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Perspective

3D printing in space: from mechanical structures to living tissues

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Abstract

3D printing stands at the forefront of transforming space exploration, offering unprecedented on-demand and rapid manufacturing capabilities. It adeptly addresses challenges such as mass reduction, intricate component fabrication, and resource constraints. Despite the obstacles posed by microgravity and extreme environments, continual advancements underscore the pivotal role of 3D printing in aerospace science. Beyond its primary function of producing space structures, 3D printing contributes significantly to progress in electronics, biomedicine, and resource optimization. This perspective delves into the technological advantages, environmental challenges, development status, and opportunities of 3D printing in space. Envisioning its crucial impact, we anticipate that 3D printing will unlock innovative solutions, reshape manufacturing practices, and foster self-sufficiency in future space endeavors.

Keywords: 3D printing in space, space manufacturing, microgravity

With the increasing ambitions of deep space exploration, extending to celestial bodies such as the Moon and Mars, there is an unprecedented demand for innovative manufacturing solutions. In this context, 3D printing technology has emerged as a leading *in-situ* space manufacturing innovation. This transformative technology facilitates the on-demand production of intricate and customized components and structures in the space environment, employing layer-by-layer additive manufacturing processes. Its revolutionary capability has garnered global attention, driven by the imperative for innovative solutions to address challenges posed by extended space missions and the need for resource-efficient manufacturing beyond Earth [1, 2].

To date, 3D printing has revealed promising opportunities across diverse space applications, including the production of space devices and food, advancements in space biomedicine, repairs of electronics and sensors, and the recovery and utilization of space resources. While global space leaders have recently explored 3D printing technologies in space (figure 1), the field is currently in the early stages of technology validation, requiring extensive foundational research and key technological advancements. This perspective aims to delve into the fundamental characteristics of 3D printing within space manufacturing, emphasizing its potential to revolutionize our approach to manufacturing processes in space exploration.

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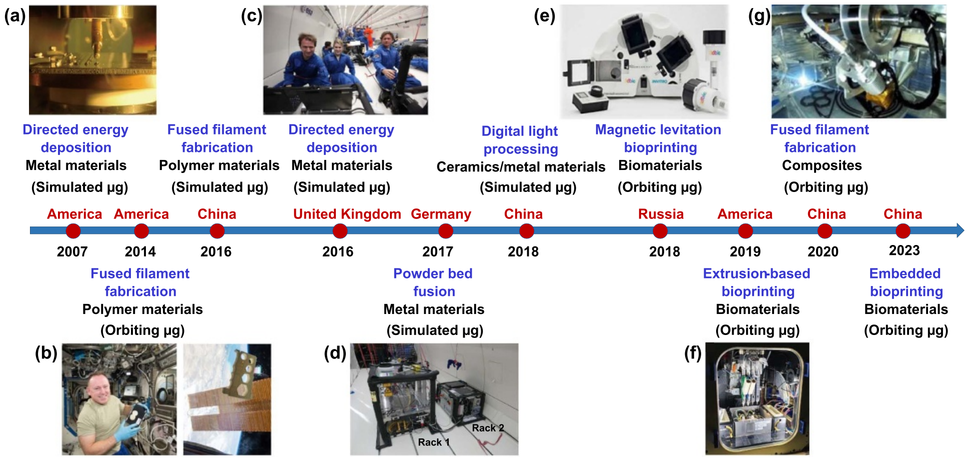

Figure 1. The representative advancements in the global aerospace industry's exploration of 3D printing in space. (a) Reproduced from [https://ntrs.nasa.gov/api/citations/20080013464/downloads/20080013464.pdf]. Image stated to be in the public domain. (b) Reproduced from [https://ntrs.nasa.gov/api/citations/20190005004/downloads/20190005004.pdf]. Image stated to be in the public domain. (c) Reproduced with permission from [3]. Image credit: Novespace Air ZeroG. (d) [4] John Wiley & Sons.© 2019 The Authors. Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (e) Reproduced from [5].CC BY 4.0. (f) [6] John Wiley & Sons.© 2019 The Authors. Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (g) Reprinted from [7], © 2022 Published by Elsevier Ltd on behalf of Chinese Mechanical Engineering Society (CMES).

