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Maintenance Factory Platform for In-space Manufacturing: Conceptualizing Design Architecture

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Abstract

Commerce, long-term habitation, and far-location explorations are the objectives of the next space era, also called Space 2.0. These objectives are the focus of in-space servicing, assembly, and manufacturing (ISAM) research. Current research in this area is focused on demonstrating various manufacturing processes under microgravity using the International Space Station (ISS) as a platform and relies on an Earth-based supply chain. Building operational infrastructure and supply chains enabling in-space manufacturing is critical for the sustained growth of ISAM to meet the goals of Space 2.0. This paper is specifically focused on discussing the need and potential architecture for a maintenance factory in space to enable servicing, maintenance, and repairs in space environments. Space presents a hostile environment and a new set of challenges to establish a robust infrastructure necessary for supporting these objectives. The realization of such an infrastructure, including physical and digital footprints, is demanding new manufacturing science and engineering tools and platforms for maintenance. The authors present requirements of a robust maintenance platform, called a "factory in space" to deliver multi-functional maintenance service station(s) across various operational points in space such as low-earth orbit, lunar surface, and Martian surface. Such factories are projected to be an essential part of the in-space infrastructure for short as well as long-term commerce, habitation, and exploration. A critical analysis of this concept is proposed through an analysis of the state of the art, boundary conditions in space and requirements of maintenance, the role of manufacturing, and the design as well as sustainability considerations for a maintenance factory in space.

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Keywords: in-space manufacturing, ISM, factories in space

1. Introduction

Recent advancements in space exploration and potential habitation have put in-space servicing, assembly, and manufacturing (ISAM) at a critical and foundational juncture. There is significant interest in developing the infrastructure in space to enable and extend the presence of humans outside of Earth's orbit and to usher in a new era of space research and development. Primarily, the majority of the existing space assets are typically manufactured on Earth and then launched into space. With an increasing number of space assets and activity, 'manufacturing on earth and transporting to space approach' is resource-prohibitive and unsuitable for sustained growth and development of extra-terrestrial activity in the long run. To minimize the reliance on launching materials/components from Earth, the development of 'factories-in-space' is critical to enable extraterrestrial manufacturing operations in space [1] and this paper aims to expand that concept using maintenance operations as a case study. In-space servicing, in-space assembly, and in-space manufacturing (ISM) are three crucial pillars to meet the above goals. Even though the infrastructure and equipment needed for these three operations differ on a case-by-case basis, they are all bound by the same stringent boundary conditions namely: 1) energy and material considerations, 2) the impact of reduced gravity, 3) extreme operating environments, and 4) supply chain and other sourcing criteria. These conditions present unique challenges while presenting exciting new opportunities

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for materials and manufacturing research. The above-mentioned trends and drivers for research were also captured during a series of workshops focused on roadmapping ISAM research opportunities [2]. The key outcomes from this ongoing activity, including sustainability, management of space debris, in-situ resource utilization (ISRU) as a part of reuse/recycle methodology, and the materials and manufacturing infrastructure development, serve as motivation for the architecture proposed in this paper.

Nomenclature

ISAM	In-space Servicing, Assembly, and Manufacturing
ISM	In-space Manufacturing
LEO	Low-Earth Obit
OOS	On-Orbit Servicing
FiS	Factory in Space
FREND	Front-end Robotic Enabling Near-term Demonstration
SPIDER	Space Infrastructure Dexterous Robot
GEO	Geostationary Orbit
EVA	Extra-vehicular Activity
IVA	Intra-vehicular Activity
ETS	Engineering Test Satellite
DART	Double Asteroid Redirection Test
ISS	International Space Station
HST	Hubble Space Telescope
ORU	On-Orbit Replacement Unit
MEV	Mission Extension Vehicle
ISRU	In-Situ Resource Utilization

Most of the current activity in the field of ISM is limited to the demonstration of various manufacturing processes in orbit using the International Space Station (ISS) as a testing platform. Additive manufacturing processes are mostly reported as demonstration case studies. The interest in the in-space manufacturing activities and proposed future establishment of commercial space stations at this stage primarily focuses on the utilization of manufacturing under microgravity for applications on Earth [3,4] as a part of the commercialization of low-earth orbit. However, manufacturing in space (for space applications) is also a critical aspect of the space economy where critical infrastructure such as factories must be considered, especially for sustainable space operations. Servicing, maintenance, and repairs of existing infrastructure in space is an important aspect of ISAM and could be a starting point for expanded ISM efforts. In other words, the manufacturing research and infrastructure needed for maintenance operations could be viewed as a demonstration case study for a wide variety of materials and processes as a stepping stone for ISM development.

