Factories-in-Space for Servicing, Assembly, & Manufacturing

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Abstract

Space 2.0 is a promising frontier for scientific exploration and the advancement of commerce, security, and technology [1]. To effectively harness this potential, it is imperative to establish a multifunctional, resilient, and sustainable infrastructure that enables the maintenance and production of space-based systems. This capability is a driver for mission success on-orbit and for interplanetary travel to other celestial bodies. Central to this infrastructure is the establishment of orbital manufacturing facilities, referred to as 'factories-in-space' (FiS) [2], which serve as critical nodes in the supply chain for the servicing, assembly, and production of systems essential for space-based operations. This paper presents a framework for understanding the key principles and design considerations underpinning FiS.

Keywords: in-space servicing, assembly, and manufacturing (ISAM), microgravity, on-orbit servicing (OOS), in-situ resource utilization (ISRU), Space 2.0, autonomous space operations, space robotics, digital twin

1. Space Infrastructure 2.0

Sustainable human existence in space requires robust infrastructure to support survival and growth [3]. Essential infrastructure includes logistics, supply chain management, and the delivery of services for the assembly and manufacturing of crucial systems for safe habitation and commercial advancement. Traditionally, these tasks were performed in factories, warehouses, and distribution centers [4]. However, the space frontier demands a new paradigm, "space infrastructure 2.0," emphasizing concepts like factories, hubs, or nodes in space, which is the focus of this paper.

Notably, the key factors driving space infrastructure growth include: (1) resource consumption limits due to population growth [5]; (2) human exploration advancements [1]; (3) declining launch costs [6]; (4) evolving in-space policies [7]; (5) geopolitics [8]; (6) advanced spacecraft accessibility [9]; and (7) demand for space technology platforms [10]. Unique opportunities stem from microgravity, vacuum environments, and valuable ores [11].

2. Factories In-Space

The "factory" concept, originating in the 17th and 18th centuries, enabled mass production and assembly using power-driven machinery [12]. Factories support service, assembly, and manufacturing processes tailored to end-product and customer needs [13]. In the Industry 4.0 era, factories have evolved into diverse physical and digital configurations, depending on products, processes, materials, and supply chains [14]. Traditionally, servicing, assembly, and manufacturing (SAM) platforms provide large-scale, mass-customized products and services, focusing on the 3Rs (reliability, reproducibility, repeatability) and 3Ps (producibility, productivity, profitability) [15][16]. Similarly, in-space SAM (ISAM) employs physical and digital processes above the Kármán Line for service delivery, assembly, and production, leveraging *in situ* space conditions for sustainable activity [17][18][19][20].

A "Factory-in-Space" (FiS) is defined as a physical or digital facility above the Kármán Line, executing autonomous or semi-connected ISAM processes for servicing, assembly, and manufacturing. FiS can be stationary or mobile, delivering ISAM products and services. Earlier NASA operations, like Skylab, are precursors, providing fundamental insights into space materials science and engineering [21]. The construction of space infrastructure relies on a comprehensive foundation of scientific, engineering, and economic principles established on Earth, with "space infrastructure 1.0," also like the International Space Station (ISS), serving as a knowledge base; however, with the ISS's decommissioning, "space infrastructure 2.0" development, like Axiom Station and Orbital Reef, must accelerate [22][23].

3. A Framework for ISAM Capabilities

In-space manufacturing can be sub-categorized into four domains (Figure 1): (1) enhancing terrestrial production through space-based systems, e.g. satellite-based communication and IOT networks for global logistics [24]; (2) utilizing the natural properties of space for making products with Earth-bound applications, e.g., the highest-quality fiber optics and pharmaceuticals [25][26]; (3) fabricating equipment dedicated for space, e.g. habitats, spacecraft, servicing stations [27]; and (4) producing goods for human or industrial bases in other extraterrestrial environments, e.g. the Moon or Mars [28].