1. Why is 3D printing essential in space exploration?

3D printing in space is essential because it can manufacture intricate and customized structures locally, offering unparalleled design flexibility while concurrently reducing time and development costs [8, 9]. The primary objective is to fabricate and assemble large structures in orbit, substantially decreasing mission expenses by launching only raw materials and essential components [10]. Current endeavors mainly focus on utilizing 3D printing to minimize space components' mass, complexity, part count, and welds. The technology is gaining traction for its remarkable mass savings, ranging from 40% to 90%, directly translating to cost reduction. Additionally, it expedites the production of complex parts, reducing fabrication times from a year to just 4 months [11, 12].

In addition to fabricating mechanical structures, 3D printing excels at manufacturing components for emergency repairs in space, offering a versatile and adaptive solution for unforeseen events such as the absence of tools or electronic malfunctions [13]. The inherently challenging space environment, marked by resource constraints and the impracticality of conventional resupply mechanisms, underscores the strategic importance of on-demand manufacturing capabilities [14]. Historical examples highlight the effectiveness of rapid fabrication in addressing critical technical challenges. For instance, during the 1970 Apollo 13 mission, the crew had to resort to the lifeboat due to discrepancies in lithium hydroxide canisters between the Command Module and the Lunar Module. Fast forward to 2013, Made In Space, Inc. promptly engineered a 3D-printed adapter for a similar issue, demonstrating its operational success within a day [15]. This capability enhances mission autonomy and reduces reliance on Earth-bound logistics for unforeseen technical difficulties.

Furthermore, 3D bioprinting extends the capability to generate 3D tissue and organs in space, establishing a technological platform for studying the impact of the space environment on humans [16]. This innovation facilitates regenerative and sustainable clinical healthcare in space, addressing the adverse effects of prolonged exposure to the space environment, such as microgravity and increased radiation [17]. While the biological mechanisms require further exploration, 3D bioprinted tissue models can replicate human body characteristics, as a tool to study the long-term effects of space conditions [18]. Besides, in cases of severe trauma or illness in space, where immediate return to Earth for treatment may be impractical, 3D bioprinting holds the potential to provide timely sources of functional tissues for astronauts.

Many crucial elements for astronaut well-being, such as food, daily necessities, and lunar living accommodations, have the potential to be fabricated through 3D printing [19]. Food 3D printing, for instance, has the potential to revolutionize space food manufacturing by addressing challenges related to nutrition, variety, and personalization for long-duration human-crewed space missions [20]. Advancements in 3D printing technology offer solutions to improve food options, reduce waste, and enable on-demand preparation in space [21]. For extending manned missions to the Moon and Mars, 3D printing becomes invaluable for utilizing *in-situ* resources. Given the challenging lunar and Martian environments, constructing artificial habitats from local materials, such as regoliths, through 3D printing is pivotal for sustainable deep space exploration, ensuring human survival, and minimizing environmental impact on Earth [22, 23].

2. Challenges of 3D printing in extreme space environments

The advancement of 3D printing technology in space encounters numerous challenges due to the harsh environmental conditions beyond Earth's atmosphere. These challenges encompass the vacuum of space, significant temperature differentials, and the impact of cosmic and solar radiation [24].

Microgravity poses formidable challenges to space-based 3D printing, affecting both the printing and post-production phases. The absence of gravity leads to molten materials forming spherical droplets during printing, causing disruptions and compromising print quality [25]. Extrusion 3D printing encounters difficulties in layer deposition, potentially resulting in print failures. Specialized printers designed for microgravity and process adjustments are essential to address these issues. Proper layer adherence becomes challenging in a microgravity environment, resulting in uneven thickness [26]. Altered heat flow due to microgravity introduces thermal issues, affecting part quality in fluctuating space temperatures. The influence of zero gravity extends beyond process parameters and 3D printing techniques, shaping the mechanical properties and topography of the final product. To overcome these challenges, comprehensive research on fluid dynamics and flow control in zero-gravity environments is imperative.