Examples of servicing/repair operations are limited to target-specific launch missions. As a part of growing space infrastructure and assets, launching target/operation-specific missions from Earth is not ideal for sustainability, time sensitivity, and resource utilization. The authors envision an orbital maintenance factory-in-space that can perform on-demand, on-site maintenance operations without relying on materials/parts supplied from Earth. As such infrastructure currently does not exist in space, hence, this paper focuses on the development of the architecture for ‘servicing and maintenance’ operations in space as discussed below through materials, manufacturing processes, equipment, and sustainability needs.

The following sections present a short overview of maintenance operations in space followed by the proposed architecture for maintenance factories in space. The key requirements and design attributes for such a factory are highlighted and discussed in brief. This is followed by the discussion on space sustainability using an additive manufacturing thought experiment example in the context of maintenance in space

2. State of the Art of Maintenance in Space

The current state-of-the-art maintenance in space involves technologies for the transfer of propellants and fluids, deployment of advanced robotic systems with multiple degrees of freedom for capture and repair of client spacecraft, and the utilization of precision cameras and sensors for autonomous rendezvous with the client spacecraft [5]. Starting in 1997, with the launch of ETS-VII, the first autonomous on-orbit servicing spacecraft and satellite equipped with a space robot, began the rapid progress of the on-orbit assembly and maintenance technologies [5]. Since then, the development of on-orbit servicing, assembly, and maintenance has improved to perform more complex tasks. These technological achievements have been effectively demonstrated in previous servicing missions, as detailed in Table 1.

From Table 1, it is clear that space servicing missions have overlooked the concept of ISAM and have heavily relied on consumables transported from Earth which has severe limitations in terms of launch costs, size and weight limits, and maintenance timeframe. Some servicing missions listed in the table are launched to solve anomalies reported during the operation of spacecraft and to provide upgrades. Others are launched as standalone flight missions to verify critical technologies that will aid maintenance operations soon. Recent works on technology development for ISAM include launching 3D printers into space for the fabrication of plastic and metallic parts, thereby reducing the number of spares and redundancies associated with a space mission [6]. These efforts are also reliant on Earth due to the use of feedstock.

Therefore, an infrastructure in space that encompasses manufacturing aspects and its associated supply chain for delivering maintenance and service operations is necessary for economically viable and sustainable deep space explorations. This highlights a notable gap in integrating maintenance and manufacturing aspects in space. The “maintenance factory in space” methodology presented below aims to bridge ISM and maintenance activities, thereby contributing to the realization of sustainable infrastructure development envisioned in the new space age, Space 2.0.

Table 1: State of the art of maintenance in space.

