aerospace

MDPI

Review

3D Printing for Space Habitats: Requirements, Challenges, and Recent Advances

Reza Hedayati * and Victoria Stulova

Department of Aerospace Structures and Materials (ASM), Faculty of Aerospace Engineering, Delft University of Technology (TU Delft), Kluyverweg 1, 2629 HS Delft, The Netherlands
* Correspondence: r.hedayati@tudelft.nl or rezahedayati@gmail.com

Abstract: Heavily resource-reliant transportation and harsh living conditions, where humans cannot survive without a proper habitat, have prevented humans from establishing colonies on the Moon and Mars. Due to the absence of an atmosphere, potential habitats on the Moon or Mars require thick and strong structures that can withstand artificially produced internal pressure, potential meteoroid strikes, and the majority of incoming radiation. One promising way to overcome the noted challenges is the use of additive manufacturing (AM), also known as 3D printing. It allows producing structures from abundant materials with minimal material manipulation as compared to traditional constructing techniques. In addition to constructing the habitat itself, 3D printing can be utilized for manufacturing various tools that are useful for humans. Recycling used-up tools to compensate for damaged or unfunctional devices is also possible by melting down a tool back into raw material. While space 3D printing sounds good on paper, there are various challenges that still have to be considered for printing-assisted space missions. The conditions in space are drastically different from those on Earth. This includes factors such as the absence of gravity, infinitesimal pressure, and rapid changes in temperature. In this paper, a literature study on the prospects of additive manufacturing in space is presented. There are a variety of 3D printing techniques available, which differ according to the materials that can be utilized, the possible shapes of the final products, and the way solidification of the material occurs. In order to send humans to other celestial bodies, it is important to account for their needs and be able to fulfill them. An overview of requirements for potential space habitats and the challenges that arise when considering the use of additive manufacturing in space are also presented. Finally, current research progress on 3D printing Lunar and Martian habitats and smaller items is reviewed.

Keywords: 3D printing; additive manufacturing; space habitats; Mars; Moon

check for updates

Citation: Hedayati, R.; Stulova, V. 3D Printing for Space Habitats: Requirements, Challenges, and Recent Advances. *Aerospace* **2023**, *10*, 653. https://doi.org/10.3390/aerospace10070653

Academic Editor: George Z. H. Zhu

Received: 16 June 2023
Revised: 8 July 2023
Accepted: 13 July 2023
Published: 20 July 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Space exploration and inhabiting other celestial bodies are important milestones in technological progress. Establishing human colonies on the Moon and Mars would serve as a gateway for exploring space even further, potentially expanding the pool of natural resources available for use [1,2]. However, there are obstacles that prevent humans from simply settling there. These obstacles heavily include resource-reliant transportation and harsh living conditions, where humans cannot survive without a proper habitat [3,4]. The absence of an atmosphere as compared to Earth exposes astronauts to intense solar radiation, a lack of oxygen and pressure, and potential meteoroid strikes. Hence, potential habitats on the Moon or Mars require thick and strong structures that can withstand an artificially produced internal atmosphere and absorb the majority of incoming radiation. It is worth mentioning that other celestial bodies in the inner solar system, such as Venus and even Mercury, have been proposed for establishing human colonies. The temperature at Mercury varies wildly during the day, from −173 °C at night to 427 °C during direct sunlight. Since Mercury is very close to the Sun, significant shielding from radiation and solar flares is required. As for Venus, the environmental conditions on the planet's surface are extremely hostile for human life, with an average surface pressure of 45 bar and an average temperature of 464 °C. Although some suggestions have been made to colonize the upper atmosphere of Venus (around 45 km above the planet's surface) by means of floating habitats, such suggestions seem extremely costly, and hence practical attempts have not yet been made by space agencies to realize colonization of Venus. Therefore, in this paper, we focus our review on the challenges and requirements of 3D printing habitats on Mars and the Moon.

Expenses related to transporting the payload into space generate additional challenges related to supplying necessities. Items required for spacecraft and other equipment maintenance or fulfilling human needs can be forgotten or broken, which might lead to mission complications or even failure. Furthermore, being independent from the resources of Earth would significantly benefit a successful settlement establishment by removing extra sustenance expenses. Therefore, making good use and reuse of limited resources and utilizing local resources is very attractive [5].

One promising way to overcome the noted challenges is the use of additive manufacturing (AM), also known as 3D printing. It allows to produce structures from abundant materials with minimal material manipulation as compared to traditional constructing techniques [6]. Moreover, automating 3D printing to construct buildings is considerably easier, as the layer-by-layer build-up procedure can be specified in computer-aided design (CAD) software [7]. Preparation for the printing process can be as simple as throwing some Lunar dust into the printer and pressing the start button, while traditional construction techniques would certainly require some extra processing of regolith [8]. To take it even further, it is possible to send unmanned spacecraft with a mobile, remotely manipulated 3D printer, which can prepare the initial habitat for astronauts who can arrive later. This allows them to spend more time on their mission by having a ready habitat for them, as their stay on other celestial bodies is usually limited due to intense radiation [9,10].

In addition to constructing the habitat itself, 3D printing can be utilized to manufacture various tools that are useful for humans. Recycling used-up tools to compensate for somewhat lower tool quality is also possible by melting down the tool back into raw material. Items that can be produced this way include various maintenance tools like screwdrivers and wrenches, surgical tools, or even vacuum cleaner heads for cleaning hard-to-reach locations [5]. Potentially, 3D printing can be used to produce part replacements for complex mechanisms as well, simplifying the reparation process and hence contributing to sustenance [11].

While space 3D printing sounds good on paper, there are various challenges that still have to be considered when thinking about printing-assisted space missions. The conditions in space are drastically different from those on Earth. This includes factors like the absence of gravity, vacuum, and rapid changes in temperature. AM machines and materials are usually sensitive to ambient conditions. Therefore, it is vital to make sure that the extreme factors listed above can be tolerated. In addition to ambient conditions, 3D printers in space and on the Moon or Mars can encounter dangers like meteoroid strikes, from which there is little to no atmospheric protection, and a lack of human interaction, meaning that the machine's artificial intelligence (AI) has to be carefully programmed and tested. A comprehensive study reviewing all the above-mentioned factors and challenges of 3D printing in Space that adds to the already existing challenges of 3D printing on Earth is missing from the literature.

In this paper, a literature study on the prospects of additive manufacturing in space is presented. There are a variety of 3D printing techniques available, which differ according to the materials that can be utilized, the possible shapes of the final products, and the way solidification of the material occurs. These techniques are discussed in Section 2. In order to send humans to other celestial bodies, it is important to account for their needs and be able to fulfill them. An overview of requirements for potential space habitats is presented in Section 3. The challenges that arise when considering the use of additive manufacturing in space are considered in Section 4. Finally, current research progress on 3D printing Lunar and Martian habitats and smaller items is presented in Section 5.

2. 3D Printing Techniques Overview

Additive manufacturing, or 3D printing, is a general term for a variety of manufacturing techniques that are based on creating an object layer by layer. These techniques vary in the materials that can be processed by them, the state of those materials, the means of solidification, and possible geometries [12–22].

2.1. Fused Deposition Modeling

Extrusion deposition prototype modeling is based on depositing semi-solid material in thin layers [23]. The material is extruded into a thin wire and solidified upon deposition because it is partially solid. Another name for this process is Fused Deposition Modeling (FDM), the setup for which is presented in Figure 1 [24]. In order to modify the thickness of the deposited wire, the size and shape of the nozzle tip can be varied. Depending on the material used for the printing, the liquefier can be set to a different temperature for optimal viscosity. During a layer deposition, the head moves along the x-y axes according to the pattern set by the computer-aided manufacturing software. After a layer is deposited, the platform with the printed scaffold lowers along the z-axis, and the next layer is deposited. Due to the state of the deposited material, layers can typically solidify into the intended shape; however, for more complex shapes, a soluble support structure might be required, which needs to be removed during post-processing [24].

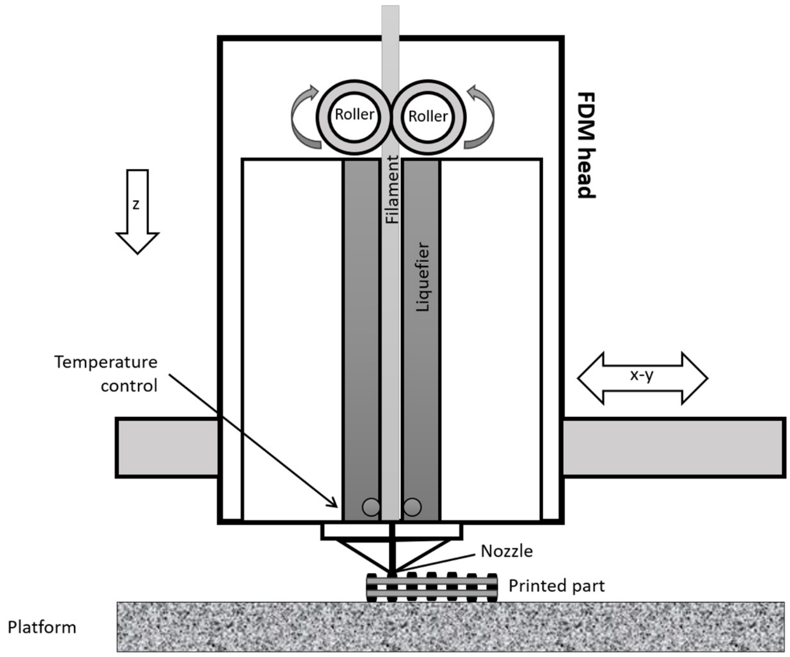


Figure 1. Schematic representation of the FDM process. Imaged drawn based on [23].

