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3D Printing in Space

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Abstract:

3D printing, also known as additive manufacturing, is a technique for making a three-dimensional object of almost any shape through additive processes in which successive layers of material are laid down under computer control to generate the precise shape of the programmed model. It is an industrial process that has opened up new ways of looking at how parts are designed. It as emerged as a leading in-situ space manufacturing innovation because it offers unprecedented on-demand and rapid manufacturing capabilities in space. 3D printing in space is essential because it can manufacture intricate and customized structures locally, substantially decreasing mission expenses by launching only raw materials and essential components. 3D printing excels at manufacturing components for emergency repairs in space. This paper examines the use of 3D printing technology in space.

Keywords: 3D printing (3DP), additive manufacturing (AM), 3D printing in space, NASA, European Space Agency.

INTRODUCTION

Traditionally, a printer is used at home or in the office to print out text and images on paper. This conventional printer prints in a flat two-dimensional (2D) space using the dimensions length and width. A three-dimensional (3D) printer uses length and width but also adds depth to the print. A 3D printer has more manufacturing capacity than a traditional manufacturing machine. It is regarded as a disruptive technology that will change manufacturing. It has been used for decades in the automotive and aerospace industries. The 3D printer is also used by hobbyists, small businesses, creatives, manufacturers, architects, and most importantly contractors to instantly create a variety of products.

Humanity has been using 3D printing in the space industry since the 2000s. In 2011, European aerospace giant Airbus sent the first 3D printed part outside of our atmosphere. The company repeated the feat in 2015, when it produced the first space-qualified 3D printed to replace a satellite component. In 2024, the International Space Station (ISS), NASA and Made in Space made history by successfully 3D printing the first object in space. These initial successes paved the way for long-term space expeditions.

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. 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. Both NASA and the European Space Agency (ESA) are pushing ahead with plans for 3D printing on the moon and the International Space Station (ISS). Their goal is to build housing, infrastructure, tools, or spare parts that are needed to advance space exploration, possibly using space dust or rock as a raw material. Figure 1 shows the world's largest 3D printing facility producing rocket [1]. Apart NASA, ISS, ESA, companies interested in 3D printing in space include Relativity Space, Orbital Matter, Rocketdyne, Boeing, Airbus, Made in Space, and SpaceX.

WHAT IS 3D PRINTING?

3D printing (also known as additive manufacturing (AM) or rapid prototyping (RP)) was invented in the early 1980s by Charles Hull, who is regarded as the father of 3D printing. Since then it has been used in manufacturing, automotive, electronics, aviation, aerospace, aeronautics, engineering, architecture, pharmaceutics, consumer products, education, entertainment, medicine, space missions, the military, chemical industry, maritime industry, printing industry, and jewelry industry [2]

A 3D printer works by "printing" objects. Instead of using ink, it uses more substantive materials– plastics, metal, rubber, and the like. It scans an object–or takes an existing scan of an object–and slices it into layers, which can then convert into a physical object. Layer by layer, the 3D printer can replicate images created in CAD programs. In other words, 3D printing instructs a computer to apply layer upon layer of a specific material (such as plastic or metal) until the final product is built. This is distinct from conventional manufacturing methods, which often rely on removal (by cutting, drilling, chopping, grinding, forging, etc.) instead of addition. Models can be multi-colored to highlight important features, such as tumors, cavities, and vascular tracks. 3DP technology can build a 3D object in almost any shape imaginable as defined in a computer-aided design (CAD) file. It is additive technology as distinct from traditional manufacturing techniques, which are subtractive processes in which material is removed by cutting or drilling [3].

3D printing has started breaking through into the mainstream in recent years, with some models becoming affordable enough for home use. Many industries and professions around the world now use 3D printing. It plays a key role in making companies more competitive. The gap between industry and graduating students can be bridged by including the same cutting-edge tools, such as 3D printing, professionals use every day into the curriculum. There are 3D printed homes, prosthetics, surgical devices, drones, hearing aids, and electric engine components. As shown in Figure 2, 3D printing involves three steps [4]. A typical 3D printer is shown in Figure 3 [5].