Name	Year	Tasks considered	Salient comments	Learnings from the mission	Ref.
Solar Maximum Mission	1984	Manual capture by astronauts, berthing of spacecraft inside the payload bay of space shuttle, and repair of malfunctioning instruments	First orbiting and uncrewed satellite to be repaired in space. The mission life of the satellite was extended after the service operation. The space shuttle was used for capturing and berthing the spacecraft	Tasks involving maintenance and repair require a serviceable design. It demonstrates the importance of astronauts in responding to abnormalities and performing repairs.	[7]
Hubble Space Telescope (HST)	1993-2009	Remove and Replace operations, Repair, Upgrade, and Refurbishing of components	Spacecraft was designed to be launched and maintained in orbit. The lifetime of the HST and its capability in terms of performance was enhanced by the servicing missions	The HST's serviceable design made several OOS missions achievable. For manned OOS, foot restrictors and rails are fitted, and doors are modularly designed to provide independent access to the instruments. Component removal and replacement were simpler with Orbital Replacement Units (ORUs).	[8]
ETS - VII	1997	Experiments related to Autonomous rendezvous and docking	First satellite equipped with a robotic arm and able to perform autonomous rendezvous and docking	The use of robotics in spacecraft rendezvous and docking procedures will be vital.	[5]
ISS	1998 - Present	Assembly, replacement, refueling, and repair of components	Largest artificial satellite orbiting the earth. Resupply missions carry the spares that are needed to cover for component failures and redundant systems are incorporated to cover unanticipated failures	Ability to assemble large structures in space. Working of humans and robots together to aid repair operations in space. The ability to manufacture components inside a spacecraft will enable an earth-independent space mission	[9]
DARPA Phoenix	2012 (Not launched)	Repurposing of satellite apertures	Satellite apertures have longer lifetimes than batteries, electronics, and solar arrays and this is a significant mission that deals with the re-use of space assets and their re-integration into a new spacecraft	Recycling, Repurpose, and Re-use of spacecraft systems into value-added components/materials could enhance sustainability and maintenance during deep space exploration missions	[10]
Orbital Express	2007	Autonomous Rendezvous and Docking, Refueling, and replacement of ORUs	ASTRO equipped with a robotic arm acts as a servicer and NEXTSat acts as a serviceable client satellite	Autonomous rendezvous, capture, and berthing. ORU and fuel transfer were made possible but was demonstrated on a serviceable satellite named NEXTSat	[11]
Orbital Life extension vehicle	2008 (Not launched)	Propellant augmentation, Repositioning of satellites, Fleet management in GEO	First commercial servicing mission for communications satellites in GEO. Acts as a “tugboat” for the client's satellite	Docking with uncooperative satellites by remote control is a challenge. Standard interfaces promote serviceability in space. Possible use of electric propulsion for interplanetary orbital maneuvers	[12]
Mission Extension Vehicle (MEV)	2020	Repair, debris removal, inspection, and propellant augmentation	It can dock with non-cooperative spacecraft and extend the lifetime of its client satellite through its thrusters and fuel supply	Spacecraft can be serviced with the help of robotics manipulators without requiring human intervention. Satellites with different designs and functions can be serviced, thereby enhancing flexibility in OOS missions	[5]
OSAM 1 mission	Planned	Refueling, Fabrication, and assembly of large structures in space	A dexterous robot SPIDER is used to assemble antennas and manufacture long composite beams	In-space assembly and manufacturing to enable the production of large spacecraft structures that are difficult to launch due to the constraints imposed by the launch vehicle	[13]

3. Building an operational infrastructure in space

In the past (maintenance in space 1.0), several on-orbit service and maintenance operations have been conducted on smaller spacecraft such as the Solar Maximum satellite, and large space structures like Skylab, Mir, and the International Space Station (ISS) [7,14,15]. The predominant range of on-orbit service and maintenance tasks encompasses activities such as refueling, repairs, assembly, upgrades, and replacements, primarily conducted within the confines of Low Earth Orbit (LEO) [5]. To facilitate these operations, only the essential payloads like tools, propellants, and On-Orbit Replacement Units (ORUs) have been transported from Earth. With increasing space traffic and the planned establishment of space infrastructure for commercialization, servicing/maintenance needs are bound to grow. Following the maintenance 1.0 model and relying on restock missions from Earth to transport the necessary goods will be cost and time-inefficient. Hence, alternative approaches for servicing and maintenance must be developed with long-term sustainability in consideration. The subsections below present key considerations for the infrastructure as well as the methodology necessary for in-space maintenance 2.0.

3.1. Maintenance in Space 2.0: In space manufacturing – an enabler for sustainable maintenance in Space 2.0

The emergence of infrastructure models such as factories, cities, and human settlements, in alignment with the vision of the new space age, often referred to as "Space 2.0" [16], places different requirements for space maintenance. Recently, ISAM has garnered global attention, spurred by the mounting volume of space debris and concepts such as in-situ resource utilization (ISRU) for settlement on other space bodies. The convergence of ISAM and on-orbit servicing (OOS) paves the way for the establishment of “Factories in space” for the maintenance and service of spacecraft and other infrastructure. ISAM represents the manufacturing of components within the extraterrestrial environment, utilizing materials sourced from Earth, space debris, and other celestial bodies [17]. This approach thus has the potential to foster sustainability and safety in deep space exploration missions through on-demand and point-of-need operations while delivering time-efficient customized solutions.

3.2. Factories in Space

The new space age involves the long-term presence of factories in space. A ‘‘Factory-in-Space” (FiS) is an ISAM facility for servicing, assembly, and manufacturing utilizing autonomous or semi-connected processes executed above the Kármán Line and can be physical or digital [18]. FiS can be stationary or mobile, delivering ISAM products and services depending on specific operation and location of interest. Different applications of factories could include refueling stations, food production facilities, asteroid processing, servicing, assembly, repairs, and others. While the current research endeavor in LEO and on the International Space Station (ISS) focuses on research and development of product solutions for on-Earth applications, the operations should continue for in-space applications (such as maintenance in space) for achieving the ISAM and space 2.0 objectives. Thus, the applications for factories in space can not only benefit Earth operations but also expand to in-space operations as a part of the space economic frontier. Deep space factories could focus on refueling for long-term space travel.