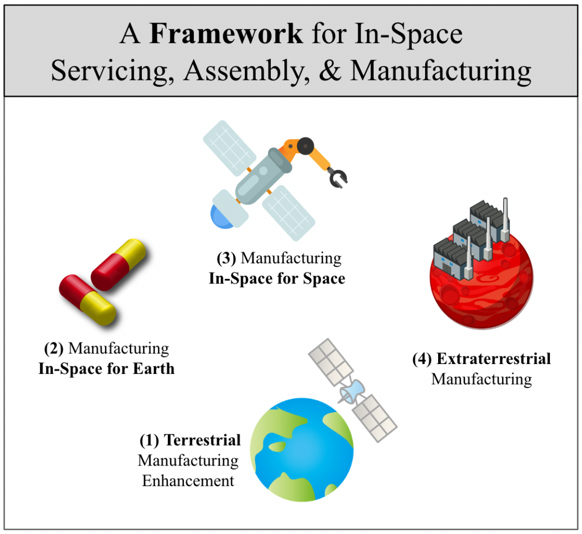

Figure 1: A framework for ISAM.

This paper emphasizes constructing space-based factories for sustained space presence, reducing costs and launch times, enabling autonomous repair to delay obsolescence, and reclaiming space debris [29][30]. It highlights managing equipment risk, lowering entry barriers [31], and calling for innovative solutions to address challenges posed by extreme space environments. The paper identifies priority research areas, including autonomous production technology, materials, logistics, and satellite development, while illustrating the "factory" concept's importance in creating a resilient and sustainable space infrastructure.

4. Motivation for Factories-in-Space (FiS)

Presently, most space operations rely on Earth-based infrastructure for servicing, assembly, and manufacturing [31]. As permanent habitation and demand for objects like satellites grow, developing infrastructure beyond the Kármán line becomes necessary, since the costs of escaping Earth's gravity for maintaining extensive networks are unsustainable long-term [32][33].
Constructing reliable space infrastructure requires accommodating vast operational environments, extreme conditions, and flexibility in servicing diverse needs at distributed points-of-need (PoN) [34]. A proposed edge distribution network features modular service fulfillment centers on-orbit for faster, cost-effective "direct-to-consumer" (DTC) delivery. To meet these demands, a modular, interoperable, and distributed platform called "Factory-in-Space" (FiS) is envisioned, serving as a space hub addressing location-specific functional needs (Figure 2).

Figure 2: Authors' vision of a factories-in-space, with separate nodes for various applications.

5. Key Focus Areas

FiS and ISAM methodologies must tackle extreme conditions such as limited resources, scarce materials, energy constraints, and minimal human involvement. Frugal engineering solutions should ensure modularity, flexibility, adaptability, sustainability, and resilience for space infrastructure development. Addressing fundamental questions is essential for a long-term vision (Figure).

What type of products & services should be manufactured?
What type of factories will be required to produce such products?
What kind of energy & material extraction systems need to be developed?
What type of processes are suitable to fabricate these products?
What fundamental advancements in our understanding of manufacturing science & engineering are required to scale these processes economically?
What peripheral systems are needed, like robots and AGVs, that can be used to maneuver & assemble components?
How sustainable manufacturing methodologies will be and areas we need to work on to achieve a completely circular economy in space?

Table 1: Examples of fundamental questions for building Factories-in-Space (FiS).

5.1 System Inputs

Raw materials and molding feedstock availability are crucial for producing finished products in FiS, especially considering payload expenses [35][36]. In-situ resource utilization (ISRU) is vital for material extraction and can reduce costs and increase sustainability by utilizing local resources [37][38].

5.2 Energy Management

Energy requirements for FiS comprise operational energy and energy for material transformation [39]. Solar energy is a popular choice; however, nuclear and hydrogen-based energy may complement solar harvesting [40]. Material processing involves selecting energy sources like lasers, microwaves, and other electromagnetic radiation forms [41].

5.3 Environmental Shielding

Space poses challenges such as temperature fluctuations, variable gravity, electromagnetic fields, and radiation, potentially causing component failures [42]. Electronic components are prone to radiation damage, and lunar dust (an abrasive oxide ceramic) causes accelerated deterioration of exposed structures [43][44][45]. Additionally, the biological toxicity of lunar dust is enhanced due to the amount of "nanophase Fe" which has magnetic properties [46].

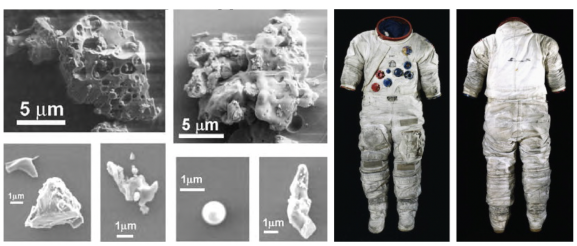

Figure 3: Left– Apollo 17 lunar dust taken by electron microscope [47]. Right– Apollo astronaut Harrison "Jack" Schmitt's space suit was covered with lunar dust, which is razor sharp [48][49].