3D PRINTING IN SPACE

The process of 3D printing involves the creation of three-dimensional objects by layering materials according to a digital model. This cutting-edge technology has found its way into diverse fields, ranging from healthcare to construction. It is already disrupting many fashion, engineering, and aerospace industries. It is often much cheaper than traditional industrial manufacturing methods, especially in low-volume applications. Today, 3D printing is increasingly becoming adopted in the space sector.

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. Standard 3D printers use plastics or metals to construct three-dimensional objects. NASA, the US space agency, is a pioneer in 3D printing exploration, providing funding for many new technologies. Its enthusiastic adoption of 3D printing is largely due to cost. 3D printing provides the low production volumes, high degrees of design freedom, and low cost that their missions require. In 2013, NASA announced funding for the development of a 3D printer that could create food for the astronauts. It succeeded in creating 3D print pizza in space, as shown in Figure 4 [6].

3D printing in space is an impressive technological feat that has yielded significant achievements. Sophisticated computer systems can help mission control systems on Earth to remotely operate 3D printers aboard spacecraft or present in space stations. Therefore, without advanced computing systems, the entire process of 3D printing, both on Earth and in space, would not be viable [7].

Regarding materials, the existing in-space 3D printing technology can be broadly categorized into three categories: polymers, metals, and cell-laden substances. Polymer 3D printing in space has evolved significantly, demonstrating technological advancements and the successful on-demand manufacturing of functional components. Metal 3D printing in space originated from the manufacturing of tools and will bring new on-orbit manufacturing capabilities.

APPLICATIONS

The 3D printing technology minimizes waste and continues to advance rapidly in terms of size, cost, complexity, and types of printable materials. It has many uses from the day-to-day, from printing whole houses to producing spacecraft parts. The following are typical applications of 3D printing in space exploration.

1. *Astronauts:* Astronauts benefit from 3D printing with devices aboard spacecraft and stations that help to sustain long missions in space between resupplying. Current astronauts contend with in weightlessness, tackled in part through exercise and medical countermeasures. This might be made more serious still by spending years rather than months in orbit. Astronauts have already used 3D printers to replace or repair plastic parts. On-demand manufacturing allows astronauts to quickly produce tools and components tailored to their specific needs. Figure 5 shows some astronauts [8].

2. *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. To comprehend these impacts and develop patient-specific tissue constructs for astronauts, 3D bioprinting has emerged as a powerful tool. A 3D bioprinting capability would allow a more flexible, versatile response to emergencies.

3. *International Space Station* (ISS): This has continuously been home to astronauts for more than nineteen years. Astronauts conduct scientific research using dozens of special facilities aboard the space station, which also provides them with a place to eat, sleep, relax, and exercise. To make all of this possible requires sending more than 7,000 pounds of spare parts to the station annually. The project sent the first 3D printer to the space station in 2014. Developed by Made in Space, this printer used a fused filament fabrication (FFF) process, feeding a continuous thread of plastic

through a heated extruder and onto a tray layer by layer to create a 3D object. This particular 3D printing process is not affected in a significant way by microgravity [9].

4. *A Zero-Gravity 3D Printer*: Using the 3D printing technology, it is now possible to manufacture spare parts in space. Astronauts have found that additive manufacturing is a viable technology to use even in microgravity. NASA and Made in Space collaborated to produce to a 3D printer that can operate in zero-gravity environments. Figure 6 shows the Zero G 3D printer by Made in Space in collaboration with NASA [6]

5. *Satellites:* 3D printing is also increasingly being used in space is for satellites. Currently, there are projects from a number of companies including Boeing and Airbus which have used additive manufacturing to create increasingly complex, lighter parts for their satellites.

6. *Aerospace:* 3D printing technology is increasingly being used in aerospace and particularly space exploration for various applications. This is because it allows for lighter, cheaper, and more efficient parts to be made due to the unique geometries that are possible with AM as well as the materials used. One such application involves using additive manufacturing for thrusters. Additive manufacturing is also being used in the aerospace industry for the creation of 3D printed rockets. The aerospace industry is facing is the creation of 3D printed food.