With artificial intelligence becoming more prevalent, expansion into autonomous servicing and self-sufficient design is critical for maintenance factories in space. In the harsh extraterrestrial environment, robotics and autonomy are required for in-space sustainability to ensure efficiency, remote operation, and adaptability. This must be aided by the expansion and usage of digital twins to complement the performance of a diverse factory infrastructure. Digital twins are virtual replicas of physical systems that can facilitate real-time monitoring, analysis, and optimization, enhancing space missions’ performance and efficiency. NASA first applied digital twin technology in aircraft for structure maintenance in 2012. A digital twin system developed based on Grieves’ three-dimensional digital twin model, a five-dimensional model was proposed in 2017, which included a physical entity, virtual model, digital twin data, connection, and service [19]. Current research on digital twins is exploring the fundamental theory and key common technologies [19]. Maintenance in space could benefit from the development of this technology so that real-time monitoring carried out from Earth enables efficient operations in space. However, it should be noted that real-time monitoring with digital twins is reliant on the collection of appropriate sensor data and data-driven analysis. The current state of this technology is dependent upon the previously available robot models and data. Hence, the digital twin models must be developed and refined simultaneously to fully utilize their capability for remote maintenance operations.

4. Conceptualizing factory architecture for maintenance operations in space

In this paper, we propose the conceptual architecture of a “maintenance factory in space” that enables self-dependent maintenance minimizing the need for resupply missions or spare inventory. This robust maintenance platform is conceived to deliver multi-functional maintenance service station(s) across various operational points in space (e.g., LEO, Lunar surface, Martian surface, etc.,). Through the next sections, the authors present the design architecture of such a factory, its locations, various input raw materials needed along with their sourcing, various processes involved, and the possible outputs of such a platform along with the logistics arrangements. Sustainable maintenance operations and infrastructure involving ISM face unique challenges that are not typically observed in the case of maintenance and manufacturing on Earth. Manufacturing in space must deal with different challenges depending on the operational scenario [20]. Depending on the location of the manufacturing or maintenance occurring, different boundary conditions become critical and must be taken into account. Reduced gravity is the main challenge faced by in-space manufacturing due to the different gravity environments influencing the modification and/or rethinking of terrestrial processes for their suitability to be applied in space. The influence of gravity leads to sedimentation in materials and convection. When gravity is reduced, relative density is negligible, and products are distributed evenly. Along with gravity, extreme temperature variances, solar radiation, and vacuum pressure are other boundary conditions that need to be considered when determining parameters for manufacturing [21]. In addition to the manufacturing process itself, one must also consider the redesigning of fixtures and material handling methods to better suit the need for space boundary conditions.

Table 2 compares on-Earth and in-space maintenance. Servicers explicitly made for maintenance would carry out maintenance in space. Different types of servicing robots must be used to perform maintenance on diverse space structures. Space vehicles equipped with welding arms to perform maintenance and reduce human interaction for repair [22]. An example of a reduction in human interaction was the Space Station Remote Manipulator System (SSRMS) assisting astronauts in extra-vehicular activities. The Hubble Space Telescope has utilized robotic arm-assisted repairs with astronauts for several repairs in 1997, 1999, 2002, and 2009 [23]. A servicer needs to be multifunctional and designed/built with the capability of undertaking several tasks such as servicing, assembly, disassembly, repair, and refurbishment [5]. The FREND (Front-end Robotic Enabling Near-term Demonstration) robot was developed for servicing spacecraft and is meant to survive in GEO space conditions providing assembly, disassembly, maintenance, repair, and refueling [5]. The goal of the FREND mission is to be able to service satellites without pre-designed custom grappling interfaces and develop the space robot technologies of autonomously uncooperative target grappling [24]. A more recently proposed servicing robot was the Space Infrastructure Dexterous Robot (SPIDER) which would have been deployed during the OSAM-1 mission [25]. The SPIDER payload was meant to assemble a communications antenna and manufacture a composite beam. Versatility is another challenge to overcome for servicing robots in space and could be addressed by the development of platform-agnostic robots to enable multifunctionality and resilience [26]. The following sections present an architecture addressing some of the above-discussed challenges and boundary conditions for achieving multifunctionality, resilience, and sustainability for the maintenance operation factory in space.