The vacuum of space, characterized by the absence of an atmosphere, fundamentally alters the heat transfer dynamics essential for the 3D printing process. The lack of convection as a heat dissipation mechanism in a vacuum requires innovative thermal management strategies. Without the ability to dissipate heat through convective processes, maintaining optimal printing temperatures becomes intricate, necessitating the development of advanced thermal control systems [27]. The vacuum environment introduces challenges in layer deposition, demanding meticulous adjustments to printing parameters to ensure the adhesion and structural integrity of printed objects.

Extreme temperature differentials in space, ranging from intense solar radiation to frigid shadowed regions, complicate material selection and process optimization for 3D printing. Rapid temperature fluctuations can induce thermal stress and differential expansion within printed structures, potentially compromising their mechanical properties. Unfiltered exposure to solar and cosmic radiation threatens the stability of printed materials, necessitating the exploration of radiation-resistant materials and shielding strategies. Researchers are actively developing adaptive printing techniques and material formulations

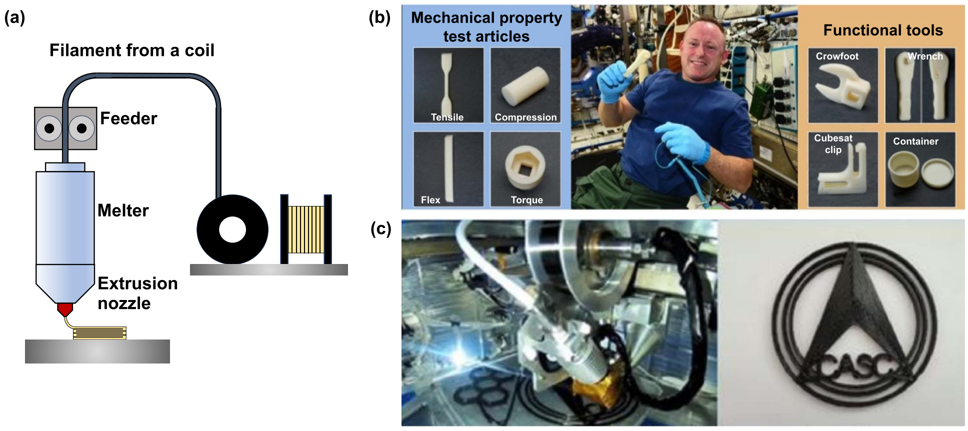

Figure 2. The representative polymer 3D printing process in space. (a) Schematic of fused filament fabrication—suitable for highly viscous polymers. (b) The 3D-printed polymer structures. Image credit: NASA. (c) Reprinted from [7],© 2022 Published by Elsevier Ltd on behalf of Chinese Mechanical Engineering Society (CMES).

capable of withstanding the harsh thermal and radiative conditions inherent to the space environment, ensuring the reliability and functionality of 3D printed objects in space.

3. Current status of 3D printing in space

Numerous initiatives are currently in progress, aiming to 3D print functional components in microgravity environments, thereby showcasing the vast potential of in-space manufacturing. These endeavors encompass a range of activities, including parabolic flight campaigns, satellite experiments, and demonstrations conducted aboard the International Space Station. Regarding materials, the existing in-space 3D printing technology can be broadly categorized into three categories: polymers, metals, and cell-laden substances.

3.1. Polymer 3D printing in space

Polymer 3D printing in space has evolved significantly, demonstrating technological advancements, expanded material capabilities, and the successful on-demand manufacturing of functional components. The National Aeronautics and Space Administration (NASA) introduced the pioneering fused filament fabrication-based 3D printer for polymer materials, known as 3D Printing in Zero-G Technology Demonstration, in 2014 (figure 2) [28, 29]. Delicate adjustments to the manufacturing process settings were implemented to ensure that specimens of acrylonitrile butadiene styrene (ABS) produced under orbital conditions exhibited no discernible microgravity-induced effects on their morphology and mechanical properties. In 2016, the first commercial Additive Manufacturing Facility installed on the International Space Station marked a significant milestone, enabling on-demand manufacturing and providing scientific support for research and industrial institutions [30]. Various functional polymer components have been successfully fabricated, including a tow hitch connecting two spheres from a synchronized position to hold, engage, and reorient payloads [31].