5.4 Autonomous & Digital Operations

Autonomous systems and digital twin technology significantly improve efficiency and safety in space manufacturing processes [50][51]. NASA's Apollo program used digital twins to replicate orbital flight conditions on Earth using two identical shuttles, one mimicking the other [52]. First published use by NASA in 2010, a digital twin is defined as, "a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level." [53][54] Autonomous operations also require minimal human intervention, maximizing safety [55].

While the adoption of autonomous systems in space has been slow, when applied, success in operations has followed [56]. Efficient, reliable, and cost-effective ISAM at focused sites like FiS could lead to sustainable and scalable space industrialization. Digital twins help predict microgravity material behavior, optimize 3D printed designs, and simulate complex space assembly [57][58]. Virtual presence is also crucial for complex scientific and production tasks, as increased distances necessitate remote connection to platforms, like FiS [59].

5.5 Modularity

The modularity of FiS advances ISAM by enabling flexible, efficient, and resilient robotic systems [60]. Modular space hardware and equipment enhance the scalability and flexibility of manufacturing operations through standardized interfaces, building blocks like modular robots, 3D printed parts, and plug-and-play components. Modular designs simplify repair and maintenance, as faulty modules can be replaced easily [27].

5.6 Repair & Maintenance

Efficient repair and maintenance are crucial for in-space manufacturing equipment's long-term functionality [27]. On-orbit servicing (OOS) has already been employed in missions like Skylab, Hubble Space Telescope, and International Space Station [61]. The Space Shuttle program advanced OOS technology, with developments including robotic servicing of geostationary satellites, Phoenix, and space infrastructure servicing [61]. Space's harsh environment necessitates routine maintenance, accounting for challenges like limited resources and accessibility [62][63]. Predictive maintenance techniques prevent failures, and advanced robotics and digital twin capabilities enable remote repairs and predictive maintenance [64][65].

5.7 Material & Product Qualification

Materials for space applications must withstand harsh conditions [1]. To tackle challenges in microgravity and extreme environments, further research must focus on developing new manufacturing approaches, such as materials and design methods that can endure harsh conditions and techniques to optimize production in low-gravity environments [66]. Rigorous performance standards are crucial for material and product qualification [67]. Quality assurance and verification procedures must ensure the reliability and safety of manufactured products and assembled structures in space [1].

5.8 On-Orbit Logistics & Supply Chain Management

Effective logistics and supply chain management are crucial for optimal FiS operations, including on-orbit transportation, storage, and waste management [1]. Waste management strategies enable the reuse, recycling, or repurposing of manufacturing waste within limited resources [1][41].

5.9 Regulatory Framework

Regulatory compliance is crucial for safety and success in space operations [68][69]. Long-term operations and human safety rely on incorporating sustainability and environmental, social, and governance (ESG) considerations [70]. Developing economic models and supportive ecosystems is vital for sustainable space infrastructure [1]. Space-based regulations tackle issues like space debris mitigation, orbital safety, commercial activities licensing, intellectual property, and resource management [48][71][72][73]. Public-private partnerships foster Factories-in-Space (FiS) growth and the broader space infrastructure ecosystem [47]. International cooperation is essential for an equitable space ecosystem.

6. Conclusion

Factories-in-Space (FiS) are critical components of space infrastructure for sustainable human presence in space, enabling robust, multifunctional, and resilient infrastructure for servicing, assembly, and manufacturing. The continued development and evolution of the FiS concept will be instrumental in overcoming the challenges of space exploration, habitation, and commerce, paving the way for a thriving and sustainable space-based economy. However, the development of FiS currently faces challenges that need to be addressed, such as developing efficient in-space manufacturing and assembly technologies capable of operating under extreme conditions, establishing sustainable and scalable supply chains, enhancing communication and coordination among distributed nodes, investigating advanced materials and fabrication techniques like additive manufacturing, and exploring the integration of artificial intelligence for improved decision-making and operations management. Immediate efforts should focus on addressing these challenges to advance in-space servicing, assembly and manufacturing capabilities.

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