Table 2. Comparison table of on-Earth and in-space maintenance.

	On-Earth Maintenance	In-Space Maintenance
Resource Utilization	Mining within the Earth, supply from external areas	Mining asteroids, resupply missions from Earth
System Design requirement	Can have complex and integrated architecture	Should have accessibility, interoperability, modularity, and standard interfaces
Maintenance task	Job shop based on dismantling and assembling tasks	Remove and Replace fixes in the form of ORUs
Level of repair	Can repair an individual piece part (eg. O-ring of a solenoid valve)	Repair is limited to the replacement of parts at the component level (Eg. Replacement of solenoid valve)
Environmental conditions	Repair actions do not require any restraints under the earth's gravity	Repair actions require foot restraints and hand braces to hold the components under microgravity
Recycling	Metal and plastic recycling	Recycling of decommissioned satellites, spacecraft, and spacecraft components
Assembly & Disassembly	Assembly and disassembly done under gravity	Assembly and disassembly done under microgravity
Automation	Some human intervention; Robotic arms and A.I.	Must be ready for no human intervention; Robotic arms and A.I; better reliability needed – e.g., longer MTBF
Feedback	Machine learning, sensors, and Human interaction	Machine learning, robust sensors, and minimal human interaction

5. Maintenance factory in space

The key considerations for a maintenance factory in space are presented below.

5.1. Platform architecture

The maintenance factory represents a highly versatile and robust space platform that has the potential to revolutionize the current spare parts supply chain paradigm. By positioning it closer to the user's location in space, it enables rapid responses to space system failures. Initially, the platform operates on a centralized supply chain model. However, as the technology matures, it evolves into a distributed supply chain, with specific maintenance depots established at various locations in space, including LEO, GEO, and planetary bodies. The platform is conceived to be modular in nature with standard interfaces for mechanical, power, data, and thermal to facilitate the scaling up of infrastructure. These requirements should be considered at all levels of design – system, subsystem, and components of the platform. The initial factory module could target basic maintenance needs with simple processes. The module can then be scaled up to satisfy more complicated operations with more processing capabilities in the future guided by the data/information collected through the emerging space infrastructure and its needs.

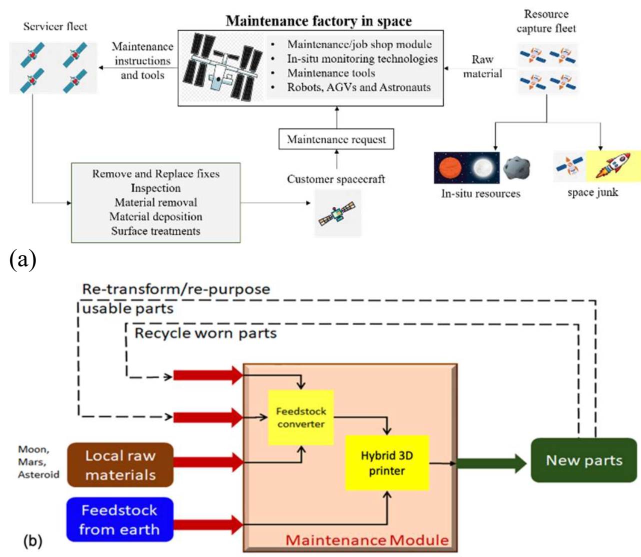

Fig. 1. (a) Maintenance Factory in Space Process Diagram, (b) Process Diagram of a Maintenance Module for spacecraft components

Mobile units play a pivotal role in this setup. They are responsible for capturing space junk or in-situ raw materials and transporting them to the maintenance depots for material processing. Other mobile units gather the necessary maintenance tools and fabricated components from the depot to perform required repairs and maintenance operations on customer spacecraft or at the point of need. These maintenance tools may include welding, brazing, soldering torches, or high-speed friction milling cutters attached to robotic arms of the servicing mobile units, facilitating on-site repairs. The maintenance tools must be small, lightweight, and capable of repairing the target spacecraft at any orientation. It should have the ability to perform inspection, material deposition, material removal, and surface treatments. These requirements will enhance the adaptability and flexibility of the maintenance platform in response to the diverse range of component failures. Fig. 1a displays the process diagram for how maintenance modules interact with other entities within the space for external repairs. In-orbit construction and fabrication require process monitoring techniques to produce large-scale structures [27].