Moreover, the range of materials available for in-space polymer 3D printing has experienced substantial growth, now encompassing a variety of substances such as ABS, polylactic acid [32], high-density polyethylene, polyetherimide/polycarbonate, and even advanced fiber-reinforced composites. In May 2020, our team achieved a significant milestone by successfully developing a

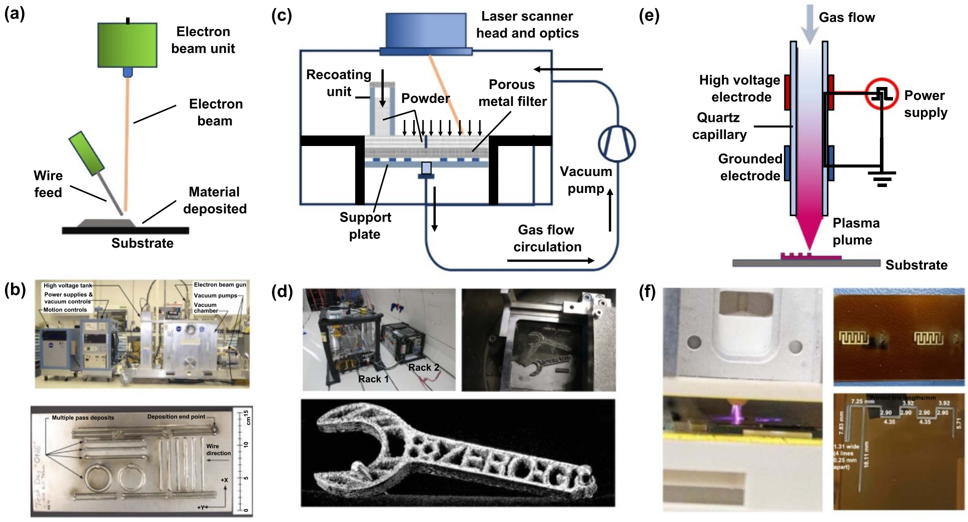

Figure 3. The representative metal 3D printing processes in space. (a) Schematic of directed energy deposition utilizes electron beams for controlled material fusion in space. (b) The directed energy deposition system and the printed metal tools. Reproduced from [https://ntrs.nasa.gov/api/citations/20080013464/downloads/20080013464.pdf]. Image stated to be in the public domain. (c) Schematic of powder bed fusion incorporates gas-flow-assisted powder deposition for precision. (d) [4] John Wiley & Sons.© 2019 The Authors. Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (e) Schematic of plasma jet printing employs high-energy plasma jets to achieve precise and efficient deposition of aerosolized ink. (f) Reproduced from [38]. © 2022 IOP Publishing Ltd.

3D printer capable of producing continuous fiber-reinforced thermoplastic composites, demonstrating the feasibility of manufacturing high-performance plastic components in space (figure 2(c)) [7, 33].

3.2. *Metal 3D printing in space*

Metal 3D printing in space originated from the manufacturing of tools. The exploration was initiated by the directed energy deposition-based 3D printing process, which utilizes focused thermal energy for controlled material fusion (figure 3(a)). NASA adopted a commercial electron beam welder for electron beam freeform fabrication of aluminum specimens, with feasibility assessed through aircraft parabolic flight campaigns (figure 3(b)) [34]. Despite differences in gravitational conditions, no discernible disparities were observed between microgravity and normal gravity fabrications [35]. However, implementing directed energy deposition in space faces challenges due to cumbersome equipment, low limited resolution, and the need for significant post-processing [36]. Our team successfully utilized a low-power laser to melt metal filaments, employing an anti-gravity configuration on the ground to simulate space conditions. In this environment, we achieved the manufacturing of high-quality metal cylindrical components with a smooth surface, maintaining a vacuum degree of 10–3 Pa and a temperature variation range of ±100 °C. Alternatively, the powder bed fusion-based 3D printing process selectively fuses specific regions within a powder bed, producing fully dense components with excellent mechanical properties. To address microgravity challenges, a gas-flow-assisted powder deposition technique was proposed (figure 3(c)). This novel technique successfully fabricated the world's first metal tool, demonstrating powder bed fusion's feasibility for producing ready-to-use metal parts in space (figure 3(d)) [4].

