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Factory in space: A review of material and manufacturing technologies

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ABSTRACT

The emergence of the new space economy, driven by national space agencies' efforts to reduce costs and promote independent commercial space stations, has led to the rise of private entities such as SpaceX, RedWire, and Blue Origin. This shift, coupled with the anticipated withdrawal of government bodies and the development of smaller, cost-effective commercial space stations, is expected to lead to changes in the design, manufacturing, and logistics of space infrastructure. Currently, the characteristics of space structures are inherently limited by launch constraints, affecting mass, volume, and costs. To address these challenges, the concept of Factory in Space (FIS) has been introduced, significantly impacting space exploration by enabling direct servicing, manufacturing, and assembly of space systems in orbit, thereby circumventing launch limitations. This paper provides an overview of current research and development efforts regarding the various technologies and materials explored for FIS applications, with an emphasis on manufacturing and related technologies. The concept of a closed-loop factory reinforces the crucial role of in-situ material utilization (ISMU), and Additive Manufacturing (AM) is identified as particularly advantageous due to its speed, flexibility, and customizability, offering clear benefits over traditional manufacturing methods. Lastly, the paper identifies areas for further research to advance the potential of FIS, highlighting significant progress in in-space manufacturing.

Abbreviation

3Rs	Reduce, Reuse, Recycle
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
AMF	Additive Manufacturing Facility
CAL	Computer Axial Lithography
CFRP	Carbon Fiber Reinforced Polymer
CFRTPC	Continuous Fiber Reinforced Thermoplastic Composite
CMM	Ceramic manufacturing Module
CNC	Computer Numerical Control
EHDP	Electrohydrodynamic Printing
ELISSA	Experimental Lab for Proximity Operations and Space situation Awareness
ESA	European Space Agency
FDM	Fused Deposition Modeling
FIS	Factory in Space
FSW	Friction Stir Welding
FSSW	Friction Stir Spot Welding
HST	Hubble Space Telescope
ISMU	In-situ Material Utilization
ISS	International Space Station
JAXA	The Japan Aerospace Exploration Agency
LBM	Laser Beam Melting
LCM	Lithography-based Ceramic Manufacturing
LEO	Low Earth Orbit
MAMBA	Metal Advanced Manufacturing Bot-Assisted Assembly
MDG	Metal Droplet Generation
MELT	Manufacturing of Experimental Layer Technology
NASA	National Aeronautics and Space Administration
OSAM	On-orbit Servicing, Assembly and Manufacturing
PC	Polycarbonate
PCL-PEO	Polycaprolactone Polyethylene Oxide
PEEK	Polyether Ether Ketone
PF	Parabolic Flight
PLA	Polyactic Acid
Roscosmos	The State Corporation for Space Activities
SAA	Self-Aligning and Adjusting
SLA	StereoLitography
UAM	Ultrasonic Additive Manufactuirng
UV	Ultraviolet
VP	Vat Polymerization

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1. Introduction

Space exploration has always embodied humanity's boundless ambition for expansion and discovery. Human spaceflight has captivated society, from the historic Moon landings of the late 1960s and early 1970s to recent endeavors in Low Earth Orbit (LEO). 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, designed to test initial capabilities in Earth's Orbit, offered vital breakthroughs in communication, global positioning, and weather forecasting [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 the National Aeronautical and Space Administration (NASA), European Space Agency (ESA), The Japan Aerospace Exploration Agency (JAXA) and The State Corporation for Space Activities (Roscosmos), 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, manufacturing techniques like Additive Manufacturing (AM), and advanced machining [9] have played a pivotal role. Additionally, introducing reusable launchers has significantly reduced costs and increased accessibility to space.

A promising solution that tackles the issues related to the transportation of large equipment during long-term space exploration is the concept of Factory in Space (FIS) [8,10]. FIS dictates the servicing, manufacturing, and assembly of components outside the Earth's atmosphere, circumnavigating logistical obstacles. FIS encompasses several in-orbit activities, including servicing, refueling, repair, life extension, de-orbiting, refurbishing, and recycling. Furthermore, this wide range of FIS activities has the potential to improve and benefit human spaceflight. Servicing operations such as deorbiting and refueling reduce collision chances and provide a more robust communication infrastructure.

Moreover, transitioning maintenance activities from astronauts (Hubble space telescope repair mission [11]) to robots (development and demonstrations of robotic arms [12–14]) would reduce the cost of operating space systems in the long run [15]. Space systems manufactured or assembled in Orbit will have significant technical benefits over those done traditionally on the ground. These systems would be spared from fairing constraints [16], whereby the volume of the launch vehicle's fairing dictates the size of the launched systems [17]. Hence, FIS serves as a way to circumnavigate these constraints through on-orbit assembly.

The modular design and assembly of the ISS by the international space community has demonstrated the benefit of in-orbit assembly, as the ISS -the size of a football field-could not have been commissioned in a single launch [18]. NASA and its partners are currently exploring FIS concepts relating to in-orbit assembly to replace deployable structures with components to be assembled, thus maximizing packaging efficiency [19], as well as the introduction of modularity during the assembly of traditional satellites [20]. In addition to in-orbit assembly, space practitioners are exploring and utilizing the enormous potential of in-orbit manufacturing, and investigations of the manufacturing of materials in space for terrestrial and extraterrestrial applications are ongoing [21]. A system manufactured and assembled entirely in space would be considerably different from the one manufactured on Earth. FIS could take advantage of materials not exposed to air and bypass the geometric, size, and structural limitations imposed by gravitational forces and launch constraints [22]. Most of the robotic platforms planned for manufacturing activities in space are very reminiscent of the technologies utilized for in-orbit assembly. After a component is manufactured, several maneuvers are required to enable its activation on a space system. Several terrestrial maneuvers, such as joining and welding, could be feasible in Orbit. The evaluation and inspection of components manufactured in space would be paramount as the complexity of components increases [23]. However, manufacturing in Orbit is still nascent compared to assembly and servicing activities. For example, the first 3D printers were installed in the ISS in 2014, with a permanent Additive Manufacturing Facility installed later in 2016 [24]; in comparison, the ISS was assembled much earlier and became operational in the year 2000 [25].

Another impact of the FIS concept is waste management in space exploration. As space exploration progresses, waste, including biological waste, clothing, packaging, and solid structures, poses a pressing issue that requires careful disposal strategies [26]. 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 space travel objectives must be explored. In this regard, the reduce, reuse, and recycle (3Rs) design, rooted in the principles of the traditional circular economy, emerges as a promising approach [27,28]. 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 [29]. The limited resources in isolated colonies, such as space stations, necessitate 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 reduces reliance on Earth for resupply and addresses ethical concerns regarding space waste generation and the preservation of extraterrestrial ecosystems [30]. 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" [31]. Space debris, as defined by NASA [32], 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 launched into space [33]. Murtaza et al. [34] reported on the threat posed by the accumulation of orbital debris by concluding that the danger of a catastrophic occurrence increases if the population of orbital debris is not reduced. Moreover, Clormann et al. [35] argue that space debris is anything but a distant outer space phenomenon; it is a subject of responsibility and sustainability. Therefore, FIS cannot only lead to a thriving space economy but also help reduce the waste and clutter in Orbit, making space exploration more circular and sustainable.

Recent works have provided in-depth overviews of FIS activities, with a focus mainly on certain aspects of FIS, such as in-space AM [36,37], on-orbit servicing [38], space robotics [39], assembly [40], and material framework [41]. Building on these efforts, this review study presents suitable materials, processes, and traditional manufacturing technologies, not just AM, that can be adapted to FIS activities. This paper aims to provide an insight into the overarching research question:

> "What are the current materials and manufacturing technologies being researched for FIS applications?"

This work focuses on the development of various materials and manufacturing technologies for FIS applications. This provides insight into what kind of systems can be adopted for FIS applications and defines the boundaries of its capabilities. A brief overview of materials proposed for FIS applications and their resulting properties are presented. Prominent manufacturing technologies reported in the literature are discussed, and how they are integrated/adapted to extraterrestrial conditions such as microgravity and vacuum is highlighted. Finally, in the discussion section, manufacturing technologies are compared, and shortcomings are underscored with an enumeration of the path of potential further research.

2. Research approach

A literature survey was conducted to identify publications relevant to FIS's manufacturing technologies. A "narrative-systematic" literature review, as Turnbull et al. [42] proposed, was adopted to understand the various technologies and designs concerning FIS. The hybrid approach was adopted such that the data search protocols followed that of a systematic literature review while the selected literature was analyzed using a narrative literature review approach. This section presents the data collection and analysis techniques employed for this work.

The review was carried out in three phases: collection, sorting, and analysis. The collection phase involved a structured keyword search on Scopus™. As formulated in Table 1, a general perspective was adopted during the collection phase to accumulate the documents relevant to FIS and its related manufacturing technologies. Keywords such as "manufacturing in space", "in-orbit manufacturing", and "factory in space" were queried on the database. Furthermore, a combination of keywords, for instance, "manufacturing" AND "low earth Orbit", "manufacturing" AND "space", and "factory" AND "low earth Orbit" were also queried. However, the majority of results of the combinations were deemed to be outside of the scope of this review, and the others were discarded upon cross-referencing with the initial search results. Table 1 demonstrates the combination of keywords and the total number of documents obtained from the query included in this work. Fig. 1 shows the correlation between the keywords. Significant attention was paid to the most prominent manufacturing technologies adopted in the traditional aerospace industry, as well as novel approaches that have been studied for FIS activities.

Upon completion of the publication collection, a sorting operation (second phase) was implemented. The publications were collected without considering constraints on the publication year or subject area and evaluating only journal or conference papers written in English. Subsequently, only publications between the ten years of 2013 and 2023 were considered (considering the relevance of technologies in this research context). This led to the exclusion of 74 contributions. Furthermore, the publications' titles, abstracts, and keywords were assessed to ascertain their relevance to FIS and related manufacturing technologies. This resulted in the further exclusion of 130 contributions.

Table 1
Keyword search on Scopus.

Scope	Keyword	Result
1	"Manufacturing in space"	62
2	"On-orbit manufacturing"	23
3	"In-orbit manufacturing"	18
4	"Factory in space"	8
5	"In-space manufacturing"	168
Total publication		**279**
Total publication from 2013 to 2023		**279–74 = 205**
Total publication after title and abstract analysis		**205–130 = 75**
Total publication after text analysis		**75–13 = 63**

Finally, a complete analysis of the publications was performed (phase 3) by thoroughly reading 75 manuscripts. This allowed for considering a final set of 63 publications assessing the manufacturing technologies relevant to FIS.

The methodology employed for the literature review is illustrated in Fig. 2. Eleven documents were considered through manual (snowballing) search and cross-referencing. Adopting the three phases as mentioned earlier and defined boundaries narrowed the total number of publications from 290 to 63. Two authors collected the publications individually to avoid any analytical bias. A comparison of the two results allowed for consistency in the selected publications. The publication selection was based on the relevance of the manuscript to FIS and related manufacturing technology.

Finally, it is essential to highlight that while this review is presented as comprehensively as possible, it only covers some FIS activities and related technologies due to the sparsity of details available in the research domain. For instance, some references are not in the form of peer-reviewed information but rather presentations by reputed organizations such as NASA. Furthermore, governmental bodies such as NASA and ESA cannot release the latest information to the public due to their sensitivity, and even less information is provided by commercial bodies such as SpaceX, Boeing, Redwire, and others. Therefore, the authors rely on peer-reviewed documentation and non-academic documents presented by reputable bodies.

3. Factory 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. A promising solution would be integrating maintenance and manufacturing systems into space missions. FIS is a concept that includes fabrication, assembly, integration, and maintenance of goods and components outside of the Earth's atmosphere. Fig. 3 summarizes the activities encompassed under the FIS umbrella.

The idea of FIS has floated around since the late 1900s. In 1973, the Skylab mission astronauts demonstrated the possibility of on-orbit operations by repairing a jammed solar array and antenna on the Skylab station [43]. Furthermore, the first in-space servicing mission occurred in 1984 when the altitude control system aboard the Solar Maximum Mission failed, and a crew of astronauts was dispatched on a repair mission on NASA's space shuttle [44]. This led to the development of the Hubble Space Telescope (HST), with in-space servicing taking a fundamental role in mission objectives [45]. The HST was designed so that astronauts could replace defunct components in Orbit to keep the telescope functional and extend its mission life. The servicing missions maintained the full mission capabilities and extended their mission life beyond the initial 15-year span [11,46]. Stoor [47] concluded that the HST validated the cost reduction goal and was a crucial lesson for future in-orbit manufacturing missions. Following the HST, many efforts have been made to develop technology that can facilitate autonomous in-space servicing and manufacturing. The "Orbital Express" - initiated in 2007 – developed with the Defense Advanced Research Project Agency, successfully demonstrated robot satellite services, including autonomous assembly [48]. Furthermore, the development of robotic arms using proprietary technology by both NASA and ESA further demonstrates the keen interest in developing autonomous technology for in-orbit applications [40]. While several studies have reported previous efforts to develop technologies for in-orbit servicing, manufacturing, and assembly [38,40,49], one key technology identified is AM.