7. *Rocket Engines:* Space companies are turning to 3D printing. More and more often, engineers are using the SLS process to 3D print rocket engine parts with a copper alloy powder, which can withstand high temperatures. They have designed a 3D printed rocket engine that is 15% more efficient than those traditionally produced. Figure 7 shows 3D printed rocket engine by SpaceX [6].

BENEFITS

The advantages of 3D printing in space are many. Advancements in 3D printing technology offer solutions to improve food options, reduce waste, and enable on-demand preparation in space. 3D printing could revolutionize space exploration by helping astronauts create objects in space and on-demand. Even though the raw material still needs to be launched, printing the part is still more efficient than transporting it whole up to its final destination. The flexibility and rapid availability of 3D printing will greatly improve astronauts' autonomy. Other benefits of 3D printing in space include the following [10-12]:

1. *Waste:* The additive nature of 3D printing means little waste is generated, eliminating the problem of waste disposal in space. The printer used for space by NASA was developed to test technology for recycling waste plastic materials into high quality 3D-printer filament. Recently, the Made in Space Recycler launched to the space station for an investigation into which materials are most effective for recycling into 3D printing filament and which ones can hold up over multiple uses without degrading.

2. *Savings:* So having a 3D printer on the space station could make crewmembers' lives easier and result in significant savings. NASA has been testing rocket-engine parts made via 3D printing, which is significantly cheaper and more efficient than traditional manufacturing techniques for such parts. Manufacturing in space can reduce the cost and time of transporting materials from earth, allowing for more sustainable and efficient space exploration.

3. *Customization:* 3D printing has the potential to revolutionize manufacturing in space, making it more sustainable, cost efficient, and flexible. The technology is capable of building custom parts and objects on demand. Manufacturing in space can enable the production of custom made parts that are specifically designed for space environments, reducing the risk of equipment failure. The option of printing replacement tissue in a customized shape to directly replace a cancer-affected part of the body is opening up treatment options not only for space exploration but also back on Earth.

CHALLENGES

While the process of 3D printing has been mastered on Earth, printing metal in space presents its own set of technical challenges. Challenges of 3D printing in extreme space environments include microgravity, high levels of vacuum, significant temperature differentials, and the impact of cosmic and solar radiation. 3D printing addresses challenges such as mass reduction, intricate component fabrication, and resource constraints. One of the main challenges that astronauts face is the lack of specific replacement parts on-board the space station. Extravehicular 3D printing and planetary 3D printing pose notably more significant challenges than intravehicular 3D printing in space. Other challenges of 3D printing in space include the following [11-13]:

1. *High Cost:* One of the major challenges is the cost of transporting materials and equipment to space. The cost of launching a single kilogram of material into space is currently around $10,000, making it cost-prohibitive to transport large amounts of materials and equipment. The hardest and most expensive thing about space is getting there. So the Pentagon is looking at ways to reduce the bill, including putting 3D printers into orbit to repair smaller satellites.

2. *Microgravity:* One of the challenges space exploration faces is the absence of gravity in space. This poses formidable challenges to space-based 3D printing, affecting both the printing and post-production phases. The microgravity environment can affect the quality and accuracy of 3D printed objects. The absence of gravity leads to molten materials forming spherical droplets during printing, causing disruptions and compromising print quality. Altered heat flow due to microgravity introduces thermal issues, affecting part quality in fluctuating space temperatures. Getting printers to function in a near-zero gravity environment and with the absence of pressure is not a trivial task. Figure 8 shows a 3D printer passing microgravity flight tests [14].

3. *Vacuum of Space:* 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. The vacuum environment introduces challenges in layer deposition.

4. *Suitable Materials*: One of the major disadvantages is the limited availability of suitable materials in space for 3D printing. This has led to the development of innovative printing techniques and materials capable of utilizing indigenous resources. In space, where there is microgravity or zero gravity, the behavior of materials is different

5. *Safety:* This involves protecting the International Space Station (ISS) from the aggressive printing environment caused by the laser and the heat it generates. The printer sits in a sealed metal box, which acts like a safe. Safety and contamination are key drivers for not only for the ISS, but for future use on the Moon.