The major materials used for FDM include thermoplastic materials, such as polycaprolactone (PCL), polyether ether ketone (PEEK), acrylonitrile butadiene styrene (ABS), nylon, and polylactic acid (PLA) [25–29] (see Table 1 for more details on their physical properties). However, it is also possible, albeit difficult, to perform this process with metals, paste-like ceramics, and even chocolate. The material can be chosen depending on the required mechanical properties and temperature behavior, and the liquefier and nozzle of the FDM head have to be of appropriate diameter and be able to withstand the processing temperature. temperature just below the melting temperature, and inert gases such as argon have been used in the printing chamber to ensure better adhesion during solidification.

Table 1. Physical properties of polymers common in FDM printing.

Polymer	Chemical Formula	Glass Transition Temperature	Melting Point	Density [kg/m^3]	Characteristics
PCL	$(C_6H_{10}O_2)_n$	−60 °C	60 °C	1145	• Biodegradable • Most common use: making of polyurethanes • Good resistance to water, oil, solvents, and chlorine
PEEK	$C_{19}H_{14}O_3$	143 °C	343 °C	1320	• Semicrystalline thermoplastic • Excellent mechanical and chemical resistance • Resilience against high temperatures
ABS	$(C_8H_8 \cdot C_4H_6 \cdot C_3H_3N)_n$	105 °C	No true melting point	1070	• Amorphous • Good impact resistance, toughness, and rigidity • Electrical properties are little affected by temperature and atmospheric humidity
Nylon 66	$(C_{12}H_{22}N_2O_2)_n$	70 °C	264 °C	1140	• Inexpensive • Good stability under heat and/or chemical resistance
PLA	$(C_3H_4O_2)_n$	65 °C	155 °C	1300	• Most widely used material in 3D printing • Low thermal expansion • Good layer adhesion • High heat resistance when annealed

2.2. Stereolithography

Stereolithography is a method of printing parts using the photopolymerization process. Polymer resin, which was originally liquid and in a monomeric state, gets polymerized and solidified under a thin beam of light. Typically, the light used is either an ultraviolet (UV) laser or a Digital Light Processing (DLP) projector [30]. Both variations are presented in Figure 2. The beam of light follows the path indicated by the CAD software over the unlinked resin in a bath. When a layer is complete, the bath gets lowered and extra resin gets added to it. The laser then goes over the newly deposited resin. In the end, cleaning the part with a solvent is required to get rid of the unlinked resin [30].

Because of the possibility of having a very narrow beam, stereolithography printing has very high resolution and is able to achieve very low wall thickness compared to other 3D printing methods [31]. Typically, supporting structures are utilized, allowing for even more complex shapes, but they have to be removed during post-processing. Since this method relies upon polymer crosslinking, the material selection is strictly limited to these polymers, which might be quite costly [31].

2.3. Selective Laser Sintering

Selective Laser Sintering (SLS) is a technique similar to the previously discussed stereolithography, except that the material used is plastic, glass, ceramic, or metal powder. The powder is placed in the printing bath, where the laser follows a layer path specified by CAD software. After the layer is complete, the bath gets lowered, a new layer of powder is deposited, and the process is repeated. The overall representation of SLS printing is present in Figure 3. It is worth noting that in this printing method, the use of supporting structures is not required, as the surrounding powder is sufficient to support the resultant structure [32]. This allows for the production of quite complex shapes without additional investment [33]. Depending upon the binding mechanisms, SLS methods can be classified as shown in Figure 4.

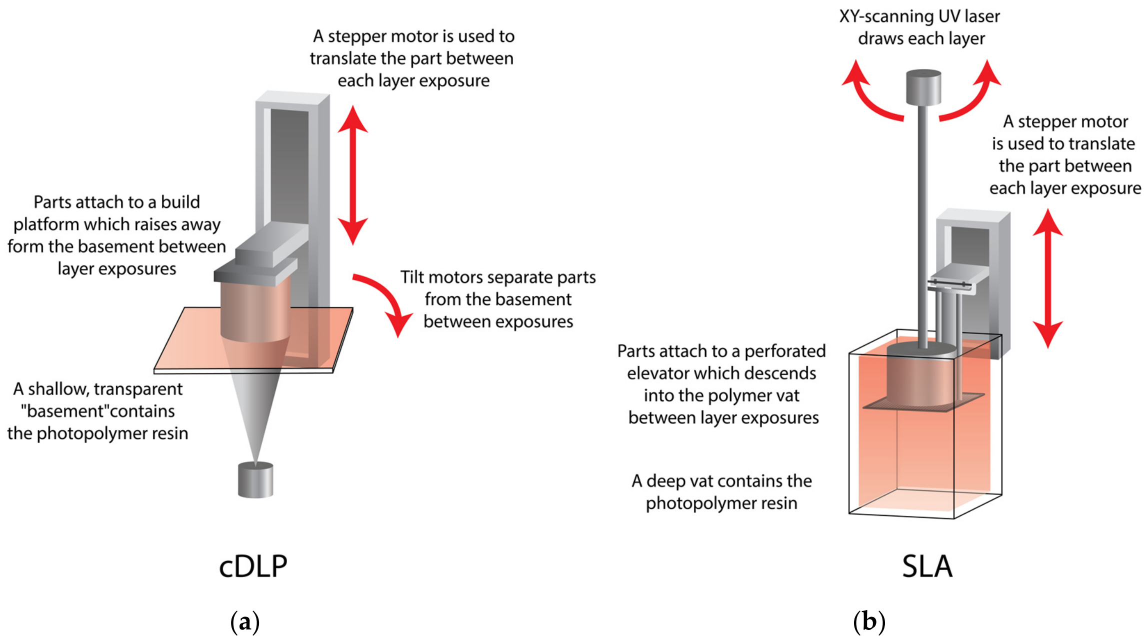


Figure 2. Schematic drawings of both the Digital Light Processing setup (**a**) and UV laser stereolithography (**b**). Imaged drawn based on [30].

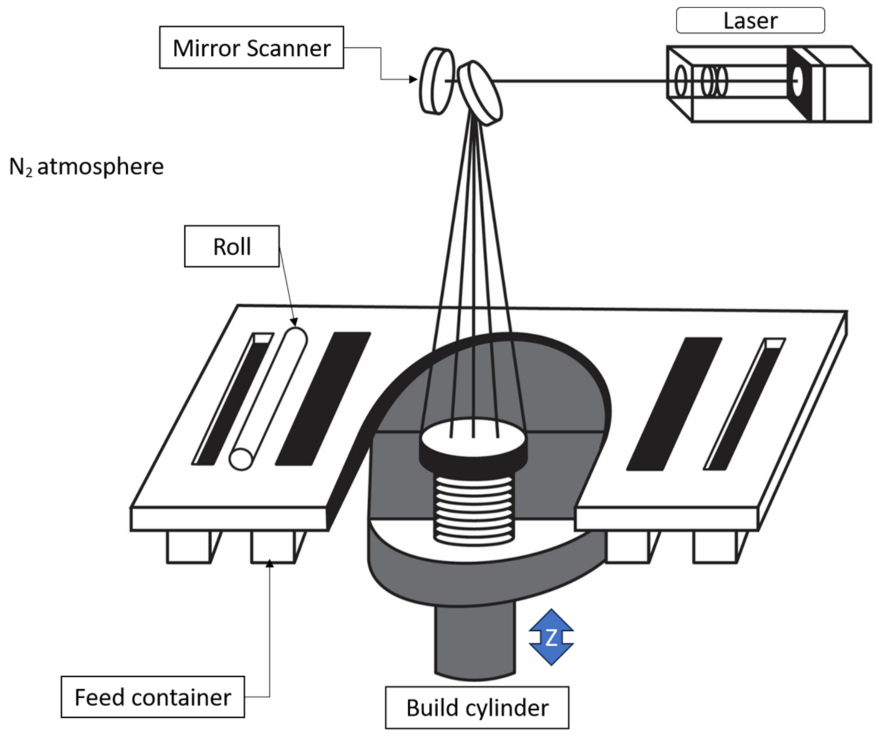


Figure 3. Schematic drawing of an SLS printer. Imaged drawn based on [34].