It is possible to draw parallels between these efforts and the transformative technology of AM. The advancement of AM techniques allows for a rapid prototyping technology that provides ready-to-use parts directly from stock material [50]. 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

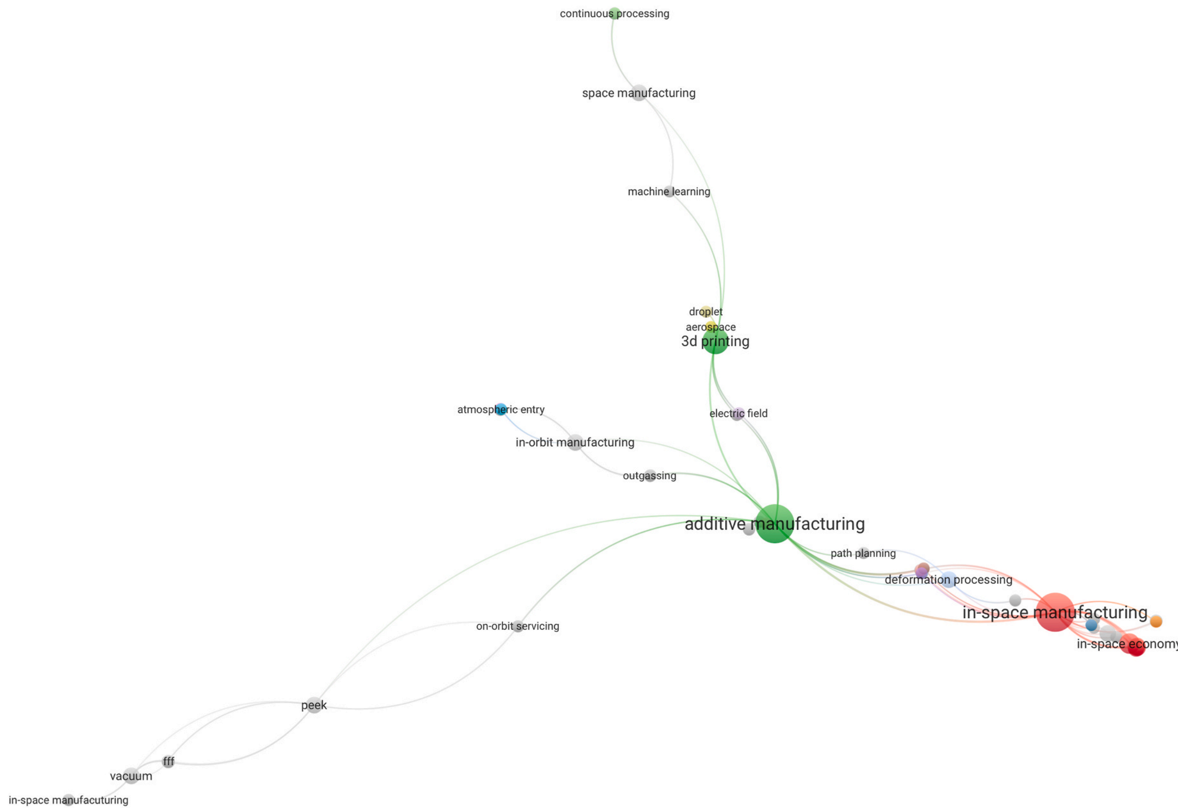

Fig. 1. Keyword correlation map.

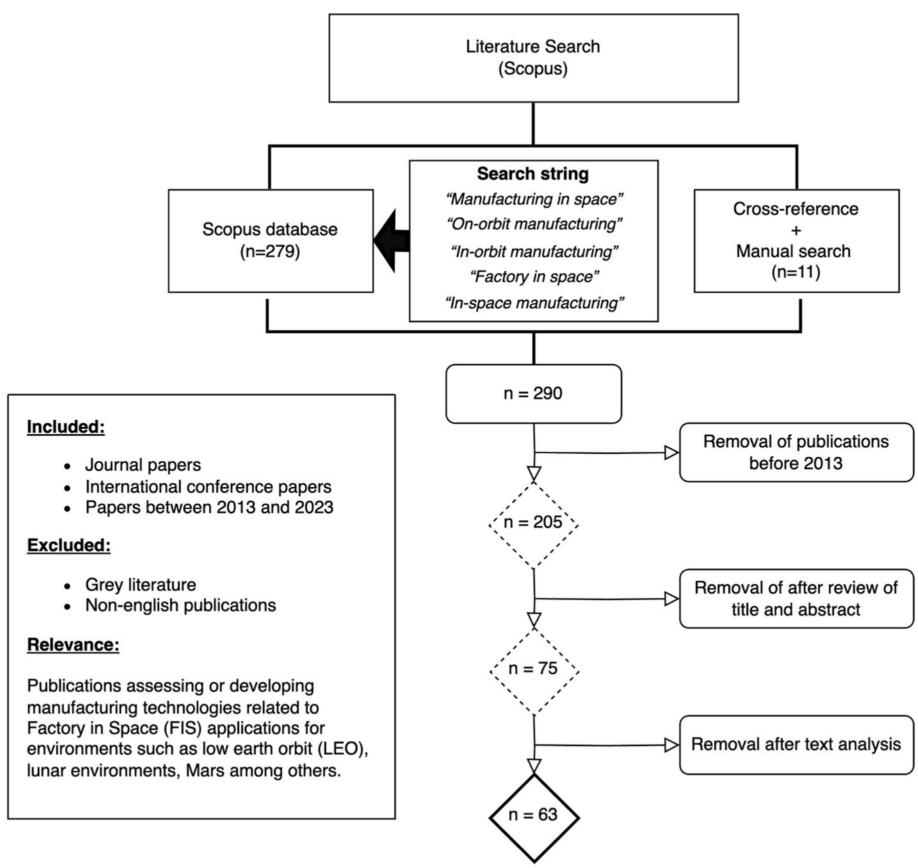

Fig. 2. Literature review methodology.

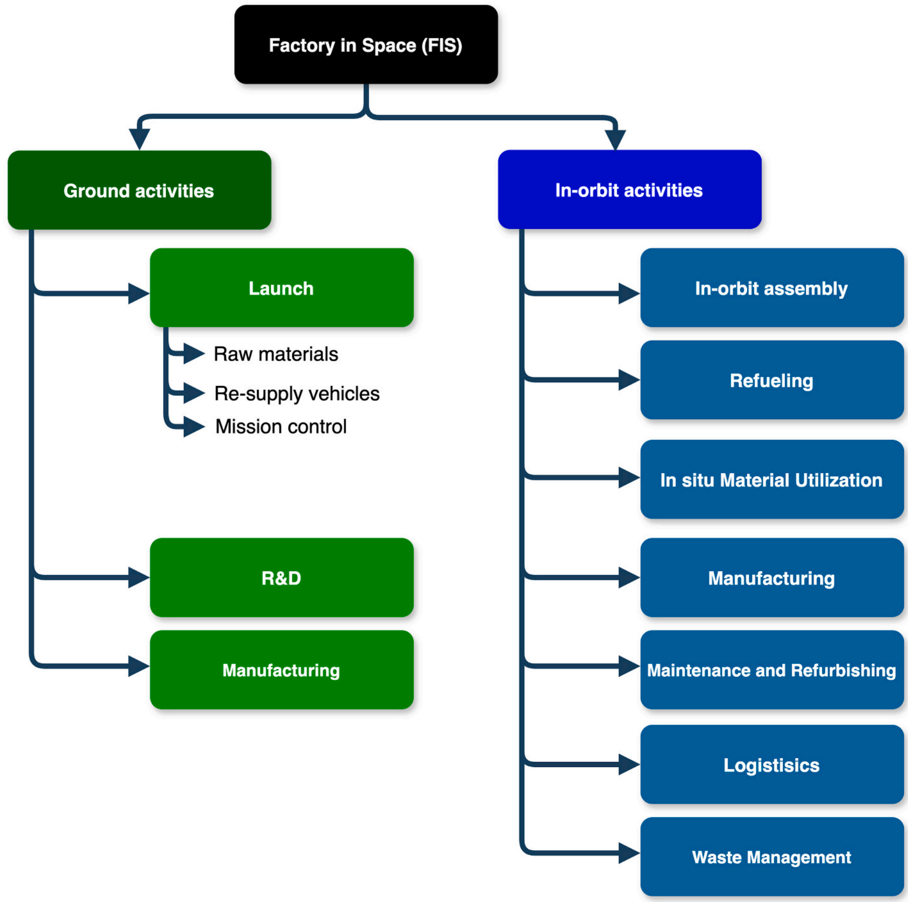

Fig. 3. Summary of FIS activities.

under the 3D Printing in Zero-G project [24]. Furthermore, in 2016, the Additive Manufacturing Facility (AMF) was installed. 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, discontinued in 2024 [51] due to "technical, cost, and schedule challenges", was supposed to refuel satellites, assemble antennas, and manufacture beams [52]. On the other hand, the OSAM-2, a technology demonstration mission, was concluded prior to flight in 2023 with valuable lessons and data stored for future projects [53].

On the other hand, the European Union (EU) is developing FIS concepts as part of their projects on AM in the aerospace industry [54]. 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 [55]. AMAZE used the AM techniques developed in the US to develop technologies relevant to 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 [56]. Makaya et al. [57] summarized ESA's activities in space manufacturing. Another recent effort is the work of the China Academy of Space Technology [58], 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.

Another essential factor to consider in the development of FIS activities is the emergence of commercial activities [54] i.e., transactions from private entities delivering products or services to private customers and not only as contracts to institutional space agencies. In addition to the usual institutional missions such as Redwire's OSAM for NASA or Thales Alenia Space's In-Orbit Servicing demonstration mission for the Italian Space Agency [59], the pivotal roles of Redwire in the development of the commercial AMF facility or of Northrop Grumman's development of the Mission Extension Vehicle for commercial customers, can be mentioned. The first FIS mission related to private

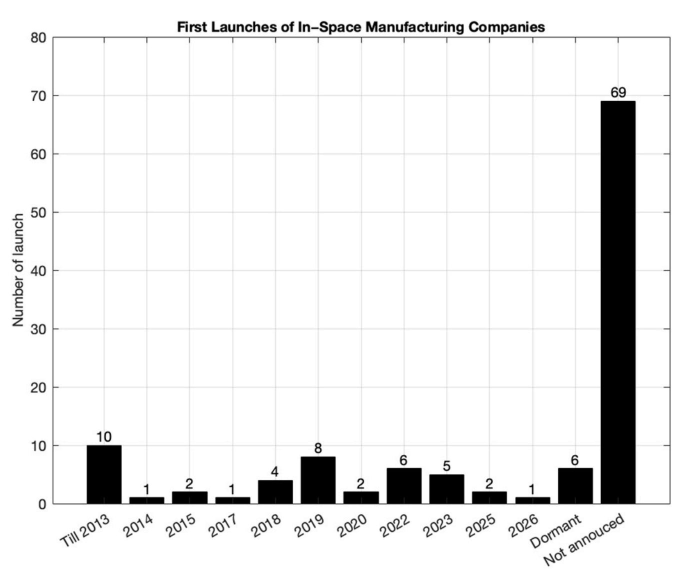

Fig. 4. First launches by commercial FIS companies (adapted from Ref. [60]).

companies is reported in Fig. 4 [60], which highlights a variety of conceptual, announced, and in-progress missions. The current status of these missions further depicts the dynamic nature of FIS and its commitment to fulfilling its full potential.

4. Materials

Understanding manufacturing technologies developed for FIS requires an overview of materials involved in FIS applications. Researchers have investigated the effect of materials found in outer space and locally on Earth with manufacturing processes developed for extraterrestrial activities. In this section, materials proposed to be manufactured in Orbit are divided into two categories, as illustrated in Fig. 5, those found on Earth and those available in Orbit, and are subsequently discussed.

4.1. In-situ material utilization (ISMU)

Transportation of materials from Earth for FIS applications during missions is not optimal, especially during long-term missions. The launch volume and costs associated with the additional payload make it pertinent to locally source/produce or sustain materials during space missions. Therefore, for extended missions, using in-situ material must be of utmost priority if the concept of FIS is to be actualized. In-situ material Utilization (ISMU) refers to the exploitation of locally-established materials to support/enhance space missions. The idea of ISMU for FIS envisions a scenario where material launch from Earth would be bypassed, and locally sourced materials would be used for manufacturing rigid and complex structures in space. Several sources of material available in outer space could be utilized for FIS applications. In this study, for simplicity, the materials are divided into two groups: raw materials and space junk.

Raw materials in this context are the materials that are readily available in extraterrestrial environments such as lunar and Martian regolith. In the case of this kind of material, the value that can be gained also heavily depends on the available technology. These materials might require additional processes before being used with traditional manufacturing technologies or need a new technology to manufacture rigid structures directly. Researchers have relied on developing simulants to imitate the properties of several space-based materials to study the raw materials found in extraterrestrial environments. The scarcity of materials for investigation also further limits the development of relevant material processing technology for implementation in FIS. The composition of the simulants is listed in Tables 2 and 3.

Notwithstanding, researchers have reported on the possibility of extracting relevant resources from raw materials found in extraterrestrial environments. Scientists at the ESA have demonstrated that the addition of specific binders in regolith can lead to the suitable

Table 2
Composition of Lunar regolith simulants and Apollo samples [66].

Oxide	DNA-1(Wt%)	JSC-1A(Wt%)	Lunar Soil Samples(Wt%)
SiO_2	41.9	41	47.3
TiO_2	1.31	1.6	1.6
Al_2O_3	16.02	15.9	17.8
Fe_2O_3	14.6	18.1	0.0
FeO	0.0	0.0	10.5
MgO	6.34	4.73	9.6
CaO	12.9	13.2	11.4
Na_2O	2.66	2.5	0.7
K_2O	2.53	1.05	0.6
MnO	0.21	0.24	0.1
Cr_2O_3	0.0	0.03	0.2
P_2O_5	0.34	0.63	0.0
Total	98.9	99.0	99.8

Table 3
Composition of martial regolith simulant [67].

