closing the loop with waste management is an essential cornerstone of FIS. During missions, waste accumulation becomes a pressing issue and requires intricate disposal techniques. The traditional method of waste disposal by burning it in the earth's atmosphere is not sustainable

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and becomes impractical for missions far away from Earth. Space debris is another type of waste accumulated from activities outside of the Earth's atmosphere. Murtaza et al. [3] reported on the threat posed by the accumulation of debris in orbit by concluding that the threat of a catastrophic occurrence increases if the population of orbital debris is not reduced. For this reason, the reduce, reuse, and recycle (3Rs) strategy, rooted in the fundamentals of the circular economy (CE) principles, can be coalesced with the concepts of FIS [2]. 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].

While several efforts and innovative efforts from several entities have increased the accessibility to space, there remain several hurdles to the actualization of FIS. In this paper, we discuss the efforts of manufacturing in LEO to date and discuss the constraints that hinder the progress of FIS. Finally, some possible countermeasures are highlighted in the discussion section.

2. Manufacturing in Low Earth Orbit

The concept of manufacturing in LEO has existed since the repair mission of NASA's space shuttle in the 1980s. The Hubble Space Telescope (HST) marked the first space platform developed with in-space servicing as one of its core mission objectives [4]. The HST allowed astronauts to replace defunct components in orbit to keep the telescope functional and extend its mission life. The servicing activities allowed the extension of its mission life beyond the initial 15-year span. Stoor [5] concluded that the HST mission validated the goal of cost reduction and serves as an important landmark for future in-orbit manufacturing missions. Subsequently, significant efforts have been placed to develop the technology relevant to FIS. The "Orbital Express" - initiated in 2007 – developed with the Defence Advanced Research Project Agency (DARPA), successfully demonstrated robot satellite services, including autonomous assembly [6]. Furthermore, the development of robotic arms using proprietary technology by both NASA and the European Space Agency (ESA) further demonstrates the keen interest in developing autonomous technology for in-orbit applications [7].

The complex nature of extraterrestrial activities means that the manufacturing efforts in LEO - especially of commercial scale - are still in the nascent phase and it is possible to draw parallels between these efforts and transformative technologies such as AM. The advancement of AM techniques allows for a rapid prototyping technology that provides ready-to-use parts directly from stock material. This has allowed for the development of AM technology for FIS applications. NASA launched the "AM in Space" initiative, which led to the first installation of an AM system in the ISS in 2014 under the 3D Printing in Zero-G project [8]. Furthermore, in 2016, the Additive Manufacturing Facility (AMF) was installed. Recent manufacturing research efforts are leveraging the knowledge acquired from the AMF in LEO to develop and demonstrate FIS capabilities. NASA's Restore-L program (launched in 2016) was renamed On-orbit Servicing, Assembly, and Manufacturing Mission (OSAM-1&2) in 2020. The OSAM-1 spacecraft infrastructure w refuel satellites, assemble antennas, and manufacture beams[9]. At the same time, OSAM-2, a technology demonstration mission, was successfully concluded in 2023 [10]. The European Union (EU), on the other hand, is developing FIS concepts as part of its projects on AM in the aerospace industry [11]. While the ESA is working on the continuous development of the ISS by providing spare parts, the EU mainly focuses on technology that leads to sustainability and circularity. In 2013, the EU, in collaboration with ESA and a British company, MTC, launched the AM Zero Waste and Efficient Production of High-Tech Metal Products (AMAZE) project [12]. AMAZE used the AM techniques developed in the US to demonstrate in-situ manufacturing on extraterrestrial environments such as the moon and asteroids. The project culminated with the establishment of four pilot-scale factories across the EU [13]. Makaya et al. [14] summarized ESA's activities in space manufacturing. Another recent effort is the work from the China Academy of Space Technology [15], where they developed an AM system called Space-based Composite Material 3D Printing System, which uses carbon-fiber reinforced composite to autonomously print objects. In 2020, the AM system was successfully tested in LEO aboard China's

Long March 5B heavy-lift carrier rocket. Similarly, several researchers [16], [17], [18] have reported on the development of various AM techniques for in-space manufacturing.

Furthermore, private entities play an important role in the realization of FIS [11]. This is evident through the works of several private companies such as Redwire's (Made in Space) pivotal role in the development of the AMF aboard the ISS and later that of the OSAM, Northrop Grumman's development of Mission Robotic Vehicle (MRV) and deployment of Mission Extension Vehicle (MEV), and Thales Alenia Space's (TAS) developing a servicer satellite with manufacturing capabilities with a demonstration launch planned for 2026. The first FIS mission of companies is reported in Figure 1[19]. Canceled and dormant missions have been categorized differently. Companies with FIS-related research activities without an announced launch date are grouped under "not announced".