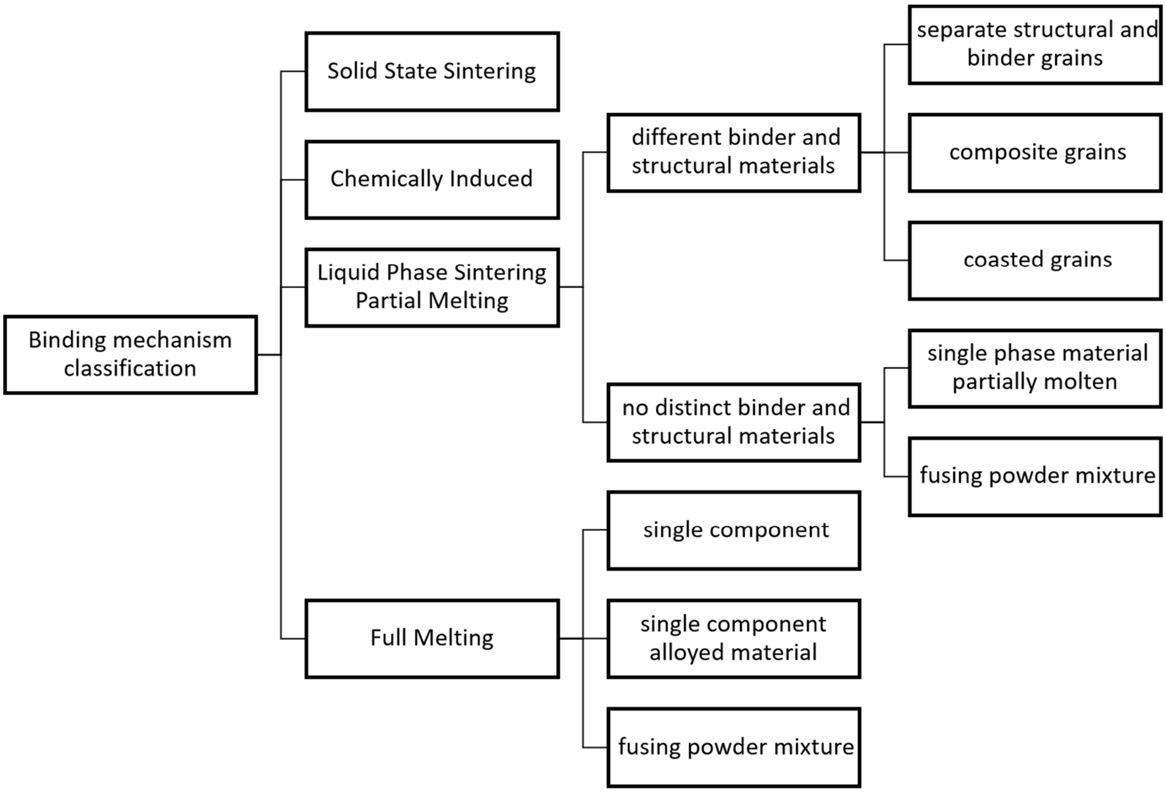


Figure 4. Methods used in selective laser sintering printing. Imaged drawn based on [34].

Solid-state sintering is performed at temperatures close to but lower than the melting temperature of the material used. At this temperature, the free energy of the powder particle surface gets lowered, allowing the particles to fuse together and hence sinter. This mechanism is similar to the sintering of ceramics but is local instead. Chemically induced binding is usually related to ceramic materials and is based upon laser inducing a chemical reaction with powder components, so binding occurs. For example, a part consisting of a mixture of silicon carbide and silicon dioxide can be made via this method, as the initial silicon carbide powder partially decomposes and silicon forms an oxide that acts as a binder for the remaining powder [34]. In the case of liquid-phase sintering, the presence of a binder is required. One way of including binder is to have it separate from the main material in the form of powder, coating, or simply fused within the same powder particle. There is another way to make the main material partially melt and act as a binder for itself. This subprocess is also called Selective Laser Melting. Due to the high variety of binder inclusions, a lot of materials are suited for this SLS variation. Finally, mostly used for metallic powders, full melting and consequent solidification can be used to create a part [34].

The major advantage of the SLS method is that a large variety of materials can be used as soon as the optimal processing method and optimal conditions are determined. As materials are being processed similarly to how they would be processed during casting or sintering, the resultant part has high mechanical properties. Achievable complexity without the need for supporting structures is also an important benefit. Disadvantages of this method include the fact that fully enclosed shapes are typically not possible to produce, as the powder that would be trapped inside the part would be difficult to remove without damaging the part. Moreover, the surface quality of this method is not as good as other methods because the powder particles are not that small, so additional postprocessing is often required.

2.4. Material Jetting

The material jetting manufacturing technique is similar to the stereolithography method in the sense that the material used is photopolymer. The difference comes in the way of material deposition, as instead of filling the bath completely, only the required amount of resin is placed in the location. This resin is being cured immediately by a light beam [35]. This way, the amount of resin used is significantly less; however, for more or less complicated shapes, the use of support is absolutely required, as there is no support from the surrounding resin. A huge advantage of this technique over stereolithography is the possibility of having multiple printing heads with different resins, allowing for the construction of parts with varying properties such as color. This technique is used by the PolyJet 3D printer, and the schematic of it is presented in Figure 5.

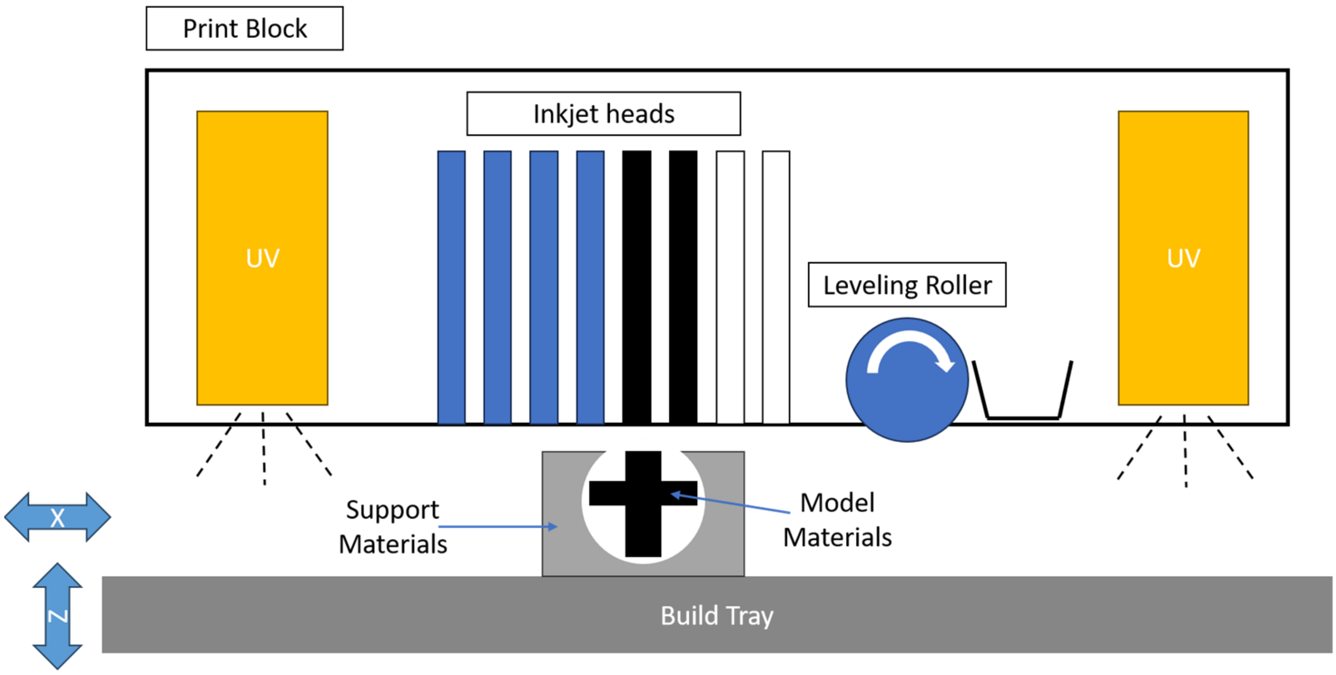


Figure 5. Schematic representation of the material jetting printer PolyJet. Imaged drawn based on [35].

2.5. Binder Jetting

The binder jetting printing process is based upon the deposition of the binding material onto the main material, primarily sand and glass [36]. Inkhead follows the path specified by CAD software and deposits binding material onto the powder, then the bath gets lowered, covered by an extra powder layer, and the process is repeated [37]. An example setup for this technique is presented in Figure 6. Commonly, between layer deposition, the previous layer gets heated up in order to dry the binder, solidifying the built layer [37]. This process is similar to SLS, except the binder is being deposited onto the material instead of being activated by the laser. Just like in the SLS process, the part often needs to be coated to diminish the powder coarseness; excess powder needs to be removed from the part, which complicates the production of fully enclosed parts; and the use of supporting structures is not necessary because of the powder support. D-shape printing technology is one of the variations of this process, which works with large structures and is considered one of the ways to build a space habitat on a surface other than Earth. This technique is further discussed in this paper.

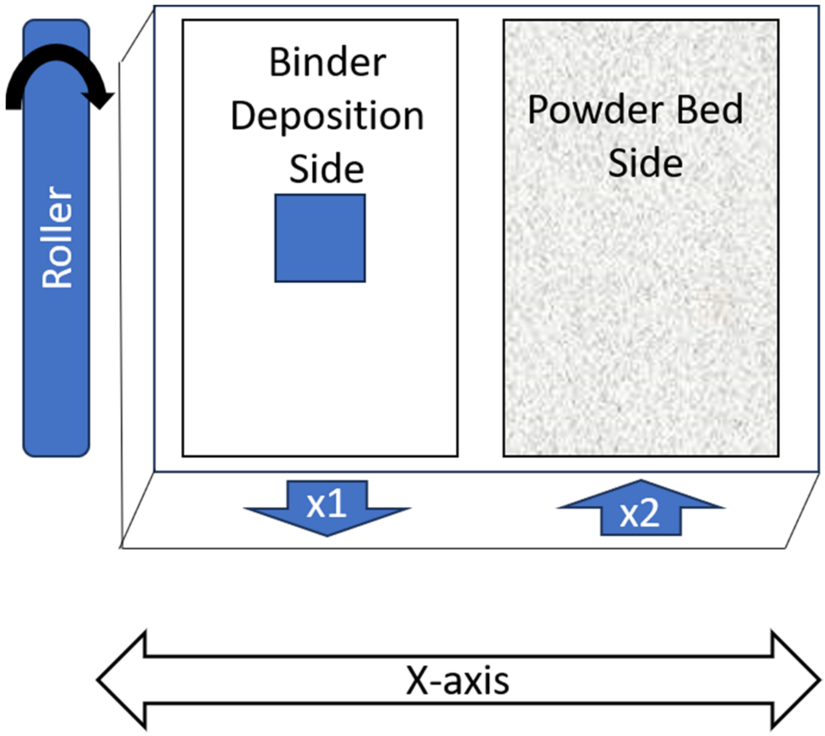


Figure 6. Schematic representation of a binding deposition printer. Imaged drawn based on [37].