Oxide	Pathfinder (Wt%)	JSC-1 Mars Simulant (Wt%)
SiO_2	44	43.5
TiO_2	1.1	3.8
Al_2O_3	7.5	23.3
Fe_2O_3	16.5	15.6
CaO	5.6	6.2
Na_2O	2.1	2.4
MgO	7.0	3.4
Total	83.8	98.2

performance of the regolith [57]. Cesaretti et al. [61] used magnesium chloride binder with lunar regolith simulant and reported that the binder allowed the simulant to achieve the desired hardening, making it a suitable material for manufacturing building blocks required for habitat construction on the moon—similarly, Buchner et al. [62] proposed phosphoric acid as a liquid binding agent for lunar regolith simulant. Furthermore, Castelein et al. [63] demonstrated that iron can be microbially extracted from untreated lunar and Martian regolith. This further illustrated the potential of ISRU for in-orbit construction of solid infrastructure and hardware during mission operations. Basalt is another earthly material investigated due to its abundance in Martian environments [64]. Basalt has been established to reinforce the mechanical properties of traditional polymeric material [65]. One crucial property of basalt is its ability to provide a shield from radiation, an essential factor when building habitats on Mars. This also means the cost associated with the construction of radiation-shielded habitats would be negligible compared to transporting materials from the earth to build such structures.

Other than raw materials, another source of material available for

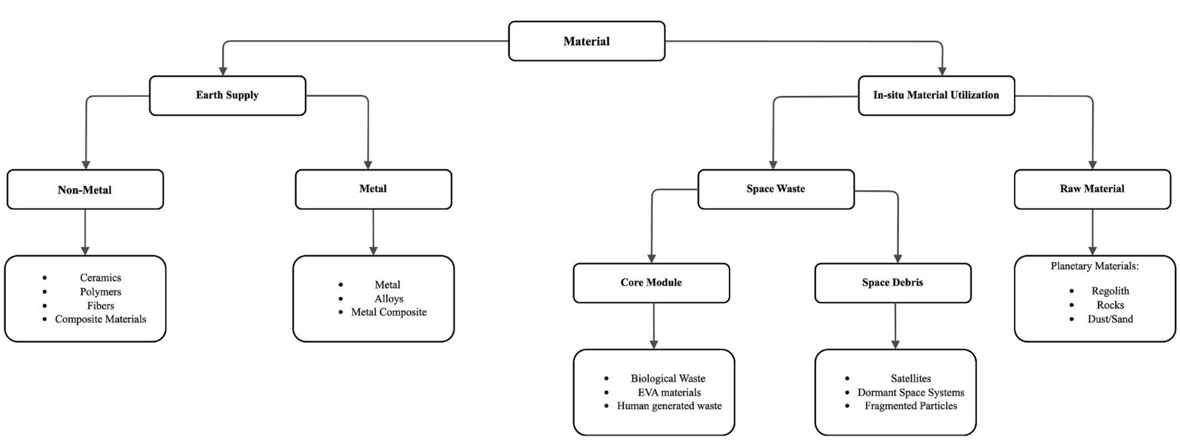

Fig. 5. Summary of material sources for FIS.

ISMU, is the space junk. Space junk is any material outside Earth's atmosphere due to the launch and entry of man-made objects into outer space. Generally, these materials can be found as debris, defunct space platforms roaming in Orbit, and materials generated from manned missions. Linne et al. [26] have attempted to understand the materials found aboard manned missions by understanding the waste generated during the mission. Two mission scenarios were considered to evaluate the type of waste generated during these missions: the Gateway and Mars exploration missions. The Gateway mission was divided into Phase I (24–90-day trip) and Phase II (90–180-day journey). A detailed waste model for space exploration was developed, categorizing the generated waste types, as presented in Table 4.

Other than materials and waste generated in the core module, orbital debris could be another source of value for ISMU. The debris value has been perfectly summed up by a NASA report [68] stating, "Recycling space debris may also contribute revenue to nascent markets for in-space manufacturing and assembly if debris can be gainfully reused in space." This material category generally comprises defunct space systems and satellites roaming in Orbit. Economic value can be obtained from the utilization of materials that exist in the defunct space systems. As Koch [69] stated, tons of scrap metals roaming in Orbit can be utilized in FIS activities. For instance, they demonstrated that the cost of scrapping aluminum in situ is cheaper than launching aluminum directly from the Earth.

Furthermore, the value of the estimated 7000 tons of orbital debris is estimated to be between 600 billion and 1.2 trillion dollars [70]. To better understand the materials that make up the debris found in Earth's Orbit, Table 5 gives a generic material composition of the payload found in Orbit. These values were estimated by Leonard et al. [70] based on satellite illustrations and blueprints, and as such, data does not currently exist in any form.

The use of debris for ISMU is not only a matter of space exploration but also that of sustainability and responsibility. Murtaza et al. [34] further argue that the threat of a catastrophic occurrence increases if the orbital debris population is not decreased (The Kessler syndrome). The economic, environmental, and social impact of the Kessler syndrome would be severe, as critical space applications such as communications, weather, climate forecasts, and global monitoring would be affected. Therefore, finding ways to manage the accumulated debris and decelerate the accumulation properly is paramount. For this reason, the implantation of ISMU for FIS could lead to the establishment of a closed-loop factory that not only focuses on the utilization of debris materials but also reduces the reliance on Earth for material resupply.

4.2. Earthly materials

Conventional manufacturing processes have continuously utilized the abundant material found on earth to produce parts. Therefore, during the initial trials of the 3D printing experiments aboard the ISS, commercial polymer acrylonitrile butadiene styrene (ABS) was successfully used as feedstock to produce several functional components without any significant chemical or mechanical degradation to the material. This led to a 24-month study to analyze the behavior of polymer filaments aboard the ISS. The findings suggested that the internal environment of the ISS is more favorable to polymers than the exterior environment, particularly when the material is stored properly [71]. In this section, the materials that have been investigated for FIS applications are investigated. Materials are divided into two groups: metal and non-metals:

4.2.1. Non-metals

Several commercially available materials have been investigated for their feasibility for in-orbit manufacturing. The properties of some materials proposed for FIS applications are tabulated in Table 6. Other than ABS, which was examined using the AMF aboard zero-g flights and on the ground before its eventual launch to the ISS. The resulting properties of the ABS material were compared and are presented in Table 7. Furthermore, the AMF has an expanded material envelope, including high-density polyethylene and ULTEM 9085 [72]. The success of the AMF led researchers to investigate the possibility of manufacturing several other polymers outside of Earth's atmosphere.

Cowley et al. [73] investigated the effects of variable gravity conditions on polylactic acid (PLA) thermoplastic filament. They concluded that the mechanical properties of the material were not significantly affected. However, some defects microstructure defects were observed, which were due to manufacturing processes. Other polymers have been investigated for extraterrestrial application to achieve better mechanical properties. Quinn et al. [74] investigated the effect of a low vacuum environment on polycarbonate (PC) filament. They reported an overall improvement in the mechanical properties of PCs exposed to a vacuum environment compared to reference material. This was associated with several parameters, such as the low thermal transfer in vacuum

Table 4
Manned mission waste summary [26].

	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

Table 5
Generic material composition of payload found in Earth's Orbit [70].

Material Class	Material (% Composition within Material Class)	Material Value ($/object Kg)	%Composition within Payload
Metallic material	Aluminum (30 %)	0.791	70
	Steel (5 %)	0.023	
	Copper (10 %)	0.932	
	Aluminum Alloy (25 %)	3	
	Gold (5 %)	0.896	
	Silver (5 %)	0.001	
	Nickel (5 %)	0.946	
	Titanium Alloy (15 %)	6.75	
	Mean	**12.53**	
Polymerics, Composites, Ceramics	Proxy Value	15	30

Table 6
Inherent material properties of selected polymers [64].

Polymer	Melting Point (^{O}C)	Density (Kg/m^3)	Properties
ABS	–	1070	Amorphous Good impact resistance Toughness and rigidity
PLA	65	1300	Most used Low thermal expansion Good layer adhesion
PEEK	343	1320	Semicrystalline thermoplastic Great mechanical and chemical resistance Resilience against high temperatures

Table 7
Performance of Polymers in in-orbit conditions.

	Ultimate strength (MPa) - Tensile		Ultimate strength (MPa) - Compressive	
	Reference	In-orbit	Reference	In-orbit
ABS [77]	38	37.8	51.5	52.9
PLA [73]	40.2	33.6	47.1	43.2
PC [74]	56.2	59.3	64.5	71.7
PEEK [50]	64 ± 4.5	82.3 ± 1.5	–	–

conditions. This could lead to better fusion between polymer threads and favorable intermolecular chain fusion between each printed layer. Another high-performance polymer investigated for in-orbit utilization is polyether ether ketone (PEEK). Zocca et al. [50] explored using PEEK in extreme environments with low pressure or vacuum conditions. They concluded that by properly regulating the temperature, it is possible to utilize PEEK for in-orbit applications. Other researchers [50,75] have investigated the development of carbon fiber-reinforced polymers (CFRP) as potential raw materials for FIS applications. Various matrix materials (PLA, PEEK, ABS) to be reinforced with carbon fiber have been proposed. Some non-metals have been studied as possible replacements for traditional materials producing functional components, especially electronic parts. Mitra et al. [76] proposed using conductive polymer filament, electrifi, for in-space manufacturing of functional components such as antennas.

4.2.2. Metals

The utilization of metals for FIS application is relatively in the nacent stages as compared to thermoplastic and polymers. This is evident with the installation and capabilities of the AMF aboard the ISS. Furthermore, the advanced material properties of metals make them significantly challenging to manufacture compared to polymeric materials. Hence, much focus has been on evaluating polymers and ISRU rather than traditional metals. However, some researchers have investigated metallic materials for FIS applications, such as Korkut et al. [78], who investigated using Tin-Lead solders to manufacture electric circuits during extraterrestrial missions. Zocca et al. [50] investigated using stainless steel for in-orbit application during a parabolic flight. Castelein [63] proposed using iron extracted from regolith simulants to manufacture rigid structures in lunar and Martian environments. Similarly, Evans et al. [79] proposed iron as a raw material for in-space manufacturing. Aluminum alloys, a commonly used material in the aerospace industry, have also been proposed [80,81].

Overall, while this section has presented an overview of materials suitable for FIS applications, it further highlights the harsh nature of the extraterrestrial environment as significant effort focuses on the utilization of materials in confined and controlled spaces such as the ISS without exposure to external conditions such as temperature and space radiation that could cause thermal stress deformation and degradation of mechanical properties [82]. Therefore, to advance the concept of FIS, there is further need to develop high performance materials that could not only function in microgravity but also withstand the harsh condition of the extraterrestrial environment outside of the ISS facility.

5. Manufacturing technology

The dynamic nature outside the earth's atmosphere dictates that traditional manufacturing technology cannot be directly adapted to FIS. Multi-physics phenomena such as microgravity, temperature, and operation platform, among others, are not considered during traditional earth manufacturing. Hence, they can be considered significant limitations to integrating manufacturing systems into space exploration. Some of the challenges associated with the integration of conventional manufacturing technologies are discussed below:

- **Physics**: The physics involved in space manufacturing is unique. Several factors must be considered, such as gravitational forces, temperature, radiation, vacuum, and the atmosphere. Moreover, the physics involved in manufacturing processes on Earth are usually constant, whereas the physical factors outside the Earth's atmosphere are typically dynamic. These factors must be integrated into the designing, manufacturing, and implementation phases of the traditional materials science and engineering paradigm.
- **Raw Materials**: The availability and definition of raw materials for manufacturing in FIS are very limited. This limitation further means it is difficult for researchers on Earth to study, simulate, and scrutinize these materials. One possible solution is the ISMU, as mentioned earlier. Fateri et al. [83] envision ISMU as manufacturing components from bulk materials such as regolith found on Mars or the Moon in abundance. Furthermore, a report from NASA concluded that space debris could be "gainfully" utilized as raw material in FIS [68]. However, the issue of de-orbiting space debris is one of the keenly debated topics in the industry [84]. Another option is launching raw materials from Earth to FIS, but that goes against the definition of FIS. Hence, there is a challenge to developing technologies and processes that can utilize a wide range of materials, from traditional earth materials to lunar regolith.
- **Platform**: This challenge is related to the limited availability of platforms to conduct experimental studies. One such platform is parabolic flights (PF). PF gives engineers and scientists a short window (20–30 s) to conduct experiments in a simulated space environment [85]. Sounding rockets is another platform that is used to simulate microgravity. It is considered a time- and cost-effective platform for simulated space conditions in experiments. They usually offer a window of a couple of minutes at altitudes greater than 100 km for scientists and engineers to gather data [86].
- **Setup**: Developing a suitable setup to be deployed in space is as important as the required platform. Most setups are experimental and are meant for demonstration purposes only. Scaling the experimental setups to commercial-grade manufacturing equipment suitable for the harsh and unique nature of extraterrestrial environment remains a challenge.
- **Iteration**: Developing technology for FIS requires understanding manufacturing processes under microgravity conditions through several iterations. Each iteration of the manufacturing process can take significant time (months and years) [85] and effort to analyze and understand. There is a limitation to process iteration due to the duration of the flights (PF, sounding rocket, etc.), where each iteration cycle lasts months at the maximum. It is, therefore, paramount to find ways to circumvent the limitation of process iteration, which is also tied to the platform constraints.