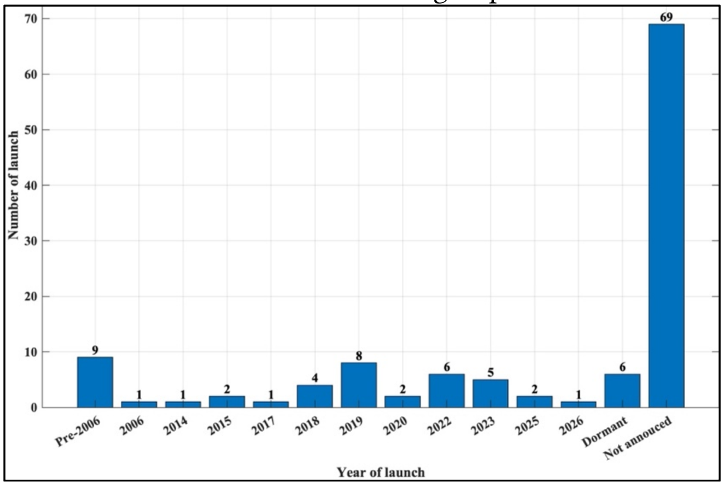

Figure 1: First launches of in-space manufacturing companies [19]

3. Constraints

The most significant barrier to the emergence of a robust manufacturing economy operating in LEO is a “chicken and egg” cycle that must be overcome. To date, commercial entities have not raised investment large enough to finance a fully commercial space station, lacking the guarantees of a demonstrated market appetite for the platform. The potential customers are also unwilling to commit to the costs of developing such a system without a validated business model that could support them. This market conundrum must be fully resolved to fully accomplish the potential of manufacturing in LEO [20]. Furthermore, conflicts between ISS international patterns threaten to erase or blur the lines between civilian and defense space infrastructures. Another mitigating factor is the accumulation of space waste/debris that increases the risk of collision and restricts access to orbit [21]. In this section, the constraints faced by FIS, for simplicity's sake, are grouped into three main categories: technical, economic, and regulatory.

The industry's technology readiness level (TRL) for the widespread adoption of FIS is strategic. Propulsion system performance is one of the most significant hurdles whenever space travel is discussed [22]. Aglietti [23] concluded that the current limitation of extraterrestrial exploration is the length of travel, which is closely related to the performance of the propulsion systems. Also, propulsion systems limit the payload that can be safely transported during space exploration. However, the Institute for Defense Analyses (IDA) reported that the maturity level of relevant technology is not considered a primary issue for the actualization of OSAM; instead, the lack of cooperation between the technologies was of primary concern [24]. Satellites are not being designed to be serviced (or even refueled) and, hence, are more challenging to recycle, which becomes a logistical issue in the search for raw materials for FIS. The development of several AM technologies and robotic modules reported in the previous section further validates this concern. Successful adoption of FIS relies not only on developing and demonstrating the manufacturing techniques but also on a profound synergy between the facets of components that make up the FIS. There is a need for deep analysis and understanding of the complexity and structure of the parts to be fabricated and how the design decisions impact the manufacturing of future components.

Concerning economic constraints, the space economy decentralization [19] (Figure 2), leading to the emergence of startups and private entities such as SpaceX, Blue Origin, TAS, and Redwire, increased the sector revenue from around $200 billion in 2005 [25] to around $500 billion in the past decade [26]. This led to increased accessibility to space due to reduced launch mass and cost, bringing innovations such as SpaceX's reusable rockets and CubeSat's revolutionary low-cost and high-impact satellites. The cost of launching heavy vehicles to LEO has significantly decreased from about $65,000 to just under $1,500 per kilogram (in 2021 dollars) [27]. The cost reduction has made LEO more accessible. While the reduction of launch cost has seen an increase in the number of launches over the past decade, the challenge with FIS is the transportation of manufacturing equipment aboard space shuttles, which goes against the essence of FIS.