3. Needs for Space Habitats

Before sending humans into space and on other celestial bodies, it is crucial to establish the necessary conditions for keeping humans safe and healthy. A comfortable stay ensures a considerably higher chance of mission success. This section elaborates on the possible needs of astronauts on the Moon and Mars.

3.1. Astronaut Needs

On Earth, humans are adapted to the atmospheric conditions, are protected from space radiation by the atmosphere, and have access to life-sustaining necessities, such as oxygen, water, and food. In space, and in particular on the Moon and Mars, the atmosphere is almost negligible as compared to Earth, and life-sustaining resources are not readily available or are even absent. In order for humans to live for an extended amount of time on other celestial bodies, Earth-like conditions have to be maintained.

First of all, the human body requires oxygen concentration, pressure, and temperature similar to the atmospheric conditions on Earth. This can be either provided by the space suits, which have been used in short-term landings so far, or by means of an artificial atmosphere inside an enclosed location. For long-term missions, the second option is more desirable. This generates a structural requirement for the potential planetary habitat to withstand the inner pressure of the artificial atmosphere on the habitat walls, minimize potential leakage of the artificial atmosphere, and be able to withstand thermal loads inflicted by the combination of high temperatures during the day, low temperatures during the night outside the habitat, and temperatures comfortable for humans inside the habitat.

Another pressing issue with human presence on other planets is space radiation, which is basically not sheltered on the Moon or Mars, unlike on Earth, which has a strong atmosphere. Even if it is possible to create a fully sustainable settlement on a planet other than Earth, the duration of a safe human stay in those settlements will be limited by space radiation. As an example, the risk of getting cancer during a 180-day Lunar mission is calculated in Figure 7 (data taken from [38]). One way to reduce the risk is to send only male astronauts above a certain age, but even then, the risk is high. For Mars missions, which are considerably longer even with a short period of stay due to long transfer times, the risks are considerably higher. However, 3D printing can help this situation in an unexpected manner by utilizing raw materials as a shield. If the raw material is stored in the walls of the spaceship, it can contribute to the wall thickness, which is a primary factor in radiation shielding [39]. On the planetary surface, the walls of the habitat have to be sufficiently thick to absorb the incoming radiation and shield the humans inside. Moreover, special attention has to be paid to the health of astronauts that are sent on planetary missions, especially regarding genetics related to oncology and heart diseases. This can significantly decrease the possibility of mortality due to radiation overdose [40].

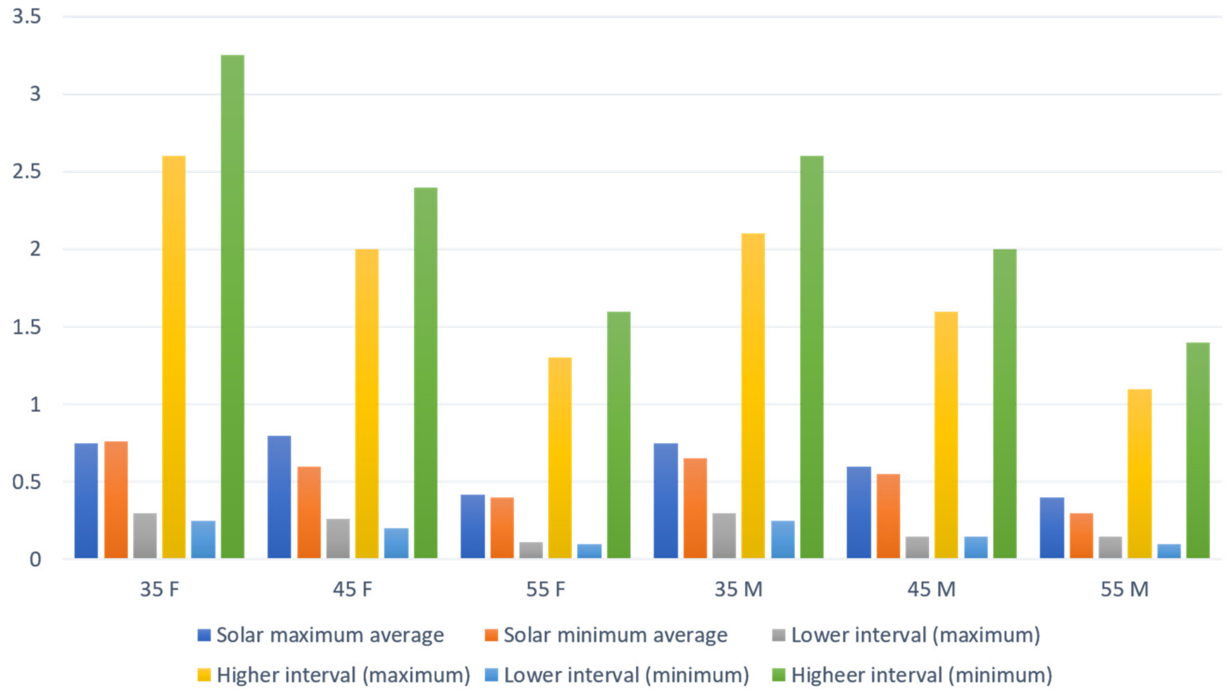


Figure 7. Risk of cancer disease during a 180-day Lunar mission at varying solar activity with a 95% confidence interval. Data from [38].

When it comes to consumable resources, they can be transported from Earth. However, in a long-term mission, this is not an optimal solution due to the added mission costs associated with an extra payload. As can be seen in Figures 8 and 9, the amount of consumable resources per human is very high. Hence, it would be convenient to be able to produce and/or sustain the necessary items in the planetary outpost itself. Moreover, human waste should be recycled or at least destroyed to avoid stockpiling waste on the planets. These solutions are all associated with the extra equipment required for generating and recycling human consumables. Along with that, tools are required for processing those consumables, for example, plates, glasses, and cutlery when talking about food and water, or a piping system when talking about hygiene. When injured, if normal surgical procedures are not sufficient, the ability to produce biomedical implants becomes very beneficial [41–44]. Using 3D printing, it is convenient to be able to manufacture such tools and parts quickly and also be able to recycle them when damaged. Using the FDM technique, which can work with a large variety of materials, required items can easily be produced in situ. The only items that have to be brought from Earth are printer parts and raw materials (which take up less space than tools produced). The ease of recyclability compensates for the possibly low mechanical properties of the tools.

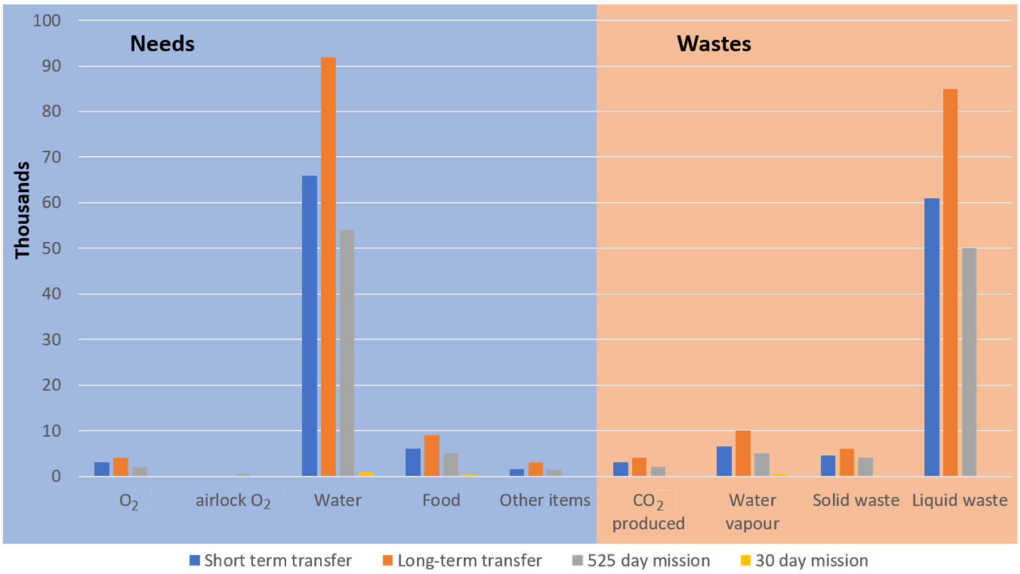


Figure 8. The summary of consumable human needs for two Mars mission scenarios: short stay and long stay. Data from [10].