Thus, additional focus must be placed on developing novel techniques to augment current manufacturing technologies, such that they are suitable for harsh conditions of the extraterrestrial environment. This section discusses the efforts made by researchers to improve and develop manufacturing technologies for in-situ utilization during space explorations.

5.1. Additive manufacturing

AM is the layer-by-layer fabrication of parts from raw/stock material known as feedstock. The feedstock is usually in the form of powder, filament(wire), liquid, or paste. The layers are fused, cross-linked, or compressed to form the desired geometry [87]. Generally, in AM the final material property depends on the AM technology and geometry of the manufactured part and this could increase the complexity associated with fabrication using AM. However, AM offers several advantages, such as the 'print and use' nature, which means parts are manufactured from stock and directly utilized without further processing. This allows for a swift and flexible response to any demand for components in an emergency or situations where resupply missions are impossible. Over the past years, AM for in-orbit applications has gained much interest and is considered a cornerstone for developing the commercial space economy. AM has primarily been proposed for space applications, focusing on manufacturing spare parts and components for the ISS, among other applications. The installation of the first commercial AM setup, the AMF, on the ISS in 2016 evidences this. The AMF is a 3D printer based on fused deposition modeling developed by Redwire (formerly Made in Space Inc.) and installed by NASA. Since its installation, the AMF has been made commercially available to private and public bodies of the ISS community to manufacture the required components in situ [88], printing hundreds of polymeric parts. The printing capabilities on the ISS were further expanded in 2020 with the inclusion of a Ceramic manufacturing Module (CMM) [89], which allows the printing of ceramic-based materials. This was similar to the technology the Chinese Academy of Sciences tested in 2018 on a parabolic flight [50]. The Chinese technology was based on digital light processing to print ceramic green bodies. Furthermore, in 2019, a 3D Bio-Fabrication Facility (BFF) [90] was developed by partners of the ISS National Laboratory. The BFF uses human cells and proteins derived from tissues as ink for 3D printing. Another development for the ISS was the "Refabricator" [91], which was used to recycle 3D-printed plastic parts. The "Refabricator" was developed by Tethers Unlimited and installed by NASA. A similar plastic recycling device was also designed and installed in 2019 by Redwire in collaboration with Braskem [92].

While many efforts are focused on LEO with the ISS, several researchers have reported on AM technology developed for other celestial bodies. For example, in 2020, the ISS national lab organized a workshop focused on AM activities in space. The workshop focused on how AM can support future explorations of lunar and Martian environments. Many techniques have been developed and simulated under lunar and Martian conditions for several scenarios ranging from the fabrication of components to constructing an entire colony of habitats. Several AM techniques developed for FIS activities are discussed in detail in this subsection.

5.1.1. *Laser beam melting (LBM)*

In LBM, parts are manufactured through layer-by-layer powder deposition with the aid of a purified gas. The manufacturing of parts starts with the selection of the desired 3D models; then, the device creates a powder layer, which is spread each time at a certain thickness from the bottom up by selectively scanning the laser beam to initially pre-heat or sinter specific areas of the metal powder layer as required to build the desired geometry. Gradually sintering the powder is needed to prevent it from spreading. Then, the selected areas are melted with full laser power, forming a molten pool, which solidifies into a dense layer with fine microstructure. The platform is lowered, and a new powder layer is spread to restart the process until the desired geometry is achieved. The stages of the LBM process are summarized in Fig. 6. LBM is an AM technique generally adopted for traditional manufacturing on Earth. However, certain considerations and adjustments are necessary to adopt this technology for FIS activities.

Zocca et al. [85], building on their previous work [94], developed a "gas flow-assisted powder deposition" process idea for LBM to compensate for the reduced or missing gravitational forces in space. They introduced an additional force acting on each particle by establishing a gas flow through the powder bed. The "gas flow-assisted powder deposition" was based on a porous platform acting as a filter for the fixation of the particles in the gas flow and was driven by a reduced pressure established by a vacuum pump underneath the platform. They claim that this process could be used to manufacture ready-to-use parts in outer space when combined with a laser source. The schematic of the proposed LBM unit is illustrated in Fig. 7. To test the design, an experimental device was mounted on a parabolic flight

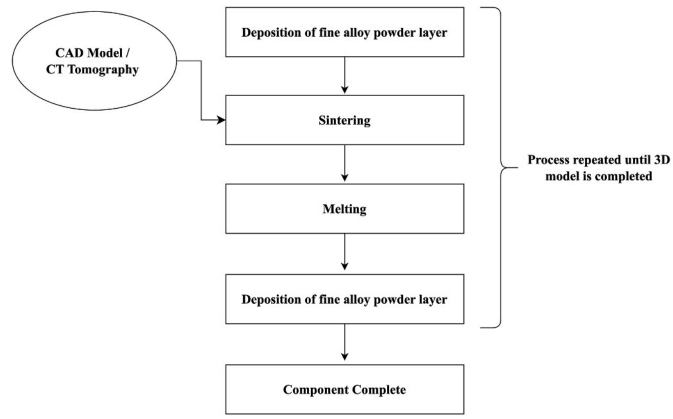

Fig. 6. Stages of LBM (adapted from Ref. [93]).

(Fig. 7c) and was used to deposition metal powders and lunar regolith simulant (EAC-1A). They successfully printed a stainless-steel wrench, the first metal parts ever printed in microgravity by LBM. However, for the regolith, they reported that the quality and homogeneity of the manufactured part were significantly reduced compared to the parts manufactured in traditional conditions. This was associated with several factors, such as packing density, vacuum, and balling effect.

5.1.2. *Fused deposition modeling (FDM)*

Fused Deposition Modeling (FDM) is another name for extrusion deposition prototype modeling, and it is based on the deposition of semi-solid material in thin layers. A schematic of a typical FDM device is shown in Fig. 8. Material is deposited as a semi-solid thin wire and solidifies upon deposition. The thickness of the deposited wire can be altered by varying the size and geometry of the nozzle. The material used for printing determines the temperature at which the liquefier operates. The FDM moves in an x-y direction while the material is deposited on a layer. Once the deposition of a layer is completed, the platform lowers in the z-direction, and the subsequent layer is deposited. Depending on the complexity of the desired part, structural support might be printed alongside the desired part, and these supports are generally removed during post-processing [64].

Some advantages of FDM include all-around hardware, low cost, and material choice flexibility. FDM generally requires less maintenance than other forms of AM, which is why it is suitable for adaptation in space. Furthermore, printing materials are in the form of filament wires, which are much easier to store in harsh environments than powder or liquid polymers [95]. The first AM devices installed on the ISS as part of the previously discussed AM in space initiative employ the FDM technology to manufacture components [96]. The success of AMF aboard the ISS led to further research on the possible utilization of FDM during extraterrestrial exploration.

Slejko et al. [97] investigated the effect of vacuum on 3D printed polymeric matrix composite using FDM technology at 10^{-4} bar. A commercial FDM device was installed in a vacuum chamber, as shown in Fig. 9. Two commercially available and highly filled PLA filaments were printed at several operating conditions. The results demonstrated that the mechanical properties were not affected; instead, geometric errors in terms of dimensional deviation were observed. These dimensional errors were traced to the surface tension of the material during printing, which is exacerbated by the vacuum conditions, and they concluded that this behavior was consistent with the printing conditions. Furthermore, they demonstrated that commercially available FDM devices can be adapted to operate in vacuum conditions with only minor modifications. This result further validates the work of Quinn et al. [74], where they investigated the ability of an FDM printer to function in orbit by studying the effects of a low vacuum environment on the FDM process. Similarly, they modified a commercial FDM printer to manufacture

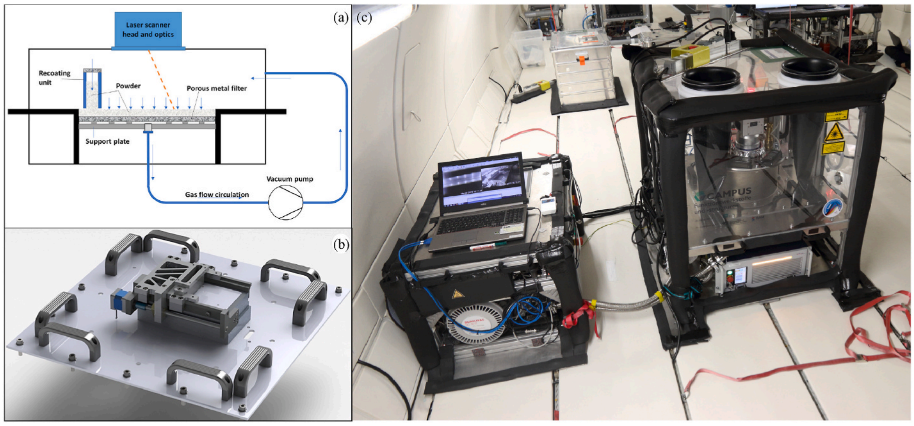

Fig. 7. (a) Schematic of the gas flow-assisted powder deposition; (b) Rendering of the powder deposition unit; (c) Pictures of the LBM unit in microgravity as mounted [85].

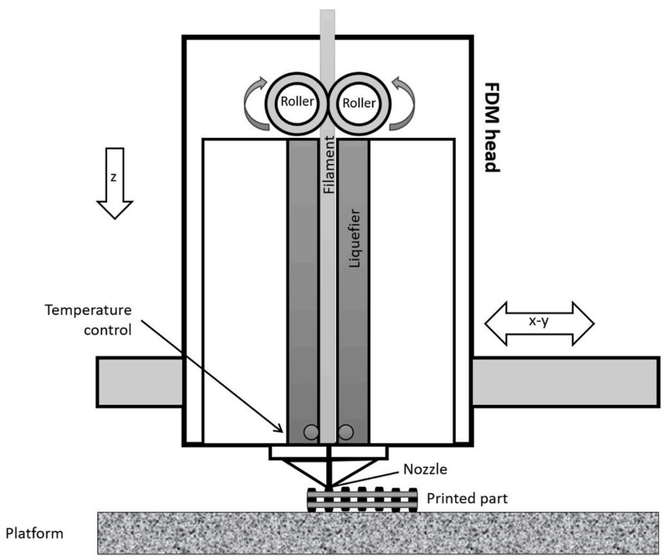

Fig. 8. Schematic of FDM process [64].

products using a polycarbonate feedstock under a vacuum environment of 10 mbar. They concluded that the results demonstrated the capability of FDM to manufacture components in situ for in-orbit applications without loss of dimensional and mechanical performance. Cowley et al. [73] investigated the effects of varying gravity on the printing process of FDM using PLA thermoplastic filament. They tested their FDM setup during a PF. It was observed that the mechanical performance of the printed specimens was not significantly affected; however, interlayer deformation was prominent, and that was related to the deposition time under varying gravity conditions. Their work further highlights the need to understand the varying effects of the multi-physics environment on the manufacturing process.

Similarly, engineers at Northrop Grumman developed an FDM device capable of operating in a vacuum for in-orbit application by modifying a commercial grade 3D printer [98]. The printer was installed in the Northrop Grumman 4x4 TVAC chamber, as shown in Fig. 10a. Initial manufacturing tests with PLA were completed, albeit with significant defects. However, the quality of the prints improved significantly when the feed material was switched to PETG. The cause of the "bubble" formation in the prints, as shown in Fig. 10b, was identified as the result of radiative heat transfer from the aluminum block nearby. A thermal blanket was used to overcome the heating issue. The parts manufactured in vacuum conditions were further characterized, and the results showed consistent patterns with those manufactured at ambient conditions. They then concluded that adapting FDM technology to vacuum conditions was feasible. However, attention needs to be paid to controlling the temperatures; otherwise, overheating could affect the quality of the manufactured parts. To overcome the risk of overheating, Tang et al. [95] proposed an FDM device with superior thermal and mechanical performance capable of manufacturing polymers such as PEEK in the outer space environment. The conceptual design is illustrated in Fig. 11. A thermal control structure was introduced to an AM unit with a radiator rather than a cooling fan. The heat straps in the thermal structure connect the radiator heat sink to the other heat sink in the center tube, as seen in Fig. 11b. Hence the resulting excessive heat would be conducted via the heat straps to the radiator. In their study, they developed and simulated several configurations to improve the efficiency of heat conduction. They concluded that including five sliver heat straps was the most suitable design and confined thermal overshooting within 2.4 °C with a fast temperature rise and stabilization around the desired target. They are currently building a prototype of the design to test in a vacuum chamber to investigate the design's experimental performance.

Other than the adaptation of commercially available FDM devices, novel AM devices using FDM technology have been reported. ESA [57] developed a device to manufacture high-strength engineering thermoplastics using FDM. The Manufacturing of Experimental Layer Technology (MELT) device, illustrated in Fig. 12, can print parts independent of machine orientation (i.e., independent of the gravity vector). The MELT was designed to satisfy the ISS's power and space requirements. Building on the achievements of the MELT, the ESA is developing another FDM device named IMPERIAL, which has the additional capacity of continuous manufacturing of large parts in microgravity with the aid of a thermally controlled conveyor belt. This enables the IMPERIAL to produce parts longer than the AM device, significantly widening the range of products manufactured on-demand in Orbit.