Customer spacecraft communicates repair requests to the maintenance depot, which then generates instructions for the required repair tasks and fabricates any components needed for replacement like valves, sensors, tubes, struts, and trusses. These instructions, along with the fabricated components, are relayed to the mobile units for executing the repair operations. The entire process within the maintenance depot is automated and monitored by a digital twin, which analyses process data and employs decision-making tools such as artificial intelligence or ground control intervention for corrective actions. For space architecture to become a reality, commercial space companies are moving toward robotic servicing as an essential addition [22]. A job shop module is conceptualized as a pressurized work volume for manufacturing and assembling small to medium-sized components like valves, pumps, and electronics. To ease the maintenance tasks carried out by astronauts, advanced tools like Augmented Reality (AR) shall be employed to identify specific components of a system or assembly and their respective interfaces [28]. These tools shall contain maintenance procedures that need to be followed while performing repair operations inside the habitable volume. Fig. 1b displays the maintenance flowchart for spacecraft components using a feedstock converter and a hybrid 3D printer for small component replacement.

Furthermore, these platforms are designed to be resilient, capable of handling emergency scenarios, and protected against cyber security attacks. The integration of advanced technologies and automation ensures smooth and efficient maintenance operations in space, significantly improving space system reliability and sustainability.

5.2. Raw materials sourcing

The core component of any manufacturing process cycle is the raw material, which is severely limited in space. To address this challenge, it is necessary to source metals and plastics required for space system components from space debris and recycle them to recover the materials [29]. For the maintenance of planetary systems, particularly regarding the fabrication of structures and tools, it is crucial to utilize the regolith in its natural form, rather than extracting individual metals from it [30]. Research activities using Lunar regolith are currently being pursued to fabricate transparent glasses, solar cells, metal alloys, and ceramic components [31–34]. Secondary raw materials like resins, binders, dispersants, and solvents must be transported from Earth, and hence the current ISM research on manufacturing processes under microgravity must consider minimal use of these secondary resources. The form of raw material is very crucial in the space environment due to the challenges associated with the handling of powder particles and liquid metals in reduced gravity [34]. Overall, the feedstock preparation, handling, and disposal are important considerations for this architecture.

5.3. Processes

The maintenance platform needs to be adaptable in processing various types of materials like plastics, metals, ceramics, and electronics to accommodate the diverse range of space system components. This requirement on manufacturing process technologies for maintenance is based on the fact that the replaceable parts of ISS encompass all these material types [35]. By integrating hybrid processes such as additive and subtractive manufacturing techniques, a versatile multi-material and multi-manufacturing approach is achieved, enabling the processing of a broad spectrum of materials with a desired level of precision. Brazing of metals emerges as a highly promising solution for repairing internal structural damages in spacecraft caused by micrometeoroid impacts [36]. Process technologies that can handle powders in reduced gravity will be of huge significance for the maintenance of planetary systems since they can utilize the powdery regolith available on the Moon and Mars for fabricating components [37,38]. Additional considerations also must be made for material handling and fixturing to ensure the reliability of the process.

5.4. Energy

Solar cells made of silicon may be efficiently extracted from lunar regolith to supply the energy needed for assembly and manufacturing operations. Given the relative abundance of silicon on the surfaces of the Moon and Mars, this appears to be an economically feasible alternative for planetary maintenance, even though the amount of output power generated is unknown [39]. Oxygen may be extracted from lunar and Martian regolith using a variety of processing techniques, including carbothermal reduction and molten oxide electrolysis [40,41]. This oxygen can then be used as a propellant to power mobile units and provide life support for humans living in habitats on the maintenance platform.

5.5. In-space Metrology

To ensure the quality and accuracy of the fabricated parts, in-process monitoring becomes imperative, thereby reducing rework of defective components, thus saving time and resources. It also allows for a fully automated process which eliminates the necessity for specialized equipment and reduces human involvement [27]. If the maintenance operation is performed on the exterior of the spacecraft, the defect/crack detection using acoustic emissions will be a challenge in the hard vacuum of space. The same can be addressed by the use of X-rays for imaging and defect analysis. The sensing probes and instruments must be robust enough to withstand temperature fluctuations and harmful electromagnetic radiation. The standards for calibrating measuring instruments in space must be established. Machine learning models and Artificial intelligence (ML & AI) provide real-time data on process parameters and can detect any defect anomalies. Apart from processes, these models can also be used to monitor and control the logistics associated with the supply chain of the maintenance platform. Both surface and bulk characterization methods are considered including but not limited to optical metrology tools, thermal sensors, ultrasonic evaluation, X-ray/tomography characterization, and others. The focus of these methods is not only on the identification of surface and bulk defects/flaws but also aid the standardization process discussed below.