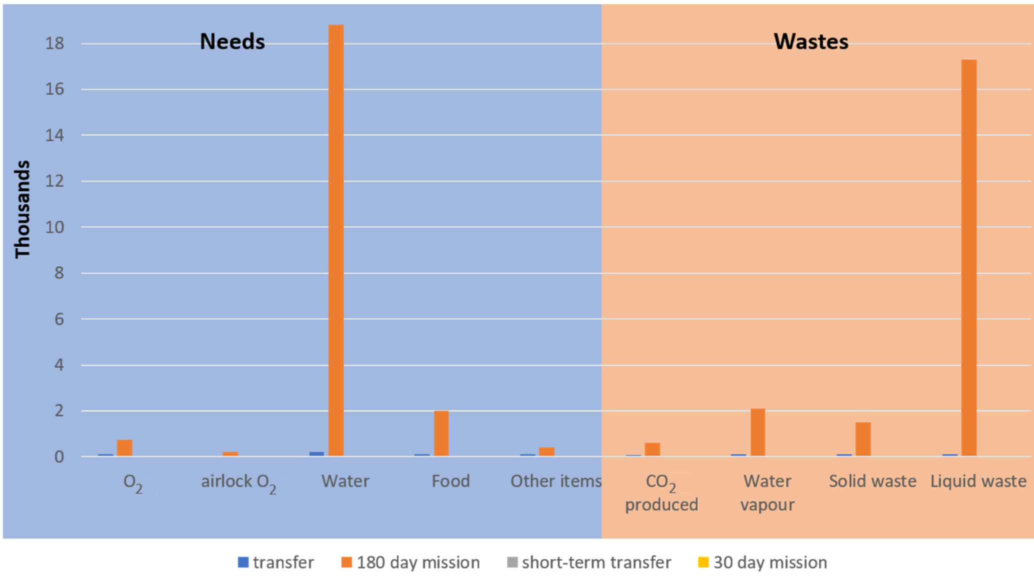


Figure 9. The summary of consumable human needs for a 180-day Lunar mission scenario. Data from [45].

Among other human needs on other planets, it is important to consider stress relief and teambuilding activities, as the good mental condition of the human on mission is vital to mission success [46,47]. Mental health affects work ethics, decision-making, and the ability to work as a team, which are crucial to preventing mortality due to accidents. Simulations of human behavior in temporarily and partially isolated conditions are being performed in order to determine optimal conditions for mental health. However, items that aid in stress relief are normally not taken in large quantities as they are not essential to mission success; hence, it would also be convenient to be able to print them. For example, a game of chess (a board and figurines) could be printed from thermoplastic. Privacy is also important to the mental condition of astronauts; hence, careful planning of the habitat layout is important to consider. This might have an effect on the amount of material consumed.

3.2. Lunar Habitat Design

Out of the needs that Lunar habitats have to fulfill, protection from harsh environments is provided by the habitat structure itself. It has to provide protection from space radiation, potential meteoroid impacts, a lack of breathable atmosphere, low gravity, and varying temperatures. While radiation shielding is performed by reinforcing the habitat walls with thick material, the other issues can be solved by generating an artificial atmosphere inside the building. The pressure on the Lunar surface is very low compared to what is comfortable for humans. Due to this, inflatable structures have been proposed as habitat cores. The pressure that is needed inside the structure has to be high compared to the outside pressure, and the material for the inflatable structure has a relatively light weight and is optimal from an atmosphere creation and transportation point of view. The issue of radiation protection and meteoroid impact can then be solved by utilizing regolith as a reinforcement, creating thick and strong walls for the habitat that protect the inflatable structure from damage, which can be crucial to atmospheric sustainability. The general structure of the inflatable habitat is presented in Figure 10.

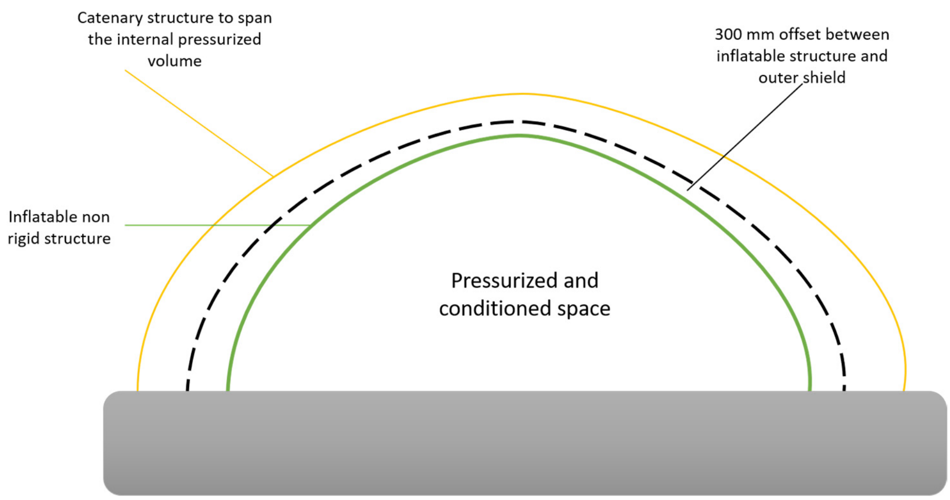


Figure 10. Proposed design for an inflatable Lunar habitat with a regolith shield. Imaged drawn based on [48].

As the size of the inner inflatable part of the building is known, the D-shape printing system has to produce the outer regolith shell. Depending on the position on the habitat shell, the wall thickness is approximated to be between 1 m and 2 m. This thickness accounts for the radiation protection necessary for long-term missions and the 99% chance of withstanding meteoroid impact over the course of 10 years. Other structural loads include:

- Internal pressure: The pressure generated by the artificial atmosphere for comfortable life inside the inflatable structure is considerably higher than the pressure on the Lunar surface (3×10^{-15} bar) [45]. If part of this pressure can be transferred to the regolith structure, it is going to be beneficial for the long-term mission needs, as it is considerably cheaper and easier to repair the regolith wall than the inflatable structure due to material abundance. The curving shape of the habitat walls without sharp corners greatly benefits their ability to withstand internal pressure.
- Moonquakes: unlike on Earth, Lunar seismic activity is very low; hence, this factor plays little role in structural planning.
- Own weight: the gravitational constant of the Moon is 1.62 m/s^2, which is only 0.165 of the Earth's gravity constants, making gravitational loads considerably lower than they would be on Earth. However, depending on the size of the structure, 1- to 2-meter-thick walls would still inflict high gravitational loads upon themselves.
- Thermo-elastic loads: Due to the absence of the atmosphere, the temperature difference between the sun-illuminated surface and the dark surface of the Moon varies from as

low as 150 °C to as high as 100 °C. Unprocessed regolith is taken from the Lunar surface and, hence, does not get influenced much by the temperature changes. However, regolith that is consolidated by the binder has to be suited for such conditions. Another issue that comes with temperature changes is the fact that the day-night cycle on the Moon progresses quite slowly (27.3 days for the full cycle), meaning that the building might be exposed to different lighting conditions for a considerable amount of time. This makes the thermal expansion of the bound regolith an issue and also makes the positioning of the habitat on the Lunar surface a major factor, and temperature differences need to be reduced.

The possible construction sequence for the Lunar base is presented in Figure 11. The deployment of the airlock module, which is responsible for maintaining the inside atmosphere, is followed by inflating the inner part of the structure. After the inflation is complete or even during it, one or multiple mobile printers follow the circumference of the building, depositing raw regolith and then binding it layer by layer. It is expected that multiple smaller mobile printers are more beneficial overall for the needs of the mission, despite the energy requirement to move the printers during construction. Another important constraint that rises during the deposition step is the maximum angle at which regolith is able to maintain the shape and not collapse under its own weight during the curing process, which might be considerably slower due to low pressure and temperature [49,50].

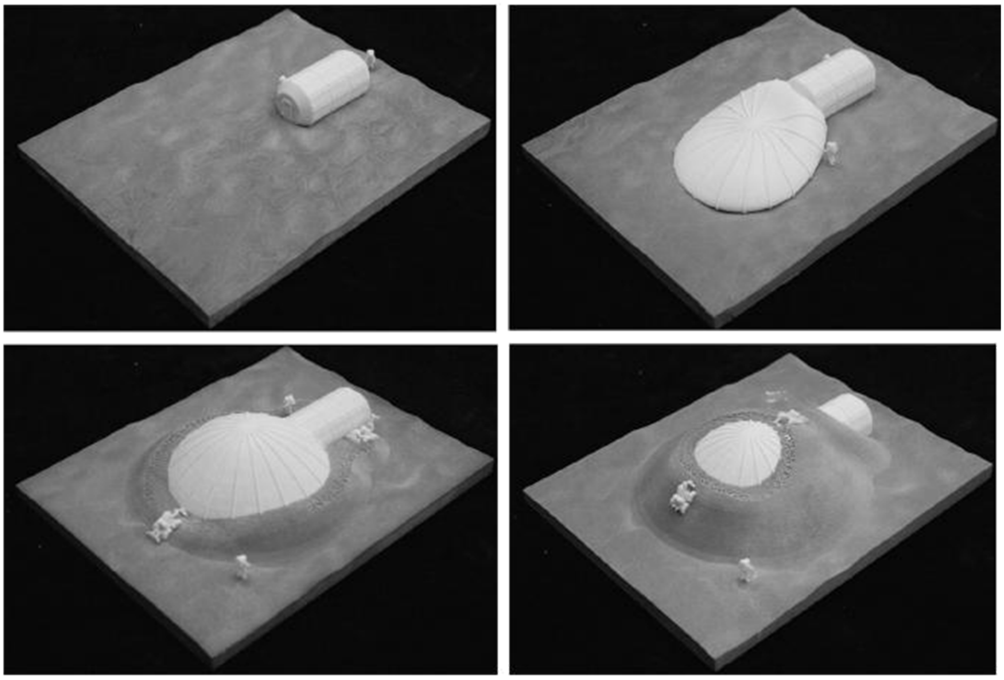
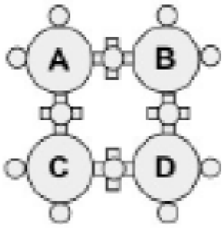
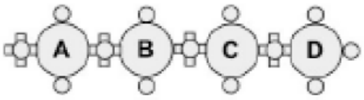
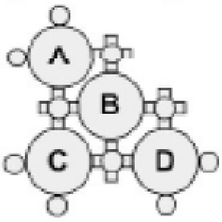
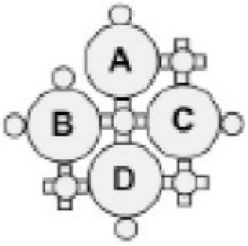
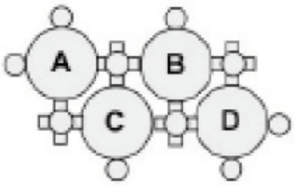


Figure 11. Construction sequence for the proposed Lunar habitat design [48].