Kuhn-Kauffeldt et al. [99] integrated a vacuum arc plasma coating unit onto an FDM device with the aim of coating UV and IR radiation-sensitive polymers to prevent their failure when operating in space conditions. The integration of the coating unit with the FDM device is illustrated in Fig. 13. A single-walled PEEK tube was manufactured in vacuum conditions with FDM and then coated with aluminum oxide to test the setup. The coating layer was visibly observable, as shown in Fig. 13e. They concluded that coating deposition rates achieved at the set conditions matched the polymer manufacturing speed under vacuum conditions. Therefore, the developed vacuum arc plasma coating process offers a promising solution for the protection of sensitive materials.

FDM devices have also been used to investigate the realization of radio frequency during space travel. Mitra et al. [76] printed a

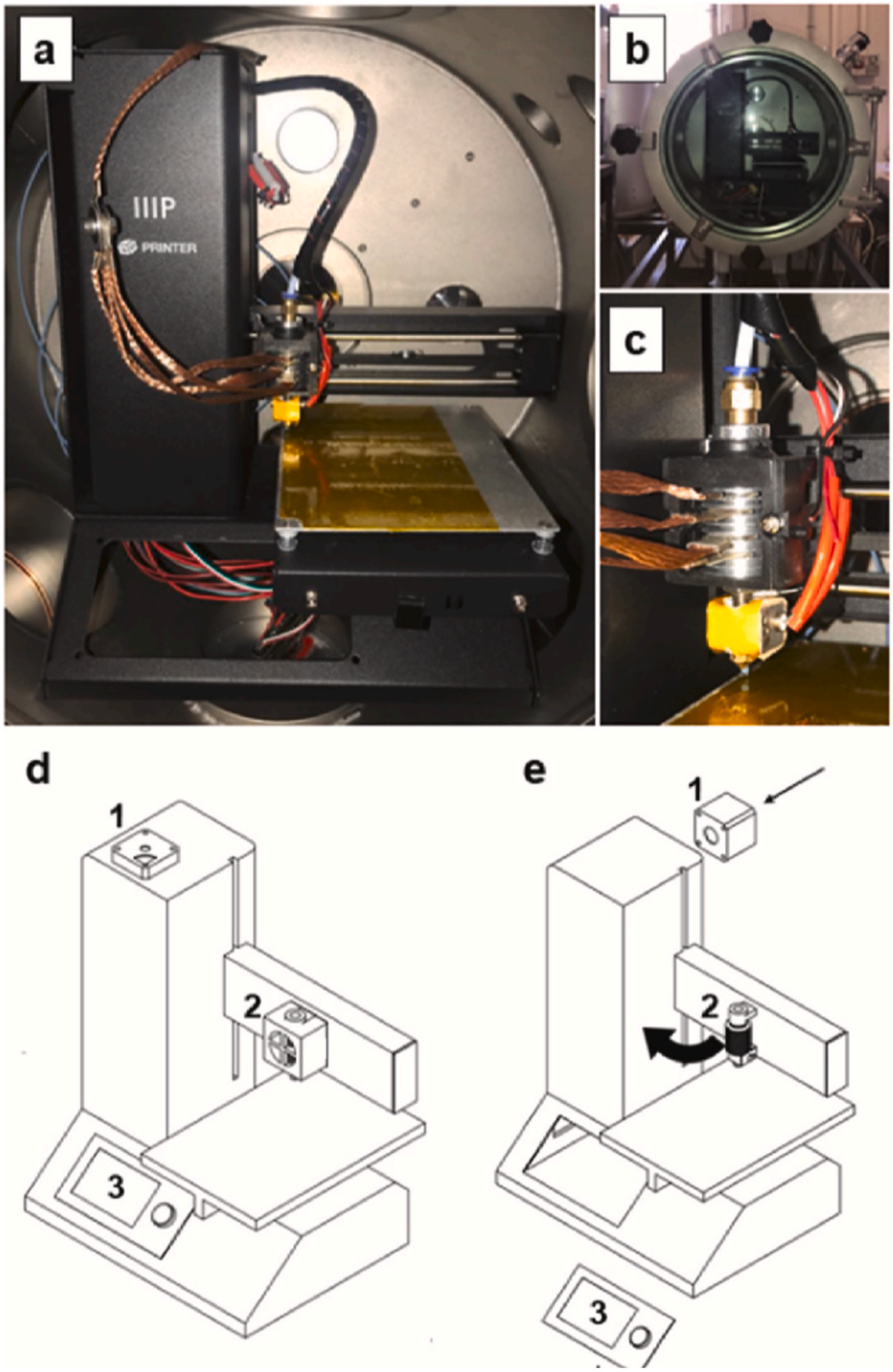

Fig. 9. a)Vacuum FDM setup, b)overall view of the setup, c)detail of the reconfigured hot head, d)schematic of FDM device before modification, e)Schematic of FDM device after modification. (1)extruder motor repositioned,(2)installation of copper braids,(3)detaching of the control board [97].

microstrip patched antenna using an improved version of conductive Electrifi filament on a planar TMM4 substrate for FIS applications under zero gravity conditions. The antenna was evaluated through a detailed comparative analysis between the 3D printed patch and a full wave model. It was concluded that, overall, a fair agreement between measurement and full wave simulation was observed, indicating that radio frequency circuits can be achieved on bench-top devices and thus could be compatible with FIS applications. Furthermore, researchers have also investigated novel materials to be used for in-orbit manufacturing using FDM technology. Coughlin [65] developed a new basalt fiber reinforced ABS for FDM to be used for Martian construction. This has the potential to significantly reduce the projected cost associated with the exploration of Mars, as basalt is easily mined from the surface of Mars. A small-scale FDM device was used to print several functional parts such as gears, wrenches, and clamps, as shown in Fig. 14, similar to those first manufactured when the AMF was installed on the ISS. The successful development and manufacturing of this composite material further the potential and versatility of FDM technology for FIS activities.

Similarly, Jonckers et al. [75] investigated the feasibility of manufacturing continuous fiber-reinforced composites by combining thermoplastic (PLA) and continuous fiber (3K carbon fiber bundle). To achieve this combination, the printhead of a conventional FDM device was modified, as shown in Fig. 15a. The modified FDM setup (Fig. 15b) was first tested in a vacuum chamber to evaluate the impact of low

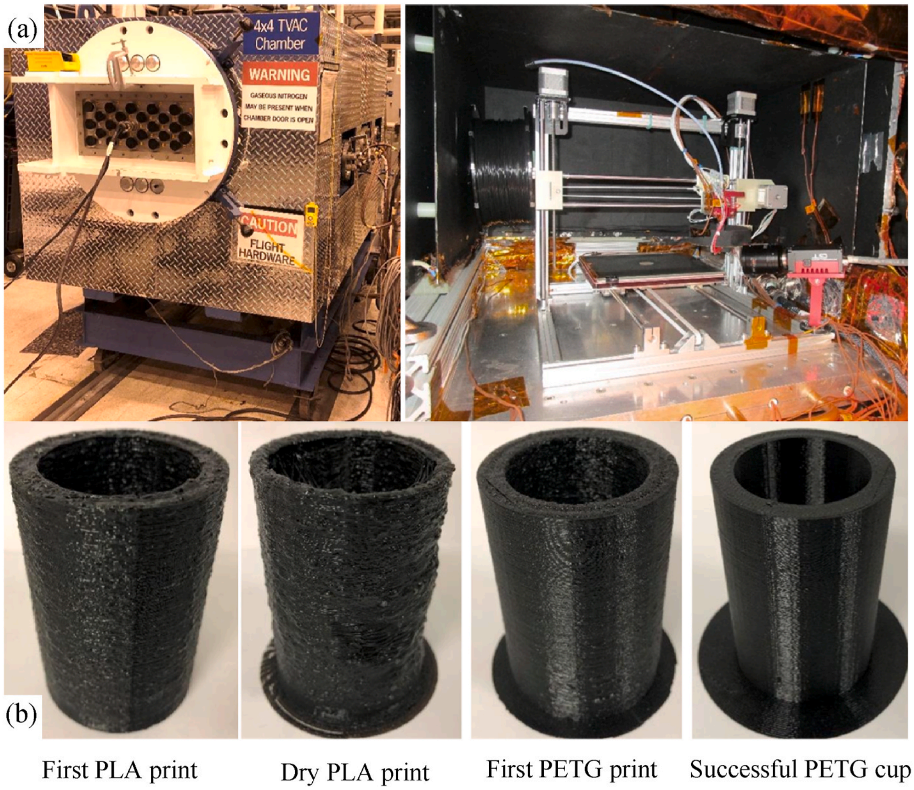

Fig. 10. (a)The modified FDM device was installed in a TVAC chamber, and (b) The cup model prints were completed [98].

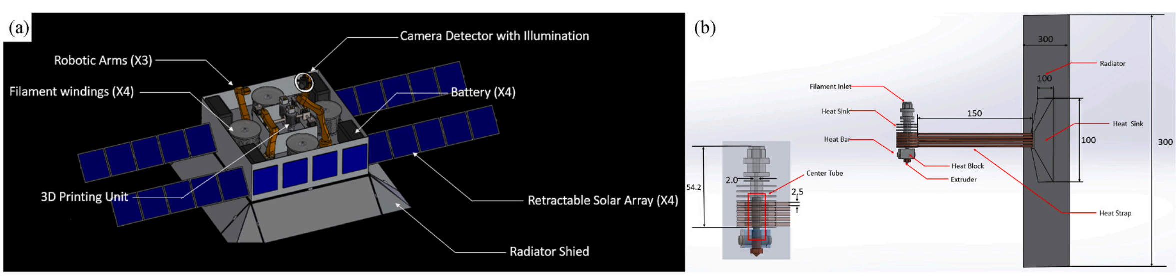

Fig. 11. (a)FDM concept for in-space manufacturing,(b) extruder and thermal unit structure [95].

pressure on the device and manufactured sample. The results were positive when compared to similar fiber impregnation samples produced traditionally. Subsequently, the device's viability to manufacturing structures in free-floating conditions was evaluated by printing trusses (Fig. 13c) in conditions simulated with the Experimental Lab for Proximity Operations and Space Situational Awareness (ELISSA) table. They concluded that the FDM device provides a promising option for manufacturing in space outside the ISS confines.

To utilize FDM in unconventional orientations and eliminate the constant need for human supervision/interaction, researchers [100] innovated an Electric field-assisted FDM (E-FDM). The E-FDM device employs a high-voltage power supply with a conventional FDM device to produce electrostatic force between the nozzle and the build plate, as illustrated in Fig. 16b. The effectiveness of the novel E-FDM device was evaluated by comparison with the traditional FDM process. It was reported that the vertical (Fig. 16c) and reverse (Fig. 16d) orientations of the E-FDM process enable much larger nozzle standoff distances than that of the traditional method, and this can have great potential to be used in an in-orbit environment in the future.

Another method of manufacturing in unconventional orientation is with the aid of robotic technology which increases the degree of freedom of the manufacturing device. Zocca et al. [85] developed an AM process capable of producing continuous fiber-reinforced thermoplastic composites (CFRTPCs) in outer space. Fig. 17 describes the developed 3D printer with additional degrees of freedom cable for printing CFRTPC structures or curved surfaces. They concluded by claiming that the robotic system has demonstrated the capability of manufacturing in space with a printing head as an end-effector and a visual identification system for positioning.

5.1.3. StereoLithography(SLA)

StereoLithography (SLA), a form of VAT Polymerization (VP), is a method for manufacturing a solid volume layer-by-layer with the aid of ultraviolet (UV) radiation. This technique can be divided into two approaches: bottom-up and top-down. The working principle is identical; the primary distinction is the position of the light source corresponding to the VAT [101]. The basic principle of VP is that the photosensitive suspension undergoes photopolymerization, meaning it is selectively cured using light radiation. Once the 3D model is fabricated, the photopolymer network must be removed and material particles consolidated. This AM process is currently one of the most prominent manufacturing techniques due to superior accuracy, with final

Fig. 12. ESA's Manufacturing of Experimental Layer Technology (MELT) FDM printer [57].

properties being manufactured via conventional methods. Low mass consumption is another benefit of VP technologies, as this means non-cured suspension can be reused, making the VP technique more competitive. Scaling and rapid implementation of prototypes in the early phases of product development with fine features are mainly required, and these prototypes can be printed during the same job. Moreover, multipart assemblies are viable in single-stage manufacturing [102].