6. *No Standards:* One challenge is that there really are not firm standards for how to test 3D printed materials, but various organizations, including NASA, are working on test procedures.

7. *On-orbit Inspection*: Another challenge is on-orbit inspection of parts made in space. To use a part in space, you need to know that it meets the requirements for its intended use. Testing these manufacturing systems on the space station paves the way to allow those missions to be more independent of Earth.

Overcoming these technical hurdles is crucial to ensuring the reliability and precision of 3D printing processes in space. Given the rate of progress so far, there is confident that these challenges will be overcome.

CONCLUSION

NASA, the European Space Agency (ESA), and the space agencies of Russia, China, and India are all actively exploring, and already using 3D printing to help meet their exploration, scientific, security, and commercial goals. NASA is working to develop and incorporate 3D printing technology on several different fronts. For example, the agency awarded a $125,000 grant to a researcher seeking to build a prototype 3D printer for food. The European Space Agency (ESA) plans to launch its own 3D printer to the International Space Station in the first half of 2015. ESA is recently investigating the feasibility of using 3D-printing technology to build a moon base using lunar materials. 3D printing offers a potential means of facilitating lunar settlement with reduced logistics from Earth [15]. SpaceX is another company using 3D printing as an integral part of manufacturing.

In space exploration, 3D printing has simply become part of life. The idea of manufacturing goods in space has gained attention. 3D printing is revolutionizing launch vehicle design by reducing component counts, integrating complex geometry into lightweight structures, and speeding the whole design and manufacturing cycle. The predictions for the 2020s are high: Space tourism will become a reality, the first woman will reach the Moon, a permanent lunar base will be built, exploration of our solar system will boom, the first human mission will get to Mars, and commercial manufacturing in space will begin. Once in space, 3D printing has several key roles to play: The "zero-g" environment of space orbit opens doors to print materials not possible under the influence of earthly gravity [1].

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Figure 1 The world’s largest 3D printing facility producing rocket [1].

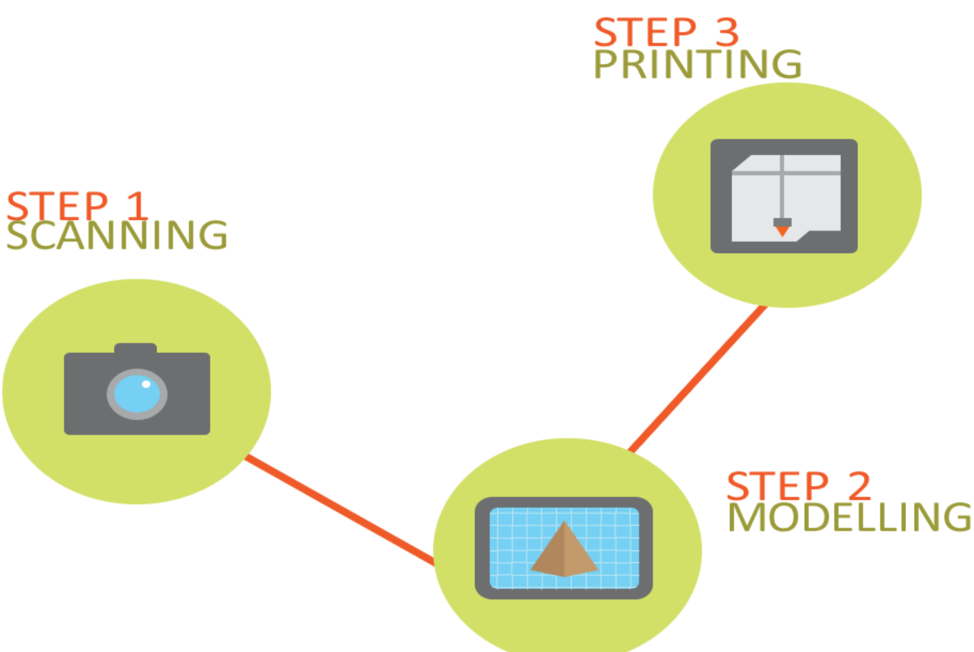

Figure 2 3D printing involves three steps [4].