It is important to consider the possible expansion of a Lunar base as well as being able to have separate building modules for different purposes. This can be achieved by building multiple inflated modules and connecting them via structures similar to airlock modules. It is considerably more convenient to expand via extra buildings than to rebuild existing structures. There are several possible arrangements with their own limitations and benefits, which are presented in Table 2. As it can be seen from the evaluation, it is considerably safer to arrange the building modules and airlocks in a scattered chess-like fashion, as it utilizes the available space efficiently, allows fast movement between the modules, and most importantly, assures safe escape in the event that one of the modules fails.

Table 2. Evaluation of possible Lunar module arrangements [51].

Lunar Base Configurations Considered	Characteristics	Assessment
Square 	• Dead zone in the middle • Four airlock exits are unstable • Airlock failure restricts access to other modules	Risk associated with airlock failure is too high. **Unacceptable**
In-line 	• Simplest build-up • Airlock failure severely restricts access to other modules	Risk associated with airlock failure is too high. **Unacceptable**
Right triangle 	• Complex build-up • Airlock failure might restrict access to the areas, depending on the airlock	Risk associated with airlock failure is present, but less than in the previous configuration.
Star 	• Complex build-up • No restricted access in case of airlock failure	Risk associated with airlock failure is absent. **Acceptable**
Staggered 	• Complex build-up • No restricted access in case of airlock failure	Risk associated with airlock failure is absent, more exits than in star configuration. **Optimal**

4. Differences between 3D Printing in Space and Earth

While additive manufacturing on Earth is already quite popular and is being applied to more and more scenarios, it is not that simple to bring it to space. In addition to the expenses related to launching extra space missions and payloads, other difficulties arise. They are related to the fact that the whole 3D printing process relies on certain conditions and physical effects. In space, a lot of these conditions are vastly different from those on Earth. In order to successfully implement space 3D printing, these differences have to be investigated, and technology has to be adapted to overcome them.

4.1. Available Materials

Transporting any payload into space is very expensive compared to transporting it on the surface of the Earth. While there is a wide selection of materials that can be used for 3D printing on Earth, only a very limited amount can be reasonably transported into space.

It is possible to have a limited supply of reusable material for printing the tools required, but taking enough material to build one or multiple habitats seems unrealistic, especially considering the fact that the walls have to be thick and strong to protect humans from dangerous environments. Hence, it is necessary to use in-situ resources when constructing the habitat and potentially utilize in-situ resources for the synthesis of usable FDM polymers.

Multiple scientific missions had already been conducted to investigate the surfaces of the Moon and Mars. This allowed us to reconstruct the composition of the Martian and Lunar regoliths, given in Tables 3 and 4. Since regolith itself has a sand-like structure, additional substances have to be added to it for the solidification process to happen. Hence, the binder deposition 3D printing technique seems convenient for this cause. Sand is easy to find, gather, and deposit in a layered fashion, and with the aid of a liquid binder ink, the walls can be formed. Therefore, it is established that it is possible to construct an initial habitat using a readily available in-situ resource until an alternative is found. One such alternative is digging an underground habitat, which requires thorough exploration of the underground of the Moon or Mars.

In the case of Mars, it is known that a large amount of basalt is readily available for use on the surface of the planet. Basalt can be partially molten and used for 3D printing, but the possible structure of the resultant building would be restricted to a truss structure due to the weight of the basalt. A truss structure would be less beneficial considering radiation protection, and an autonomous assembly would be considerably more complicated. Moreover, the energy consumption of such a process is expected to be higher due to the high melting temperature of basalt. However, the mechanical properties of basalt are quite good, and the walls made of it would have good shielding capabilities from potential meteoroid impacts. Basalt can also be potentially used for 3D printing tools or furniture, which is quite convenient.

The mentioned in-situ materials (except maybe basalt) do not have desirable properties when it comes to making smaller tools required for mission maintenance or fulfilling human needs. Furthermore, in-situ resources are not available in space itself, for example, on the way to the planet. Instead of taking a large variety of ready-to-use tools for all potential uses (and possibly forgetting some of them), it is a safer option to take raw, reusable material and print the required part on demand. The software related to the printer can have a database of potential tools and possibly offer the option to design a completely new tool if required. It is important for this material to be reusable, as the mechanical properties of 3D-printed parts are generally inferior to those manufactured using traditional methods.

Finally, for a self-sustainable Martian or Lunar human habitat, a source of more universal material for 3D printing would be convenient. With the presence of humans on these celestial bodies, an in-depth exploration can be performed in order to find and harvest the resources and potentially improve the habitat design as well. For example, by exploring the underground of the planets, it could be possible to dig and construct an underground shelter that offers high protection from meteoroid strikes and radiation due to the potentially high wall/ceiling thickness. However, for this to become possible, more exploration is required. If the raw resources are not usable, perhaps the possibility of synthesizing printing material will open once more information about the availability of those resources is known. This would require extra energy and possibly complex equipment, but the result might make the Lunar or Martian colony further independent from Earth.

Although the technology is not yet there, in the future it might be possible to fully synthesize polymers, such as ABS ($(C_8H_8)_x$ $(C_4H_6)_y$ $(C_3H_3N)_z$), PET ($C_{10}H_8O_4$), and recently deployed PEI ($(C_{37}H_{24}O_6N_2)_n$) on the surface of the Moon or Mars. Hydrogen is present near the poles of both the Moon and Mars and can be extracted. Oxygen is also present in the soil of both celestial bodies in various oxides and ice in the case of Mars. Nitrogen is present in various ground minerals, and in the case of Mars, there is a small (1.9%) amount of Nitrogen in the atmosphere. Carbon, however, as the backbone of polymers, is nearly absent on the Moon, which makes the polymer synthesis questionable without importing some carbon from other places (e.g., Earth or some asteroids). On Earth, carbon is present primarily in the atmosphere, organics, and resources like coal, all of which are absent on the Moon. In fact, the formation of life on Earth happened primarily due to atmospheric carbon. Overall, the absence of readily available carbon and the lack of technology make in-situ synthesis of printing polymers on the Moon unrealistic in the near future. Mar contains carbon in the atmosphere and in the minerals close to the poles, making the potential synthesis more promising.

4.2. Meteoroid Strikes

Due to the near-absence of atmosphere on the Moon and Mars, small space objects like meteors and asteroids cannot be incinerated by the impact with the atmosphere, like it happens around Earth. Instead, these small celestial bodies collide with the surface of the Moon or Mars. Even small-sized impactors can cause catastrophic damage to man-made structures due to the very high speeds of the impactors and hence their high kinetic energy [52,53]. Every day, roughly 2800 kg of various meteoroids collide with the Lunar surface. While some of them are very small and barely cause any damage to the surface, larger ones can create impact sites called craters. On Mars, 11 times more meteorite mass impacts the surface every day compared to the Moon (30,800 kg per day) [54]. Earth receives considerably less meteoroid mass (between 2900 and 7300 kg per year, excluding dust particles), and it is slowed down considerably by the atmosphere [55]. Overall, Mars and the Moon have similar numbers of craters on their respective surfaces, as the impact strength on the Lunar surface is in general higher than on Mars [56–58].

The danger of meteoroid impact persists not only for potential humans and habitats on Mars and the Moon but also for 3D printing equipment and unfinished habitats. In the case of the inflatable habitat core, which has to be covered by the printed walls for protection, failing to do so on time might result in a damaged inflatable wall, rendering the structure useless and, hence, wasting the material. Printing equipment itself can contain vulnerable components that might get damaged by smaller strikes. Initial stages of printing, which are expected to be most vulnerable due to unfinished structures and exposed printing equipment, are expected to be performed without supervision by humans, eliminating the possibility of easy repair.

It is not possible to completely prevent the impacts of meteoroids with the Moon or Mars; hence, there is always a chance that a space rock might collide with the working location. However, the following precautions can reduce the risk of 3D printing equipment being damaged:

- Reacting to the upcoming collision and moving the mobile 3D printing system out of the way: This option seems to be feasible only for Lunar operations due to the difference in distance. The delay in sending and receiving command signals between Earth and the Moon is relatively small (approx. 2.6 s), but for Earth and Mars it is considerably larger and depends upon planetary positions (between 516 s (8.6 min) and 2516 s (42 min)). Arranging cameras around the printing site and carefully observing potential incoming bodies might allow them to send a command to the printer so it moves away from the impact. This option only works for mobile printers and does not save the structure that is being printed.
- Introducing redundancy in the printing system: In other words, several printers can be deployed for the habitat printing procedure, so one of them being damaged does not mean a failed mission. This step can be further enhanced by printers being able to print the parts for each other; however, this is considerably more complex and requires a kind of 3D printer that is used for producing tools, not habitats themselves.
- Building a protective dome around the building site: This suggestion is implemented in Section 5.2, where the first step of building a habitat is making a large dome that houses the rest of the operations. That large dome was later converted into one of the habitat modules. While such a measure offers more protection for the printer than

simply printing out in the open, making a large dome still requires some time to be completed, leaving the printer exposed during that time.

- Optimizing printing speed: This measure simply means that if the printing process is fast enough, the risk of collision with a meteoroid is diminished.