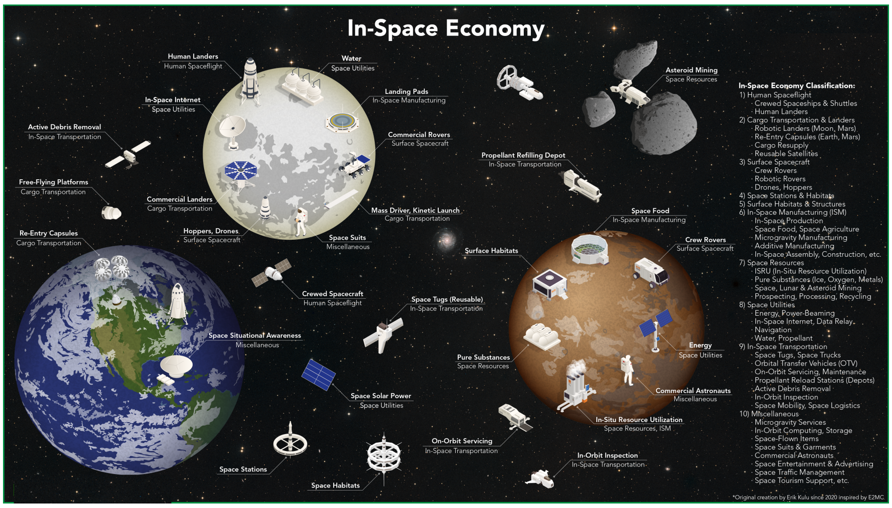

Figure 2: Summary of in-space economy[19].

FIS is intertwined with space debris issues, as NASA's report suggests debris recycling could bolster in-space manufacturing's emerging markets [29]. Therefore, it can be argued that the existing space law, established before the conception of FIS, is not only outdated but also a hindrance to the actualization of FIS [31]. This parallels Hobbs et al.'s findings of FIS and debris removal's shared concerns [30]. Similarly, the question by Hobbs et al. [30] can be mapped to a FIS context such that it becomes: "what to manufacture, how to manufacture, who manufactures, when to manufacture, and who pays for it". The pre-FIS era space law now impedes FIS's realization, requiring a legal framework for its governance.

Furthermore, the ongoing phase 5 (2018-2033) [32] of the space industry development needs to introduce a series of new actors and stakeholders to shift the sector from its traditional definitions. For instance, Paladini et al. [33] developed a framework for integrating the CE, the space sector, and Industry 4.0. However, Industry 4.0 is at its peak when all nine fundamental pillars (i.e., Big data & AI, Horizontal and Vertical Integration, Cloud Computing, AR, IoT, AM and 3D Printing, Autonomous Robot, Simulation, and Cyber-Security) are in synchrony. The ongoing development phase must leverage globalization and the digital revolution to develop a framework for easy access to space information and data.

4. Discussion and Conclusion

Preliminary achievements in FIS activities have enabled ambitious human and robotic space missions. The ISS, HST, and MEV established that historical operational missions can be realized with FIS capabilities. Many current flight demonstrations are advancing areas that will enable the next generation of civil, national security, and commercial space missions, enhancing the possibility to realize FIS. Currently, FIS activities (such as servicing operations) are at a tipping point, and while national and international bodies would continue to demand servicing operations to operate current space platforms such as the ISS, the economics of space activities continue to be a driving force behind the commercialization of extraterrestrial activities. As FIS technology continues to mature with multiple commercial companies planning to develop/demonstrate capabilities over the next few years, civil and commercial space operators need to explore how to leverage these capabilities to enhance their existing constellations, and how to optimize and prepare their next generation of space systems for the coming paradigm shift. Although more sophisticated and longer lasting, satellites today are the same lonely outposts that have existed since the Sputnik era. In contrast, satellites launched a decade from now will have servicing and manufacturing companions and be designed for this communal environment.

Advanced technologies such as AM, digital engineering, and AI could serve as catalysts for the accelerated growth of FIS. While some of these technologies are already being exploited by key practitioners in the space industry, their convergence will further amplify their potential. For instance, NASA recently demonstrated the use of generative AI in concert with AM to develop components that are lighter and stronger than those produced by traditional engineering approaches [21]. Therefore, both commercial and national bodies need to seek ways to adopt facets of Industry 4.0 including but not limited to the usage of generative AI to design hardware and software with shorter cycle times and increasing the scope and scale of digital engineering to add flexibility and agility across the enterprise.

While several uncertainties and challenges are associated with FIS activities, a pragmatic collaborative, and value-driven approach would enable steady growth toward a self-sustaining factory in LEO. The public and private collaboration of space practitioners can build models to enhance the value obtained from the utilization of microgravity. Once economically viable business cases that can generate substantial revenue in the long and short term are identified and relevant technology developed, FIS has the potential to be a significant aspect of the next industrial revolution.

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Declaration on Generative AI

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

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