5.6. Standardization

The fundamental attributes of the factory design that will facilitate the maintenance of future space systems are modularity, interoperability, and compatibility. These key attributes are encompassed within the proposed maintenance platform, ultimately contributing to the standardization of space operations. The platform's architecture is designed with modularity in mind, incorporating standardized interfaces for mechanical, electrical, thermal, and data connections, as exemplified by the iBOSS mission [42]. Additionally, standardized tools, fixtures, and mounts for both Extra-vehicular activity (EVA) and Intra-vehicular activity (IVA) enhance compatibility across various service missions. The inclusion of ISM capability within the maintenance platform not only ensures design interoperability but also extends to the compatibility of raw materials.

The above-discussed attributes present architecture guidelines for designing a maintenance factory in space and its key components. Apart from the above considerations, the need for hardware development and energy sourcing to deliver various aspects of operations is paramount for the success of this approach. Additionally, one must carefully consider the sustainability of each operation step from start to finish to ensure any unintended consequences and also for a move towards circularity in space operations. The following section provides a brief representative architecture for sustainability considerations in space.

6. Sustainability considerations for maintenance operations in space

The motivation behind the maintenance factory in space architecture stems from enhanced sustainability of in-space operations by eliminating the need to launch desired components/arts from Earth and reducing if not eliminating the reliance on the Earth-space supply chain. While this approach has a sustainability impact and benefits to Earth (e.g., by reducing the fuel costs and emissions for launches), it also has an impact on space sustainability. It must be noted that the concept of space sustainability is a nascent and evolving topic at this stage with limited conceptual understanding and definitions and the discussion below is aimed at expanding the maintenance factory architecture discussed above to provide a starting framework for sustainability models.

Since ISM is at its early stage of development and execution, it is imperative to plan for the long-term sustainability of maintenance operations as well as for the space environment. As such, all the operations discussed above from capturing space debris -to conversion to an appropriate feedstock to processing for the end application must be carefully considered from the perspective of sustainability. Fig. 2 shows a proposed framework for various sustainability touchpoints and considerations serving as a potential foundation for future research, especially when the concept of space sustainability is not fully defined. As depicted in Fig. 2, the considerations for maintenance are divided into three individual branches namely, 1) feedstock considerations, 2) manufacturing process(es), and 3) qualification/testing methods. Each of these branches is further subdivided into sub-branches that offer potential space sustainability touchpoints. At this stage, this fishbone diagram framework is aimed to provide a pictorial and qualitative representation and categorization of the various factors that could impact space sustainability using representative cases. The presented list is not an exhaustive list of all possible operations/techniques and factors. With continued research in this field, the authors believe that this diagram could be further enhanced with a deeper understanding of the sustainability implications through quantitative analysis. It should be noted that these considerations are presented based on the materials and manufacturing process perspective under the assumption that required equipment and energy infrastructure are developed as a part of ongoing research, and technical and commercial developments. Fig.2 is further explained via a