The combination of measures listed above can help reduce the risk of 3D printing equipment being destroyed; however, this risk always persists due to atmospheric absence. Strong habitat walls and constant monitoring of incoming objects are required to ensure the safety of a long-term mission.

Meteoroid strikes present danger mostly to the habitat printing equipment, as the defensive structures have to be made while having these printers exposed. However, smaller polymer printers might also be in danger of being destroyed by an unfortunate impact. Thankfully, there is no urgent need to station them out in the open. The safest option would be to bring those printers together with the astronaut squad when the habitat is already complete and the printers are already protected by the walls. However, depending on the circumstances, it might be more convenient to station them before the astronauts arrive. Due to the relative fragility of the FDM equipment compared to D-shape printers, it is not a good idea to leave them outside without any protection at all, as even a small impact might critically damage it. Possibilities for protecting a small printer in this case include:

- Keeping the printers inside the spacecraft until the habitat is constructed and then transporting them inside: This way, the printers will be either dormant or restricted to printing smaller items, as it is not expected to have a lot of space available inside the spacecraft. The transportation system will have to be included with the rest of the equipment for reallocating the printer inside the habitat. However, this is not an issue, as it is likely necessary to have some sort of transportation equipment for moving items like printing materials and printed tools. After the habitat is constructed, printers can be moved and produce large items like airlock doors, which can be installed nearby.
- Keeping the printers inside the spacecraft until humans arrive: As in the previous scenario, FDM printers are going to be restricted to small item production inside the spacecraft. Humans can reallocate the printer where required upon their arrival and start producing larger items. It is a cheaper option, but less convenient for the astronauts. Moreover, some sort of transportation module is expected to be included in the mission anyway.
- Digging an underground cave and transporting the printers inside: Although this option seems to be the most attractive due to underground caves offering potentially better protection than the habitat itself, it would require considerably more resources and preparations to execute properly. The structure of the underground has to be known in order to have a safe cave, which is an identical concern that arises when thinking of underground habitats. Failing to account for the ground structure might result in the cave collapsing, which would mean a critical failure of the printer. Furthermore, additional equipment is required for digging and reinforcing the cave, meaning more payload and higher mission costs. Transportation of the printed items to the habitat is expected to be longer than transportation within the habitat. However, despite all the concerns, cave protection seems to provide the best defense against meteoroid strikes and could potentially be a good basis for designing underground habitats for humans. After all, it is better to sacrifice a printer in order to test a new technology than a human being.

4.3. Combination of High and Low Temperatures

Unlike on Earth, where the presence of atmosphere and water stabilizes the temperature in individual regions, the Moon and Mars have large temperature variations during the day/night cycles. Particularly in the equatorial regions, The Lunar surface temperature varies from -173 °C to +127 °C. The Martian surface also experiences a swing from -153 °C to +20 °C near the equator. Near the poles, just like on Earth, day/night cycles are considerably longer, hence the smaller temperature swings. Temperature affects 3D printing to a very large extent, and therefore printing machines, processes, materials, and habitat locations have to be established together as they affect each other closely. Overall, the following measures have to be considered when designing an interplanetary mission with respect to temperatures:

- Balance between the binder chemical reaction rate and evaporation rate: This measure is a result of both temperature and near-vacuum conditions. On Earth, water evaporation is controlled by the amount of water vapor present in the atmosphere and the temperature. On the Moon or Mars, however, there is no water present in the atmosphere, no pressure, and hence water or any other liquid is free to flee the location where it was deposited and then freeze due to low temperatures. In the case of high temperatures, liquids simply evaporated without any resistance. Still, the rate of evaporation is controlled by temperature to some extent, and at lower temperatures, evaporation is considerably slower. As it is known, low temperatures also reduced the reaction rate in the binder ink. It is, therefore, necessary to find an optimal point between reaction rate and evaporation risk and print the habitat only at that temperature. This optimal point is the temperature at which the amount of necessary binder is at its minimum while the chemical binding reaction still occurs fast enough without jeopardizing the structural properties. This issue is not present for FDM polymer printing, assuming that the polymer used is sufficiently thick (which it is). However, too fast solidification of the polymer might result in bad adhesion between the layers, while slow solidification might result in a loss of shape. Depending on the polymer properties, low temperatures might be turned into an advantage from a temperature control point of view.
- Establishing habitat in the location with the least temperature change rate: The absence of an atmosphere results in large temperature swings during the day/night cycle. This induces large thermal loads on the potential structures, as the material is going to expand and shrink according to its thermal expansion coefficient. Due to this, the structure is affected by thermal fatigue, and hence failure is rapidly accelerated. It is advised to settle the habitats closer to the poles of the Moon or Mars, as the temperature at the poles experiences significantly fewer swings. Furthermore, useful resources like hydrogen are also concentrated near the poles, making it convenient to try and extract them.
- Using polymers that have an appropriate operational temperature range: This measure is quite straightforward; depending upon the potential uses of printed tools and the location of the settlement, the polymer should have a glass transition temperature below the ambient temperature during use. For example, thermally stable PEI would be more convenient to use on the Moon (T_g = 217 °C), while on a significantly colder day on Mars, ABS ($T_g = 80 - 125$ °C) and PET ($T_g = 67 - 81$ °C) would be sufficient. Perhaps in the near future, other thermoplastic polymers can be explored regarding space 3D printing, and those polymers have even more convenient temperature properties.
- Testing the printers at expected temperatures: It needs to be verified that the printers can operate properly at low or high temperatures (depending on the applications). All the printer parts must remain functional with respect to temperatures. Otherwise, those parts have to be replaced by another material, or the design has to be modified to ensure reliable performance.
- Establishing an artificial atmosphere inside the operational location: In the case of a polymer FDM printer, it is possible to delay its usage until an artificial atmosphere inside the habitat is established. This way, the design does not have to be modified that much, and no meteoroid protection is required as well. However, this essentially delays the use of the printer for a long time. Assuming that the airlock doors have to be made from polymer material, this option is also hardly feasible, as maintaining the atmosphere inside the habitat is impossible without the airlocks. Establishing a large dome for the habitat printing is completely unrealistic as well, as too many extra items

would have to be brought from Earth for that. However, this option is convenient for small general-use polymer printers when humans arrive in the constructed habitat. Moreover, printers inside the spacecraft with astronauts are by default covered by this measure, as astronauts require an artificial atmosphere on board a spacecraft anyway.

4.4. Near-Vacuum Conditions

This section is focused on the habitat binder deposition printer. Issues imposed by near-vacuum ambience that are related to polymer printing are the same as those caused by low/absent gravity; hence, they are discussed further.

Binder, which is used to solidify Lunar or Martian regolith, is a liquid. On Earth, the evaporation behavior of liquids is governed by the presence of water vapor in the atmosphere. However, the atmosphere is nearly absent on the Moon and Mars, and no water vapor is present. This, together with no pressure effects, would result in deposited liquid rapidly evaporating into the atmosphere and, afterwards, freezing due to low temperatures.

Overcoming ink evaporation is one of the biggest challenges that space exploration is facing. Careful testing and planning can help overcome it and optimize habitat printing:

- Balance between reaction time and evaporation rate: The same reasoning as discussed in the previous section applies—the absence of water vapor in the ambience negates the humidity equilibrium effects. This leads to liquids rapidly evaporating from the surface where they were deposited. Lowering the temperature slows down both the reaction time and the evaporation rate. An optimal temperature for the reaction has to be determined, which reduces the ink loss and does not slow down the reaction too much. Hence, this is another motivation for a careful choice of habitat location.
- Modify the ink structure or composition: One way to avoid ink evaporation is to force the ink to be in droplets with sufficiently high internal pressure. Two factors affect the evaporation of the droplet: droplet size and cavity size inside the bulk of regolith. If the cavity size is small enough as compared to the droplet, liquid behavior is driven mainly by capillary forces, which stop it from evaporating. These effects have to be thoroughly tested with either real regolith or regolith simulant and the proposed ink. Ink structure or composition might result in a different droplet size, benefiting the process. Optimizing the droplet size might also offer a bigger temperature window for the printing process, allowing you to choose the habitat location from a wider range of locations.
- Perform printing inside a pressurized chamber: This measure is only related to the small FDM printers, as having a large, pressurized dome for habitat printing does not seem to be feasible. Pressure can allow for more reliable tool printing, as the molten polymer will be less likely to float away and more likely to stick with the previously deposited polymer. Although it is not necessary, if other precautions are taken and the polymer is sufficiently thick, it might be a guarantee for a good printing outcome. However, pressurizing a chamber might require a lot of energy, and perhaps it would be better to simply reprint the part. Furthermore, if astronauts would require a small tool to be printed, it would usually mean that the habitat is already fully set up and an artificial atmosphere and pressure are present.

4.5. Low Gravity

In 3D printing, gravity is a crucial element that makes layering and the adhesion of layers to each other possible. It allows both material and, if applicable, ink to properly set and solidify. Lowering gravity has a drastic effect on the whole printing process, especially lowering it to zero, like inside a spaceship in open space. Conventional 3D printers that are functional on Earth are simply not going to work in space conditions and have to be modified to account for reduced gravity.

In the case of the binder deposition habitat printer, gravity is still going to be present. Due to the abundance of regolith on the Moon and Mars, escape of the material from rolled layers should not be an issue. Furthermore, the layers are going to be rolled before the ink deposition step, pressing the sand particles together and lightly binding them this way. On the Lunar and Martian surfaces, gravity is present, unlike in open space, making the use of supporting structures possible. The only issue that persists is the binding ink behavior. The combination of low gravity and near-vacuum results in binding ink escaping into the ambient instead of dropping onto the regolith layers when depositing it using conventional methods.