The focus has shifted from large mechanical structures to precision crafting high-resolution electronic components. Techniques like direct ink writing are used to explore the potential of metal 3D printing in space for circuit board repair.

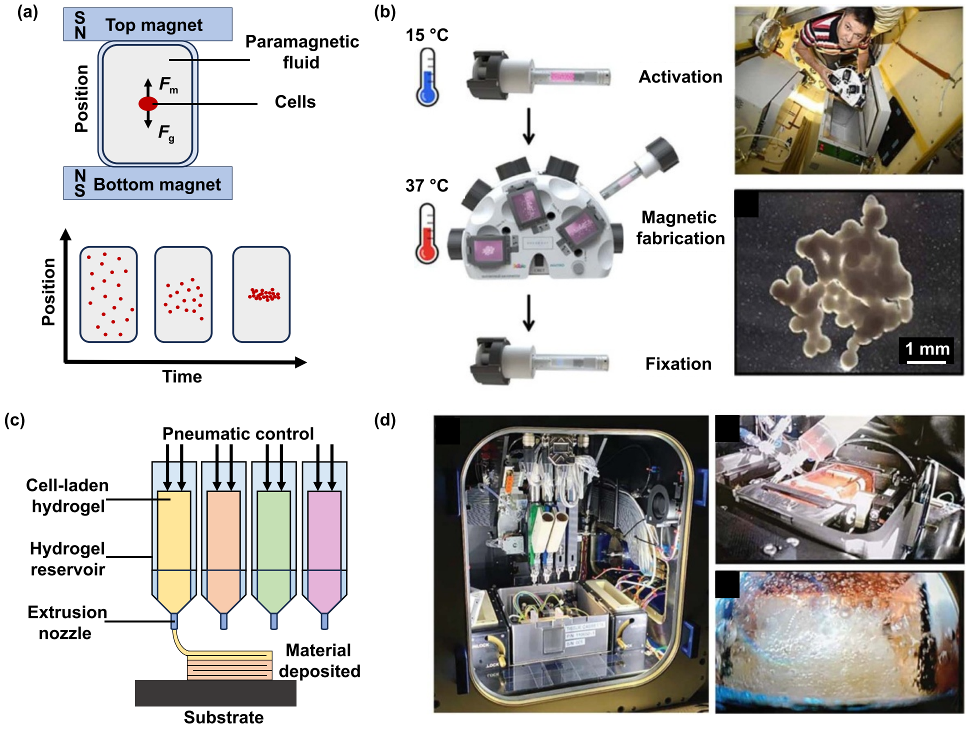

Figure 4. The representative bioprinting processes in space. (a) Schematic of magnetic levitational printing—two magnetic fields drive the cells toward the minimum magnetic field strength region. (b) Reproduced from [5]. CC BY 4.0. (c) Schematic of Extrusion Bioprinting—cell inks were extruded through the multiple printing heads. (d) [6] John Wiley & Sons.© 2019 The Authors. Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

Colloidal suspension ink enables the creation of uniform structures in weightless conditions, overcoming the challenges of zero/microgravity [37]. Additionally, solutions like plasma jet printing (figure 3(e)) have proven effective in printing intricate metal features, including submillimeter-resolution silver lines, pads, interdigitated electrodes, and a Wi-Fi antenna (figure 3(f)) [38].

3.3. *Bioprinting in space*

Prolonged exposure to the space environment, marked by microgravity and increased radiation, leads to detrimental effects such as muscle and bone mass loss, reduced cardiovascular activity, altered motor functions, and impaired wound healing [31, 39, 40]. To comprehend these impacts and develop patient-specific tissue constructs for astronauts, 3D bioprinting has emerged as a powerful tool.