Some researchers have explored the potential of SLA for FIS applications. Miller et al. [103] investigated five commercially available materials to evaluate their feasibility for in-orbit SLA-based manufacturing. Despite their shortcomings, it was concluded that parts manufactured with SLA technology can be utilized for FIS structural applications, and their excellent resolution surface finish and geometrical complexity can be an advantage. Furthermore, a modified version of SLA has been studied for FIS applications. Altun et al. [104] proposed using Lithography-based Ceramic Manufacturing (LCM), as shown in Fig. 18, for the AM of lunar regolith structures. This is a ceramic manufacturing technique that involves preparing suspensions by the mixture of regolith simulant with a photocurable binder, additively manufacturing a green body of the part by illuminating the suspension and consolidating the part by sintering the green body at a temperature in the range of 1000 °C. Advanced geometries with high quality and accuracy could be printed. This LCM process was limited to the small hardware due to the dimensional constraints of the device. Similarly, LCM was used by researchers at TU Delft to demonstrate that iron could be extracted from regolith simulant and printed into tough structural material [63]. They showed the potential of biological-magnetic treatment to enhance the strength of material to be used in situ during space exploration by magnetically extracting Fe-rich lunar regolith simulant from untreated simulant. Compression specimens were prepared using

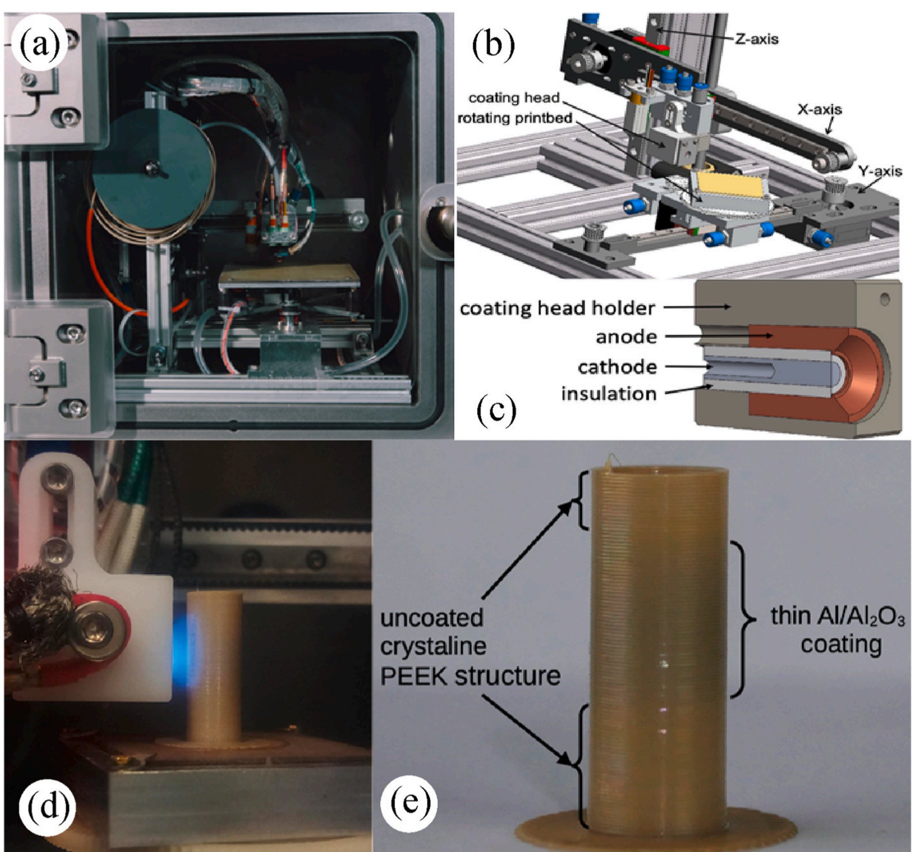

Fig. 13. (a)The FDM device in a vacuum environment, (b) a 3D model of the coating apparatus, (c) a schematic of the vacuum arc coating source, (d) a vacuum arc coating process, (e)a PEEK tube printed and coated withAl_2O_3 [99].

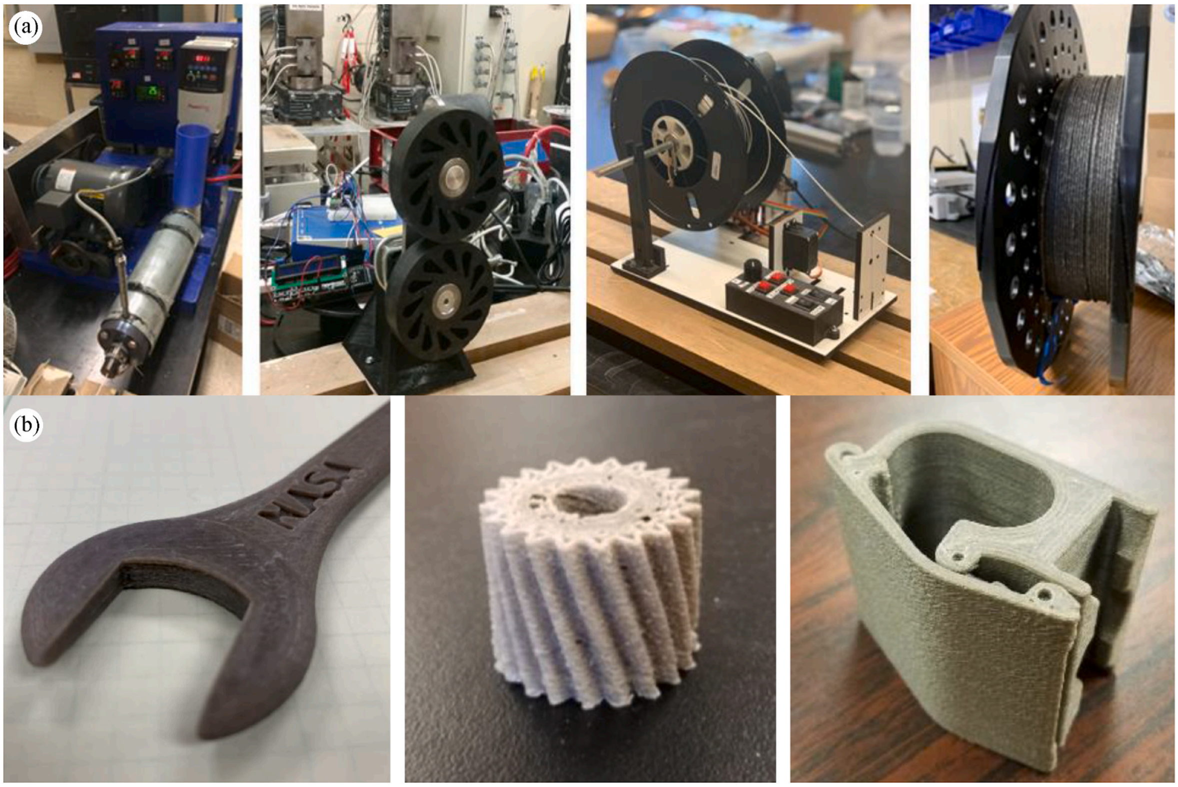

Fig. 14. a) Filament extrusion process, b) Printed basalt-ABS samples [65].

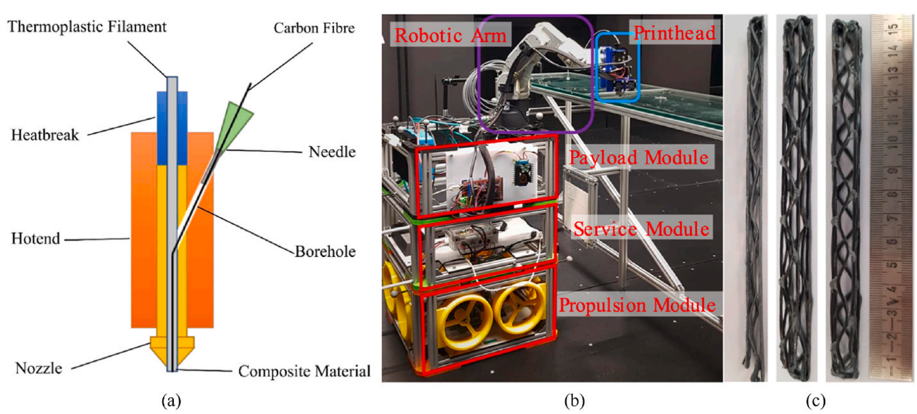

Fig. 15. (a)Schematic of modified FDM printhead, (b)modified FDM device,(c)printed samples [75].

LCM, resulting in specimens that showed a fourfold increase in compressive strength compared to untreated simulants.

5.1.4. Supplementary AM techniques

5.1.4.1. Computed Axial Lithography. Computed Axial Lithography (CAL) [105] is a volumetric AM technique that bypasses traditional layer-deposition-based manufacturing by simultaneously creating all points in a 3D geometry. CAL uses a tomographic reconstruction to define a 3D light dose distribution within a polymer volume. A time-evolving light pattern is projected into the rotating polymer precursor, progressively absorbing light as it penetrates the volume. The volumetric capability of CAL allows it to print faster than layer-deposition-based AM techniques. Also, it reduces material wastage since the precursor liquid or gel itself generally supports the object being printed, eliminating the need for supporting structures. Some challenges related to CAL include the shrinkage/expansion of components during solidification and the inability to produce internally hollow structures.

Theoretically, CAL is a promising technique for in-orbit AM since it does not require a flat liquid-gas interface to be upheld during printing. To investigate this, Waddell et al. [106] investigated the use of volumetric AM for FIS activities by developing an experimental system, the spaceCAL. The spaceCAL was mounted aboard a PF to demonstrate and analyze its capabilities. Initial results showed that 0.12 Pa-s low viscosity precursor can be printed in microgravity with less geometric distortion than an Earth-based gravity counterpart. They concluded that with suitable development, the spaceCAL has the potential to manufacture parts such as flexible seals, rigid trusses, and microstructures for space exploration.

5.1.4.2. Metal Droplet Generation (MDG). The pioneering work done by Orme and Muntz [107] led to the inclusion of Metal Droplet Generation

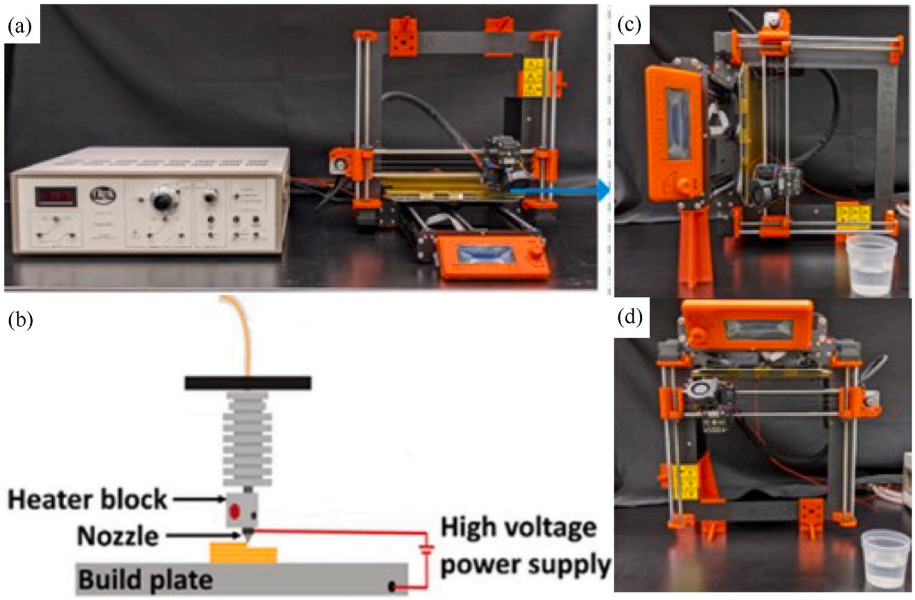

Fig. 16. a)E-FDM device, b)E-FDM schematic diagram, c)E-FDM vertical printing orientation, d)E-FDM reverse printing orientation [100].

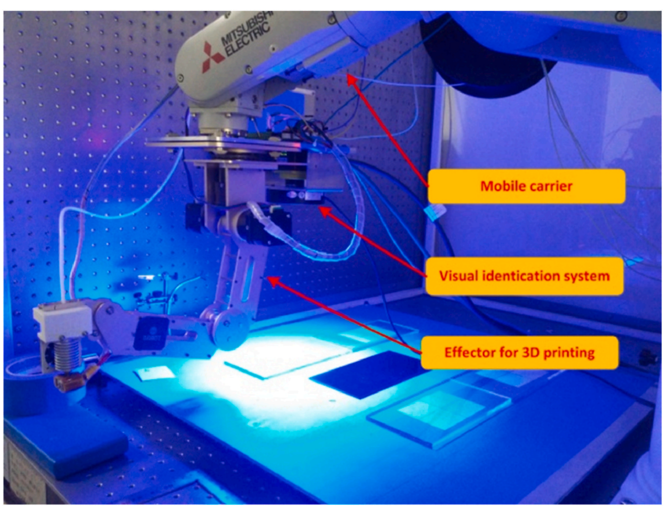

Fig. 17. 3D-printing end-effector on a multi-degree-of-freedom robotic arm [85].

(MDG) in the group of AM techniques. The MDG, based on inkjet technology, implements an actuation mechanism to eject materials in droplets. The properties of these droplets are usually controlled with the aid of the ejection mechanism. Since then, the technology has successfully manufactured solder deposition-based electronic products while demonstrating that it can be a cost-effective alternative for electronic applications. Korkut et al. [78] proposed an in-space AM technique based on MDG. To develop this technique, they employed microscale droplets formed by a vibrated actuator. Reporting that droplets could be deposited in desired patterns when the ejection parameters are correctly configured and that such a system allows for fabricating metallic structures in non-laboratory environments such as a space station or a space vehicle.