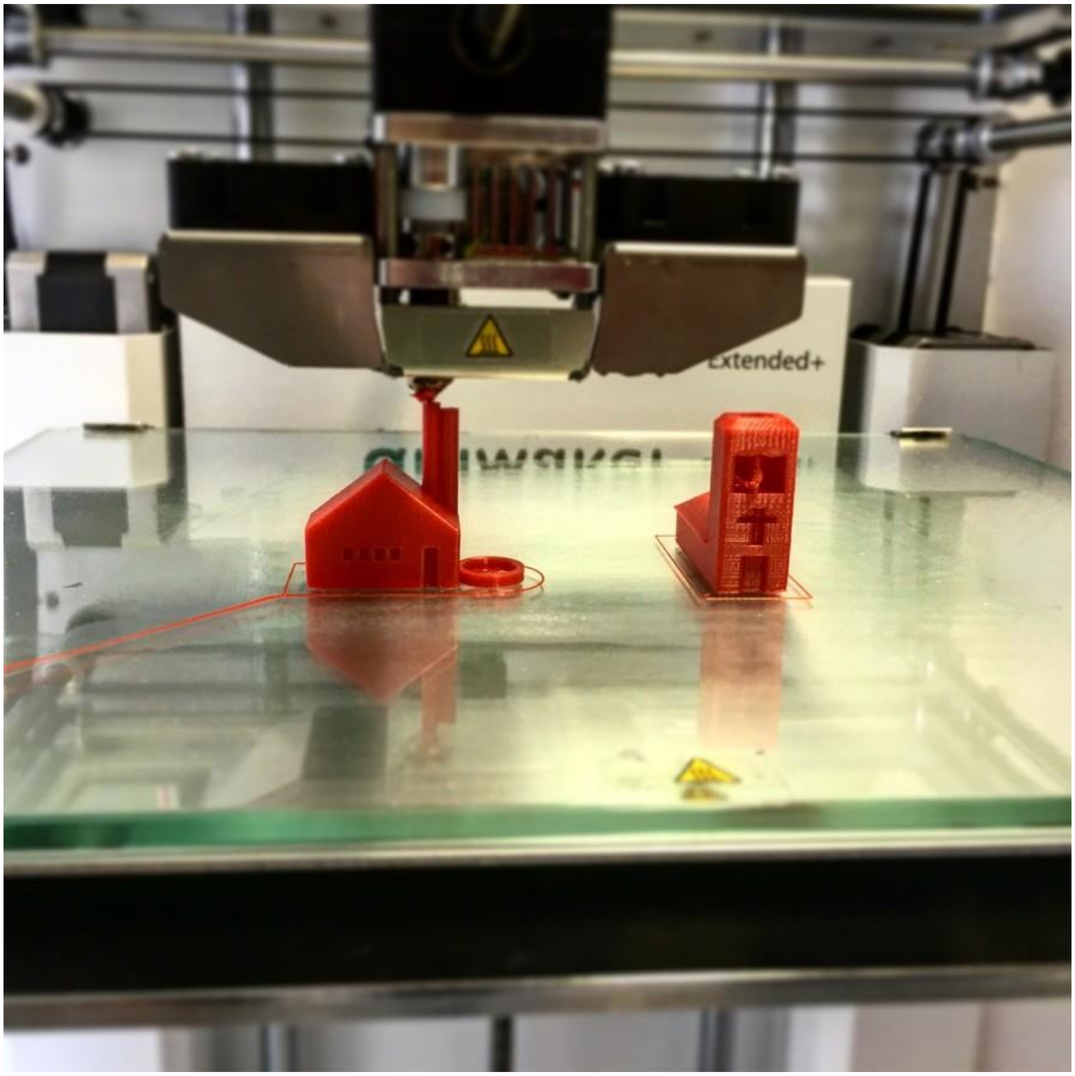

Figure 3 A typical 3D printer [5].

Figure 4 3D print pizza in space [6].

Figure 5 Some astronauts [8].

Figure 6 The Zero-G 3D printer [6].

Figure 7 3D printed rocket engine by SpaceX [6].

Figure 8 A 3D printer passing microgravity flight tests [14].