The magnetic bioassembler Bioprinter Organ. AUT, delivered to the International Space Station in February 2019, achieved the world’s first bioprinting in microgravity, producing 3D cartilage tissue constructs via magnetic levitation (figures 4(a) and (b)) [5, 41]. This milestone study confirms the feasibility of bioprinting under microgravity conditions. In the same year, the 3D Biofabrication Facility on the International Space Station, equipped with four ink-extrusion systems, generated complex tissue structures, including cardiac tissue-like structures with specific cell types and components (figures 4(c) and (d)) [6, 42]. Recently, a Chinese space-based 3D bioprinting system with a cultivation unit using microgel printing ink was launched. This breakthrough is anticipated to advance anti-tumor therapy research and other disease treatments in space. However, further exploration of high-resolution bioprinting techniques in space is essential for creating more biomimetic models and tissue analogs in the future.

4. Perspective: manifesting space 3D printing—a gradual revelation

Advancing intravehicular 3D printing in space (inside the spacecraft) hinges on mastering controlled material deposition in microgravity. Current strategies involve imparting initial velocity to material droplets or utilizing forces such as electric fields and magnetic forces [5, 43]. Notably, using high-pressure electrostatic driving forces in electrohydrodynamic printing provides the necessary driving force and enables precision printing of materials at the micro and nanoscales, including electronic structures [44]. This approach proves particularly advantageous in circuit manufacturing, offering a promising avenue for enhancing the efficiency and functionality of space-based additive manufacturing. As we delve deeper into these innovative driving mechanisms, the prospects for achieving controlled material deposition in microgravity environments expand, opening new frontiers for applying 3D printing technology in space exploration.

Extravehicular 3D printing (outside during spacewalks) and planetary 3D printing (on celestial bodies), potentially integrated with remote sensing and control systems, pose notably more significant challenges than intravehicular 3D printing in space. However, the anticipated benefits make these initiatives exceptionally promising. Lunar regolith simulants have been employed to create intricate structures through digital light processing-based 3D printing in a microgravity environment. The rheological properties of the ceramic slurry were precisely regulated by integrating thickening agents, thereby ensuring the ceramic paste's resilience against fluctuations in gravity [45]. This initial endeavor exemplifies humanity's ambition for planetary 3D printing as we explore using *in-situ* resources. The prospect of fabricating structures and conducting research in the harsh environments of space holds immense potential, paving the way for groundbreaking advancements in space exploration and technology. While the complexity underscores the ambitious nature of these missions, the potential rewards make them endeavors worth anticipating.

Considering the limited availability of platforms for experimental work in space or simulating space environments [46], anti-gravity 3D printing research is a more accessible means for validating and refining technologies intended for space applications on Earth [44]. Besides being cost-effective, this terrestrial experimentation offers iterative testing and continuous improvement opportunities before actual deployment in space. Serving as a practical platform for mission preparation and team training, it ensures the successful adaptation of technology to the unique challenges posed by the absence of gravity in space.

When utilized strategically, space challenges can transform into opportunities, fostering innovative approaches and broadening the horizons of 3D printing technology. Microgravity, for instance, stimulates inventive designs that surpass Earth's constraints. In a vacuum, restrictions in convective heat transfer lead to heightened crystallinity in materials, especially polymers and metals, enhancing their mechanical properties [33]. The absence of atmospheric influences simplifies processes, eliminating the need for protective atmospheres and reducing system complexity inherent in on-ground 3D printing. Additionally, extreme temperatures and vacuum conditions open up possibilities for handling specific materials.

Anticipating the future, the prospects for 3D printing in space are promising and challenging. The capacity to fabricate intricate structures in the distinctive space environment unfolds new horizons for exploration and sustainability. Yet, substantial obstacles, including microgravity, material constraints, and the demand for heightened precision, necessitate focused attention. Ongoing research endeavors aim to broaden the technology's applications, enhance efficiency, and uncover novel materials, fostering optimism about its potential to revolutionize manufacturing practices and contribute to industry advancements. As space 3D printing continues evolving, it is critical to unlock innovative solutions and foster self-sufficiency in future space endeavors.

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