5.1.4.3. Electrohydrodynamic printing (EHDP). Electrohydrodynamic printing (EHDP) is an AM technique where the electrostatic field force and gravity act as the driving force to overcome the surface tension and viscous forces of the printed materials for jetting a fine fiber. However, the microgravity environment makes it difficult to achieve precise

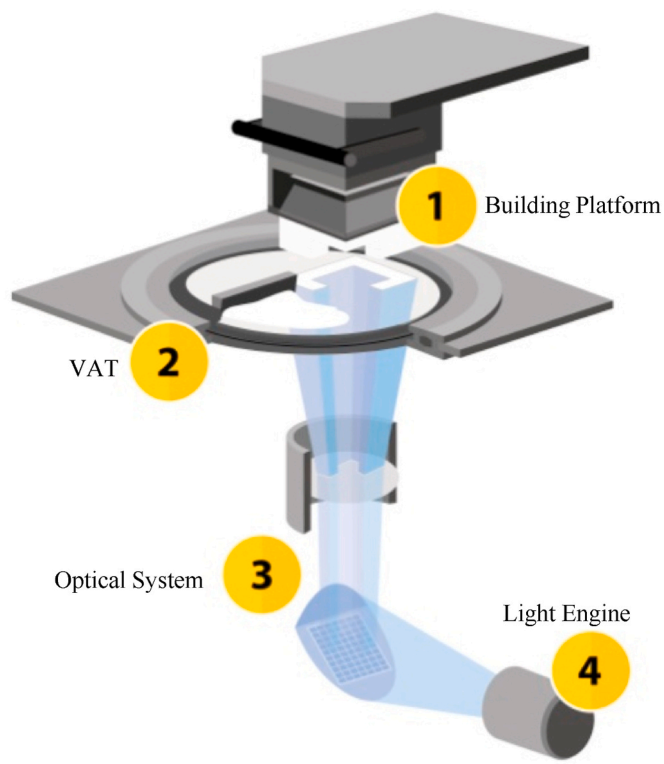

Fig. 18. Schematic of Lithography-based Ceramic Manufacturing [104].

deposition and stacking of printed material, especially for microscaled structures. To overcome these challenges, Qu et al. [108] proposed the use of high-voltage electrostatic force in the EHDP process for an anti-gravity (AG-EHDP) printing of microscale structures. The AG-EHDP method was able to print Polycaprolactone-Polyethylene oxide (PCL-PEO) structures with a high resolution ($3.65 \pm 1.31 \mu m$). Furthermore, the proposed method exhibited a great electrothermal capability, heating the cold plate from $25^{o}C$ to $180^{o}C$ within 3 min with an applied voltage of 3V. They concluded that the proposed AG-EHDP provides a promising strategy to fabricate microscale and functional structures in

FIS conditions.

This subsection presented the recent efforts in developing AM strategies for FIS activities. The application of AM in space manufacturing offers notable advantages, such as the ability to fabricate complex objects without the need for additional assembly and the flexibility in the design-to-manufacturing process, resulting in less waste of raw materials. Additionally, various materials, including metals, polymers, ceramics, and fibers, can be used in AM. It can be concluded that the strategy (machine technology) and feedstock (raw material) are intertwined in AM processes. Hence, for a compelling selection of an AM strategy, it is paramount to understand the physical properties of materials, production process, and desired product properties. For example, microgravity has a negligent effect on the feedstock but significantly affects the process (print speed) and technology. Contrastingly, the vacuum has a limited impact on process and technology but significantly affects the material. A better understanding of all parameters would help design an appropriate AM unit.

5.2. Welding

An area of manufacturing that could enhance FIS activities is the joining of materials with welding. The ability to join materials or components would allow the building of large structures in Orbit and enable the crew to create load-bearing structures and machines. One of the most prominent joining techniques is friction stir welding (FSW). Since its emergence, FSW has been an attractive process for the space industry. FSW utilizes the engagement of a rotating tool to deform parent material along their faying surfaces and then forge them together. Maintaining proper tool-workpiece engagement is critical due to workpiece variation and machine deflection. Therefore, CNC milling machines and robotic platforms have been used to perform the FSW process, meaning the process has been mainly confined to factory environments due to the size of the equipment. However, the equipment involved must be compact and portable for in-space FSW to become a reality. Several researchers have worked on developing FSW technology suitable for FIS applications.

Longhurst et al. [80] developed a bobbin style, self-adjusting and aligning (SAA) FSW tool that floats freely, without any external actuators, along its vertical axis to adjust and align the workpiece's position and orientation, as shown in Fig. 19 (a). The SAA tool drastically reduces the axial forces, which are usually very large during the FSW process. A successful demonstration was carried out with the butt welding of aluminum, and it was reported that there was a significant reduction and near elimination of the axial process force. This reduction in force leads to less power consumption, as Strawn et al. [109] reported during their investigation of FSW for lunar applications. Furthermore, the authors also introduced a real-time process monitoring technique using a magnetoelastic sensor, as seen in Fig. 19b. The sensor detected voids of up to 1.6 mm in diameter. They concluded that the developed device could be suitable for a portable and automated FIS device to be utilized in FIS applications.

Additionally, to realize the in-orbit application of FSW, Li et al. [81] developed a portable FSW equipment based on the principle of Non-Tool-Tilt Friction Stir Welding. The demonstration of the device, starting from the weight measurement till the test in simulated conditions is shown in Fig. 20(a–e), proving that the portable FSW equipment can weld aluminum alloys up to 6 mm in thickness. Thus, it was concluded that the device could be used for FIS applications such as joining and repair processes.

Another welding technique very similar to the FSW is Friction Stir Spot Welding (FSSW), and it has also been proposed for joining processes in FIS [79]. The FSSW and FSW are very similar techniques such that joints made from one process indicate a high possibility of replication using the other. FSSW is performed on a lap joint with a single weld, while the FSW process is usually on configurations such as butt, T-joints, and lap. Moreover, the FSSW process requires less material and tools than the FSW process. This led Evans et al. [79] to evaluate the use of FSSW for FIS activities by investigating the weldability of iron meteorites. Meteorites obtained from Campo del Cielo were successfully welded using FSSW, and metallurgical analysis indicated that it behaved like the FSSW of low-carbon steel. They concluded that their study demonstrated the viability of iron meteorites as a practical resource for ISRU and that FSSW can be used for FIS activities.

5.3. Forming

Yan et al. [110] proposed a piece of equipment for in-orbit manufacturing of large tubular structures using roll forming technology. Like traditional roll forming devices, the proposed equipment mainly consisted of an unrolling module, raw material transport module, temperature module, forming module, cooling module, and traction module. The forming process is primarily applicable to thermoplastic prepreg. The optimum forming parameters were determined by investigating the influence of tape size accuracy on the roll forming process and the influence of forming process parameters on forming quality. The determined parameters were used to verify the developed prototype (Fig. 21). The verification experiment indicated that the device was able to manufacture a PEEK tube at forming and splicing temperatures of 200^oC and 340^oC, respectively, with an advancing speed of 1.5 mm/s. The forming equipment and manufactured PEEK tubes are shown in Fig. 21. The geometric accuracy of the samples was quite good and uniform. Hence, the authors concluded that the proposed forming equipment could lay a foundation for the in-orbit manufacturing application of composite rods with a high length-to-diameter ratio.

Bhundiya et al. [111] manufactured and investigated the compressive behavior of isogrid columns using a novel in-space manufacturing

Fig. 19. (a) SAA-FSW tool, (b) process monitoring setup [80].

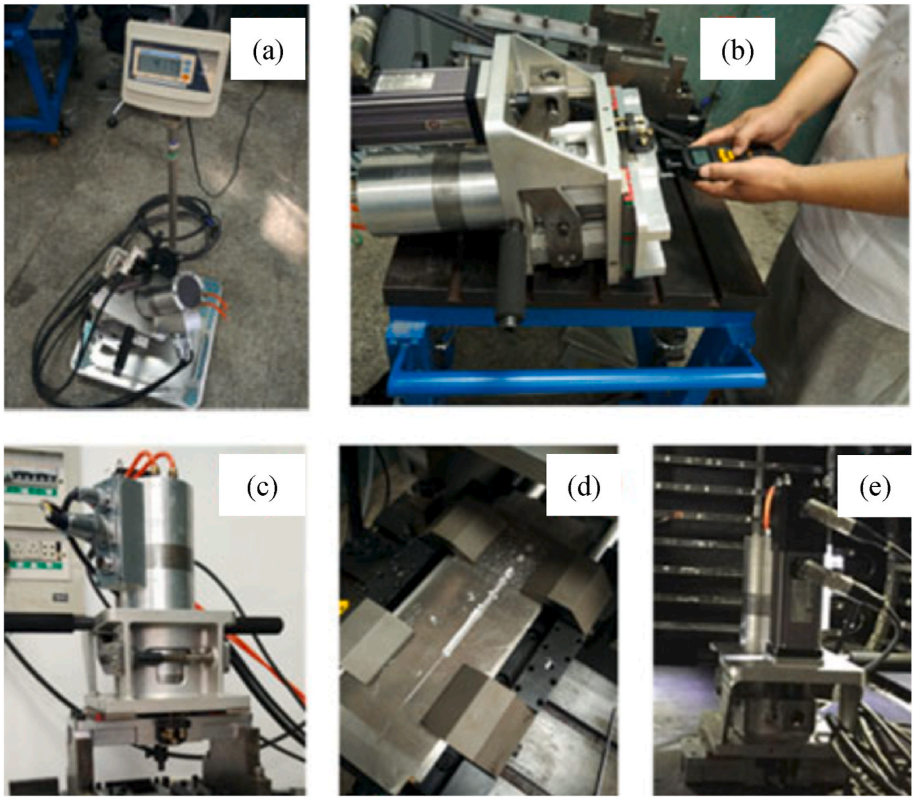

Fig. 20. Portable FSW equipment: (a)Weight measurement, (b)rotary speed test, (c)ground weld test, (d)weld seam, and (e)test in simulated conditions [81].

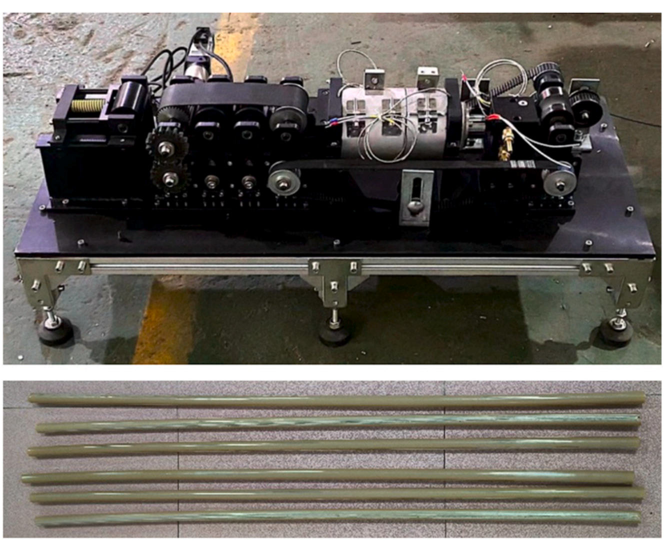

Fig. 21. Forming equipment and samples [110].

bend forming process with low power consumption. This process uses a bending device to form a flat lattice from a continuous wire strand. The columns were manufactured by using 3D printed joints at bend locations and rolling the lattice to form a 3D column. Several configurations of the 3D columns were manufactured and investigated via compression tests. The experimental results indicated that the bend-forming process undergoes a smooth formation of buckling, and unlike thin-shelled columns, they do not abruptly destabilize past their first bifurcation. Enhanced mechanical properties coupled with lower consumption make this novel bend forming process a promising technology for FIS applications.

5.4. *Hybrid manufacturing technology*

Hybrid manufacturing systems employ a combination of subtractive and additive manufacturing technologies to produce the desired parts. To overcome the limitations of each manufacturing technology, researchers have been working on developing a system with hybrid features with a focus on automated machine tool change, reduction in tool wear, improved feedstock management, and optimized machining conditions. Engineers at UltraTech Machinery developed an Ultrasonic Additive Manufacturing (UAM) [112] process that can manufacture metal components by using a solid-state welding process. Multimaterial printing can be achieved with this technology as UAM can print dissimilar metals without forming intermetallic and non-metals that can be embedded to create metal matrix composites [72]. The UAM system integrates a Computer Numerical Control (CNC) mill head for machining metal parts in the same platform, as illustrated in Fig. 22.

Similarly, Made in Space developed a multi-material hybrid manufacturing unit called the “Vulcan” [113]. The Vulcan combines FDM and CNC milling to fabricate metallic components in a single platform with an automated system capable of moving parts between sub-systems. Furthermore, Tethers Unlimited developed a Metal Advanced Manufacturing Bot-Assisted Assembly system (MAMBA) [114] in a project that ended in 2020. The MAMBA built on the promise of the Refabricator’s -a combination of AM and plastic recycling [77]-positrusion process of recycling plastics to create ingots from virgin or scrap metal, which then undergoes machining operations to finish the part.