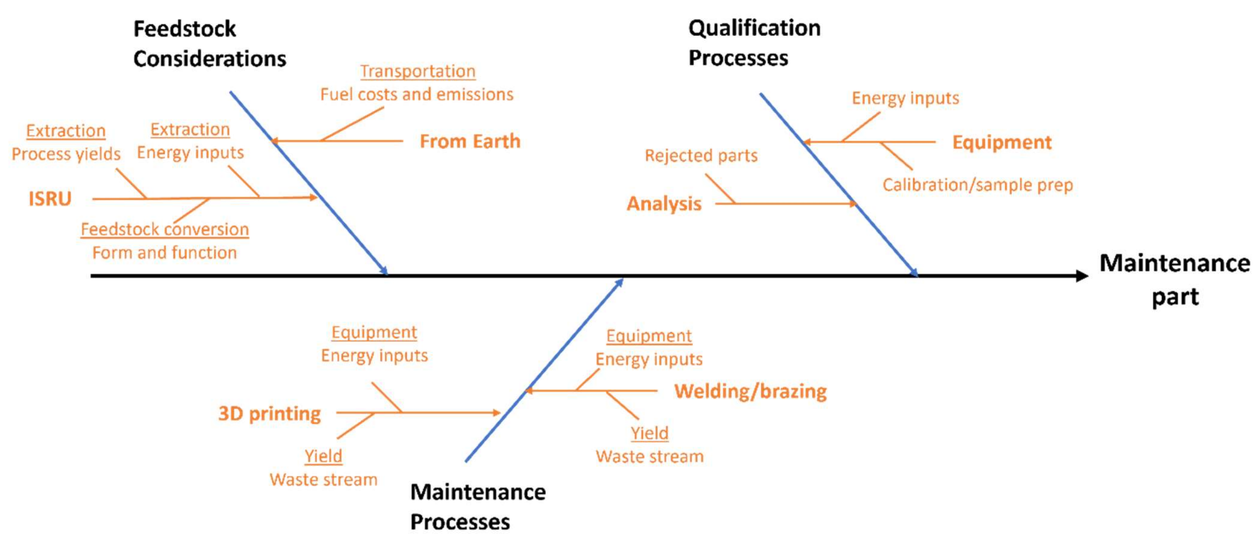

Fig. 2: Proposed framework for depicting sustainability impacts of maintenance operations in space.

hypothetical maintenance operation scenario using additive manufacturing as a manufacturing process illustrative example.

As a representative example, an additive manufacturing process is considered to perform maintenance operations in space (e.g., repair of an electronic component or repair of a structural element). Under the assumption that the right raw materials are available and can be resourced from space. As a part of the ISRU methodology, these raw materials could either be sourced from existing resources on lunar/Martian surfaces (e.g., regolith) or could be reclaimed from the on-orbit space debris (e.g., non-operational/decommissioned satellites). In either case, achieving the right material chemistry/composition to suit the maintenance needs requires extraction operation from the source material. As a sustainability touchpoint, the extraction processes should consider extraction efficiency, energy and material usage, and identification of waste streams and/or disposal strategies. As a post-processing operation, the extracted material needs to be further converted into the right shape, size, and form to serve as a 'feedstock' (e.g. wire spool for FDM or DED processes) for the maintenance additive process which again should be analyzed through same energy and material efficiency analysis from the sustainability perspective. Similar considerations could be made for other potential repair processes such as welding or brazing. In addition to the feedstock requirements and material extraction, the manufacturing process itself carries sustainability touchpoints concerning the energy required to carry out the maintenance/repair operation as well as the generation/disposal of any byproducts (e.g., fumes, scrap) generated during the process. The third consideration is related to the qualification/testing required to ensure that the maintenance/repair operation meets the required integrity and properties. The requirements for the analytical technique in terms of energy or materials in addition to the possibility of failed inspection leading the resource waste would factor into the sustainability aspects of maintenance.

The sustainability framework proposed in Fig. 2 represents a generation 1.0 diagram for in-space maintenance. As the research in this area continues, this framework could be further built upon to develop a more detailed version that consists of more pertinent information and any new knowledge for completeness. It should also be noted that there are some commonalities (e.g., raw material sourcing) in terms of assigning sustainability touchpoints to various manufacturing processes of interest. Also, the framework discussed within this paper does not specifically address the development of equipment/systems that would be used for addressing sustainability and would be a critical consideration for future research.

7. Summary and future directions

This paper presents an idea and conceptualization of the design architecture along with the sustainability framework for the development of 'Factories in Space' necessary for the advancement of maintenance operations to be performed in space. As of now, the extent of maintenance operations performed in space is limited to replacing electronics and refueling missions. The 'maintenance factory in space' architecture presented in this paper aims to target a broader range of operations as a part of ISAM philosophy for Space 2.0 while proposing a framework for sustainability considerations. Maintenance platforms in space aim to redesign the supply chain logistics of maintenance in space using novel techniques such as automation and artificial intelligence to streamline maintenance, limiting the human interaction required. Factories designed in space need to be versatile and multifunctional in order to tackle various application scenarios depending on location and operational requirements. Maintenance factories would employ servicers dedicated to the repair, assembly, and disassembly of spacecraft or other desired components. In-space manufacturing currently faces challenges with ISRU and processes for space boundary conditions. Future research should work toward resolving these challenges to develop processing capabilities while keeping the sustainability of the space environment and the sustainability of ISAM in consideration.

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