6. Discussion

Traditionally, acquiring replacement components during space travel is only possible by launching another space mission. However, the timeline governing the launch is constrained by propulsive capabilities, orbital mechanics, volume and mass of the associated payload, and,

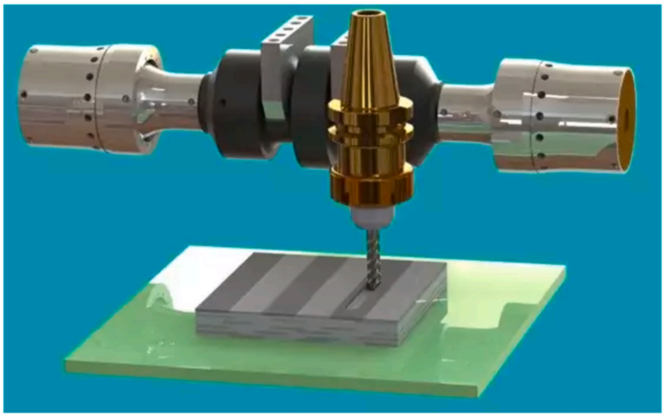

Fig. 22. Ultrasonic Additive Manufacturing unit [72].

more importantly, the associated cost. Currently, the scale of the payload launched is dictated by the fairing volume. This means single-component structures cannot exceed the size of the dedicated fairing. While the advent of deployable devices has helped ease these concerns, the efficiency of deployable structures is still short of those that can be achieved with bulk-density material. Furthermore, introducing reusable launch vehicles has reduced associated launch costs and increased accessibility to space. However, there is still a need for a more robust and swift response to unforeseen incidents during space exploration, further reducing the reliance on Earth. For this reason, the concept of FIS was realized. FIS advocates for performing manufacturing and assembly processes directly in space, circumventing logistical obstacles. Additionally, FIS emphasizes the need to reduce reliance on Earth for resupply by minimizing resource consumption and maximizing 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 that also addresses the ethical concerns of space waste generation and the preservation of extraterrestrial ecosystems. The circular nature of FIS dictates a shift away from the traditional "make-use-waste" paradigm of space exploration. Waste material, such as space junk, could find new value in FIS as raw materials, while structures can be designed such that, when necessary, it is completely burnt in the atmosphere to prevent the further accumulation of space debris. Furthermore, FIS could lead to reduced vehicular launches and increased service time of satellites, further reducing the environmental impact of space explorations. The importance of FIS becomes more pronounced with the plans to return humans to the moon and create habitable colonies on Mars.

Deep exploration missions such as the planned Martian and lunar missions will not be able will not be able to rely on regular Earth-based resupply such as the ISS receives and will be denied the comfort of rapidly returning to Earth in an abort scenario. Thus, for these future long-endurance missions, FIS can help reduce the reliance on Earth to an acceptable level of risk. On-demand manufacturing can be used in this capacity to fabricate spare parts and lost items on an as-needed basis, upgrade components during a mission, and recycle and repurpose component mass. Additionally, the flexibility of FIS enables risk reduction by improving resilience to handling unknowns that may manifest during an exploration mission. The key value-adding attribute of on-demand manufacturing is the ability to fabricate a wide range of components from a common raw material source. Thus, typical manufacturing processes for on-demand spare manufacturing include highly flexible ones regarding the geometries and materials that can be fabricated. Moreover, the processes must produce parts with sufficient quality to deliver the desired component function. However, the part quality does not necessarily need to match that of the terrestrially manufactured component because of the additional system-level benefits provided and the fact that another copy of the part can be fabricated as needed. The production rate in this use case must be sufficient to keep the lead time for spare parts below the time to hazard for the failed component. Since the manufacturing of spare parts often occurs in the pressurized volume of the spacecraft, it is important that any fumes, chips, coolant, or solvents involved in the process are handled appropriately and that the impact of noise and vibration of the process on the crew is mitigated. In this paper, the typical manufacturing processes suitable for FIS applications have been discussed in detail. To understand the implication and potential of integrating manufacturing systems into space exploration, it is paramount to understand the kind of supplies that are generally required during space travels and the materials available to exploit for ISMU. Raw materials and feedstock availability are vital to producing finished products in space, especially considering payload expenses. ISMU is crucial for material extraction and utilization while reducing costs and increasing the long-term sustainability of extraterrestrial travel. Regarding ISMU, the successful studies on the mining and processing of lunar and Martian regolith demonstrated the potential use of these materials as input for FIS. Furthermore, orbital debris is estimated to weigh around 7000 tonnes and is valued at around 600 billion to 1.2 trillion USD, which should encourage actors in the growing field of FIS services. Finally, Earthly materials have been discussed at length, as it would be ambitious to envision a scenario where FIS would be completely independent of Earth for any supply or material. Metallic and non-metallic materials have been studied to investigate space conditions' influence on material properties and characteristics. While changes occur to the material, these changes were generally not significant enough to be considered to have adversely degraded the materials. It can then be generalized that the advancements in material science research, along with the associated architecture, equipment, and logistics, have made building FIS more feasible.

The continuous development of manufacturing technology has presented promising processes for manufacturing in space with associated concepts and materials. These activities have covered various aspects related to the needs of future sustainable human and robotic exploration activities in-orbit or at the surface of celestial bodies. This includes the construction of infrastructure elements and the manufacturing of required tools and spare parts. Increasing focus is also dedicated to in-orbit manufacturing of large structures in space for various applications. The manufacturing processes in this condition must be flexible to the properties of feedstock material as the raw material could either be obtained locally with ISMU or transported from Earth. In this paper, the progress of manufacturing technology adaptable to FIS has been thoroughly presented. Several traditional manufacturing processes, such as FDM, metal deposition, stir welding, forming, and laser-based AM, have been investigated and adapted to the requirements of FIS activities. Some novel/hybrid techniques, such as the VULCAN and UAM, have also been proposed. Table 8 summarizes the manufacturing technologies presented in this study.

Among the processes reported, AM offers the most potential for FIS applications due to its ease of use and fast prototyping times. The aerospace sector, especially those related to extraterrestrial exploration, demands custom-made and low-production volume parts, which are ideal for AM. The aerospace industry has already adopted AM in a variety of applications, including FIS (AMF aboard the ISS), for primarily two reasons. Firstly, due to the significant reduction in material and product mass. Unlike traditional subtractive manufacturing, AM starts from nothing until the desired geometry is achieved through layer-by-layer deposition. In contrast, conventional processes such as machining operations reduce a bulk material to achieve the desired geometry by chipping away much material, and sometimes these chips are non-recyclable. Furthermore, layer-by-layer deposition allows for the production of lightweight components since materials are only deposited at the necessary destinations, and component weight affects the required thrust and fuel, contributing to the overall mission cost. Secondly, the flexibility of AM to manufacture complex and intricate

Table 8
Summary of manufacturing technologies for FIS.

Technology		Material	Advantage	Disadvantage
Additive Manufacturing (AM) [50,73–76,94,95,97,103,115,116]	Laser beam melting	Metal Powder	Tough metal parts. High dimensional accuracy. Wide range of metals	Costly. Inert gas required.
	Fused deposition modeling	Polymers Composites	Inexpensive. Highly resistant components. Wide range of polymers.	Average accuracy. Only non-metals. Requires support structures.
	Stereolithography	Resin polymer	High precision. Complex geometries. Very good surface finish.	Costly. Limited to photosensitive resin.
Joining [79–81,109]	Friction stir welding	Metal	High quality weld. High strength. Fatigue resistant. Automated.	Costly. Usually adapted to a CNC.
Forming [110,111]		Metal Polymer	Cheap Simple tools. Improved mechanical properties.	Inconsistent tolerances. High power consumption.
Hybrid [72,77]	Ultrasonic additive manufacturing	Metal Composite materials	Metal matrix composite. Minimal residual stress.	Costly. Usually adapted to a CNC. New technology.

geometries faster than traditional processes has led agencies such as NASA and ESA to adopt AM in their manufacturing processes. Furthermore, other characteristics such as reduced tooling, material range, on-demand production, and safety make AM more attractive for FIS application than traditional manufacturing technologies. While AM offers a promising path toward the actualization of FIS, there are still areas that require further investigation, which are highlighted as follows:

- Material characterization and product qualification:

Qualification and characterization are integral and expensive parts of product development in the aerospace industry. The properties required of aerospace materials, especially those related to FIS, can be established. However, no generalized standard (such as ISO standards) exists for the characterization and qualification of FIS-related processes and products. Furthermore, research needs to focus on developing material and technology that is easily transferrable and reliable enough to overcome harsh extraterrestrial conditions. Design for qualification guidelines needs to be created such that components and materials are only considered demonstrated once they can perform in the designated space conditions as intended.

- Energy Harvesting:

Energy sources and requirements of FIS are yet to be defined. Under ISMU, locally available solar energy is a popular choice for energy sources. However, sources such as nuclear and hydrogen could also complement solar sources. Furthermore, the processing of materials in space requires sources such as lasers, microwaves, and other forms of energy. Therefore, a comprehensive definition of energy sources and suitable harvesting techniques needs to be created.

- Large structure manufacturing:

Advancements such as ESA's IMPERIAL AM system have shown promise in the manufacturing of long single-part materials. However, the IMPERIAL still needs to be tested in a space environment to evaluate the impact of space environments on the components produced. Hence, there is still a need to develop robust systems to produce single-unit bulk large structures. For large structures, the effect of vacuum and thermal gradients is significant. The additional radiation could have a troublesome effect on the material and manufacturing process. Therefore, the FIS equipment should be able to produce large and extended structures, typically larger than the FIS manufacturing equipment itself. Furthermore, the production rate must be quick and rigorous enough so that the desired structures can meet the mission demands in the most extreme conditions in outer space.

- Modularity:

Modularity and FIS share a symbiosis rooted in their core definitions, as modular space systems - designed to be upgraded and refueled – could be launched with fewer modules and fuel than needed for the entire mission duration [117]. 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, increasing changeability as faulty modules can be replaced easily [118]. Therefore, enabling technologies such as modular spacecraft need to be researched and leveraged to further amplify the potential of FIS.

- Regulatory framework:

Complying with rules and regulations is crucial for the safety and success of space operations. Incorporating factors that cover sustainability, governance, and socio-economic factors into long-term space explorations would allow for the development of a robust space economy and, in turn, a robust FIS ecosystem. Space regulations generally cover issues such as debris mitigation, licensing of commercial activities, intellectual property, orbital safety, and resource management. However, the current international space law needs to be updated as it was developed before the significant accumulation of orbital debris and the conceptualization of in-orbit operations. Therefore, the inadequacy of the current governing laws requires the development of a regulatory framework for space exploration with the incorporation of FIS activities as significant proponents of the space ecosystem and the identification of private entities as crucial components of the space economy.

- Supply chain and logistics:

Optimal transport and supply chain management, such as orbital transportation, storage, and waste management strategies, is vital for thriving FIS operations. FIS requires a support infrastructure with minimal human interference. Material and product transport to and from the FIS ecosystem needs to be defined with a focus on concepts such as space tug, material mining, integrated processes, and customer identification. Overall, there needs to be a definition of the eco-system of FIS and its needs, which would allow for the identification of suitable manufacturing processes considering the logistical and supply chain demand and constraints.

- Waste management:

Waste accumulated during space missions has been stated. Waste management strategies enable the reuse, recycling, or repurposing of manufacturing waste within limited resources. This would allow for the establishment of a closed-loop factory. However, the method of gaining value from the generated waste still needs to be adequately defined. Techniques such as propellants generated from waste and burning of waste in the earth's atmosphere have either not shown significant promise or are not suitable for deep space exploration. Therefore, there is a need to understand the value of space waste from the perspective of FIS.

7. Conclusion

Factory in Space (FIS) is a concept that proposes the manufacturing, servicing, refurbishing, recycling, reusing, and repairing of components in situ during space exploration. As humans venture deeper and more extended into space, relevant structures must become reliable and adaptable to the increasing complexity and demand of the harsh extraterrestrial environment. To overcome this challenge, space system designers and practitioners introduced the concept of FIS, where components would be fabricated and integrated either in Orbit or on another planetary surface. One of the main advantages of FIS stems from its ability to create novel solutions to existing problems because of the newfound design freedom that is no longer limited by launch-related constraints such as volume and mass of fairing and transit times. Several studies have been conducted to investigate and develop suitable materials and manufacturing technologies for FIS applications. This study aims to provide an overview of the current research and development efforts on manufacturing activities for FIS applications by analyzing material and related manufacturing technology for FIS applications. The materials investigated for FIS applications are discussed in section 4 of this paper. The materials were categorized as earthly materials and locally available materials through In-situ Material Utilization (ISMU). In the former category, traditional materials used on Earth were adapted to space conditions, while some other materials have been utilized aboard the International Space Station (ISS), where it was observed that no significant degradation occurred to the materials as long as they were in confinement. For the latter categorization, resources locally available in space were presented, and it was established that the transport of materials from Earth is not optimal, especially for long-term space explorations, further highlighting the importance of ISMU, especially from an environmental perspective, as the utilization of local resources reduces the need for resupply missions from Earth. Furthermore, materials found on celestial bodies and in-orbit propose a value for FIS activities through habitat construction and material/component recovery, among others. Considering the materials available, the investigated and developed technologies are discussed in section 5. Table 8 provides a summary of the prominent technologies discussed in this paper. Generally, traditional manufacturing techniques were modified, by adapting/simulating them in outer space conditions with consideration for different orbital conditions and environmental properties. Concerning FIS, one promising technology is Additive manufacturing (AM). For a fast, robust, and reliable solution, the flexibility of AM provides ready-to-use parts directly from wire (filament) or powder feedstock. National agencies such as the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have been exploring using AM for several space applications, including FIS activities. Finally, the dynamic and complex nature of space exploration requires a robust, fast, and flexible solution to unforeseen events. For this reason, FIS could serve a key role in the new space economy that is continuously being characterized by commercial/private entities and increasing complexity. The ability to circumnavigate launch constraints while maintaining mission integrity would allow companies and researchers to further expand their horizons during deep and long-term space exploration, which would otherwise not be possible without FIS operations. Certain aspects of FIS have been discussed in this work, and this review helps to establish the materials and manufacturing technology for FIS. The whole process of manufacturing in space (material and technology) has been reported and can serve as the foundation for subsequent research on in-situ manufacturing in space.

CRediT authorship contribution statement

Farouk Abdulhamid: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Brendan P. Sullivan:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Sergio Terzi:** Writing – review & editing, Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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