FDM printers on Earth rely heavily on gravity to do their job. Through the use of supporting structures, a wide range of possible shapes is available for production. A lot of thermoplastic polymers together with metals can be used to produce an item, so the material can be chosen depending upon application and price. During the printing, molten material is simply "dropped" down on a supporting structure and solidified, and the part can be easily removed after the solidification is complete. In space and, to a lesser extent, on the Moon or Mars, a lot of these points do not hold. Overall, FDM machines have to be heavily modified to be able to work in low-gravity conditions.

Thus far, testing of the FDM printing method in space has been quite successful; hence, it is definitely already possible to have an FDM printer suitable for space missions. Considerations that are already fulfilled and that still need to be accounted for are listed below:

- Depositing the material directly onto the buildup instead of "dropping" it: This measure can be used for both binding deposition and FDM techniques. On Earth, due to gravity and pressure, liquid and molten substances flow directly downward and reach the designated place to solidify. In space, this is not necessarily going to happen. In the case of D-shape printers, the nozzles can be modified to inject the binder directly into the layer of regolith. In order to prevent deformities due to injection, the layer where binder is injected has to be rolled or evened out in some other way immediately before the binder solidifies the deformed regolith. Thankfully, due to the low reaction rate discussed previously, there is a wide time window for doing this. When it comes to FDM printers, it is possible to make a fully mobile nozzle (movable in all three axes and also rotated), which can follow the path specified by the software and directly deposit the material on top of previously placed material. In fact, this method is already being successfully used by the current FDM printers that are operating in space.
- Using sufficiently thick material: This is one of the reasons why only three thermoplastic polymers (ABS, PET, and PEI) out of a wide selection are used in space. A thick polymer is less likely to start floating around when deposited in a molten state and is more likely to bind to previously deposited layers. It also ensures a more uniform material distribution without irregularities. This measure is less valid for the binder deposition, as the optimal binder composition is determined by the regolith composition, and the binder should be more liquid in order to wet as much regolith as possible and ensure a good structure.
- Accounting for no supporting structure when designing a tool: This measure is quite straight-forward, as supporting structures are useless in zero-gravity conditions. Humans will have to adapt the commodity tools to have a less complicated shape so they are printable by the FDM printer. On the surface of the Moon or Mars, it might be possible to deploy supporting structures again (especially on Mars, which has higher gravity than that on the Moon), giving more freedom in tool selection. This measure is again not applicable to binder deposition habitat printing because gravity is still going to exist on the Moon and Mars, making printing over the inflatable support possible.
- Accounting for microgravity effects: Microgravity effects are one of the biggest issues when it comes to zero-gravity printing. When there is no general gravity acting upon the whole printing setup, the printed item might be essentially glued to the platform or other support that was used for the printing due to the attraction between them. Potential solutions to the problem include fully suspending the printed item inside the printing chamber, which goes in line with a fully mobile printing nozzle, or applying

some sort of release agent, which prevents the surfaces of the tool and supporting platform from strong contact and hence microgravity adhesion. The former measure requires a more complicated printing mechanism (which is already implemented, however). The latter required extra material to carry into space, but it can help when a small amount of gravity is present, making suspension not feasible.

- Adapting traveling mechanisms for the Moon and Mars: This measure is more related to the safety of the printers than printing itself. Different gravity combined with ground composition and surface topology might create issues when transporting the fragile printer mechanisms on the surface of other celestial bodies. It has to be ensured that printers are transported safely and gently, without the risk of tripping over them. Multiple Lunar and Martian missions have already been conducted with various rovers deployed, and those should be able to provide enough information about the friction and viscosity of the ground.

4.6. Autonomy

3D printing on Earth can be supervised by the operators in order to ensure high-quality products are produced. While ideally a 3D printer can be fully automated, in case something goes wrong, a person can detect and solve the problem. In the scenario where an unmanned mission with 3D printers on board is sent to the Moon or Mars in order to prepare a habitat for humans to arrive, there is not going to be a supervising person who can easily maintain the printing procedure. Hence, it is vital to fully automate and test the printing software to reduce the risk of mission failure.

When programming the behavior of the printer, there are multiple factors to consider that can reduce the chance of mission failure:

- Mobility of the printer: The printing machine will have to be moved from the spacecraft and installed on the building site. In some scenarios, the printer is fully mobile on its own. In any scenario, having to automatically move the printer without human involvement to the required location is necessary. To ensure safe transportation of the printer on a Lunar or Martian surface, factors like ground structure (homogeneous solid surface or sand), evenness, and friction are important. The movement of the printer has to be carefully adjusted for these factors to ensure safety and reduce energy consumption.
- Choice of the landing site: Related to the previously discussed point, the landing site has to be chosen carefully to account for readily available printing resources, optimal ground composition, the amount and periodicity of incoming solar light (for energy purposes), and temperature conditions. The goal of choosing a landing site is to reduce the total energy required for building a habitat, ensure safe construction, and reduce the effect of environmental hazards in the printing process.
- Material delivery: Besides the 3D printer itself, there has to be an additional robot for gathering the material and delivering it to the printer's feed. It is likely going to be more optimal to have a separate machine do it while the printer is constructing the habitat. It is also safer for the printer, as during the material gathering, accidents might occur and damage the equipment. However, it needs to be made sure that the gathering module transports and deposits the material into the printer feed with no issues, which can be tested on Earth.
- Assembly: Depending on the printer type, it might be necessary to transport printer parts and assemble them on the Lunar or Martian surface. For example, a D-shape printer takes up a lot of volume when assembled and is considerably more compact when taken apart. Therefore, there has to be an assembly module included with the rest of the payload for such transportation, and the autonomous assembly has to be thoroughly tested on Earth and in orbit, as failing to assemble can damage the components and fail the mission. In the case of orbit testing, however, it might be necessary to simulate the gravity conditions of the Moon and Mars, as absolute zero gravity is vastly different from at least some gravity present.

- Communication with Earth: As it was mentioned previously in Section 4.2, the possibility of human interference depends upon the mission destination, whether Mars or the Moon. If something goes wrong on the Moon, communication delays are considerably more forgiving, and humans can input the commands that might solve the problem on time. On Mars, the delay is too long to react to the problems. One way to avoid it is to either slow down the preparation and printing processes or to separate the steps into modules, so after each step of operation, the command center on Earth can assess the situation and react accordingly before the next module starts. This might result in considerably higher energy consumption and a longer mission time, but it can significantly reduce the risk of mission failure due to a software error. However, it might be more convenient to use the Lunar mission as a test for the printing handling software, polish it, and then proceed to Mars.

The guidelines above are discussed in relation to the Habitat 3D printer. However, the majority of them can also be applied to smaller tool printers. It is assumed that at first only habitat printers are sent without humans to the Moon or Mars to prepare the habitat; however, it might be convenient to send smaller printers as well. This way, furniture items like doors and chairs and small convenience tools can also be ready when humans arrive. Overall, the autonomy for these tool printers is less crucial than for habitat ones, unless preparing items like airlock doors has to be performed. Even then, it might be easier to deploy additional robots that can carry materials and install printed items than to automate the tool FDM printers, as tool FDM printers are expected to be more fragile than the habitat binder printers.

Overall, the more automation is performed on the printing setup, the less work will be required from humans, both at the control center on Earth and by mission crews that arrive on the Moon or Mars. It is vital to consider the potential risks, failures, and challenges regarding printer operation and prepare an appropriate course of action if any of those problems occur.

5. Current Progress of 3D Printing in Space

The dream of inhabiting the Moon and Mars has been alive for quite some time, and a lot of progress has already been made to make it true. Quite a few concepts for human habitat related to 3D printing were proposed in various literature, and some of them were not very realistic due to their high price or complex technology. However, some other propositions look very promising and are already quite developed.

5.1. Habitat Printing: Moon

The human habitat on the Moon's surface requires the ability to shield the inhabitants from the harsh Lunar environment, which is mostly the result of the absence of a definite atmosphere. This includes shielding from micrometeoroids and space radiation and providing climate control to protect from extreme temperature variations and the absence of breathable air. There are three realistic options for building the habitat:

- Transporting assembled parts of the habitat to Earth and assembling them on the Lunar surface.
- Transporting the building equipment to the Lunar surface, which can process Lunar soil in order to assemble the habitat.
- Transport equipment is needed for digging under the Lunar surface and establishing underground habitats.

The first option is clearly not feasible at the moment due to the high costs associated with transporting the payload into space, especially considering that any kind of reparation action would require an extra shipment from Earth, which is very inconvenient. Furthermore, high-thickness walls are likely unachievable because of the same transportation reasons. The other two options are both significantly more favorable from an economic point of view; however, digging the Moon's surface requires geological knowledge of the Lunar underground. Hence, the option of building the habitat in situ using Lunar soil seems to be the most optimal one at the moment [48]. The conceptual representation of a printed Lunar habitat can be seen in Figure 12.

Figure 12. Conceptual representation of a Lunar base. Photo: ESA.

D-shape technology is the kind of printing that is convenient for producing building blocks or the entire building. It is a variation of the binder jetting technique (see Section 2.5), as the binder gets deposited on a prepared layer of material. The schematic of the printer and the complete printer are presented in Figure 13. The main components of the printer include: four vertical beams designed for moving the printing platform along the z-axis; the actual printing platform; the printing head, which consists of an array of nozzles; the beam that mounts the printing head; and the rollers that apply uniform pressure on the freshly deposited layer. The nozzles are located at a distance from each other; hence, they can move along the y-axis on the beam itself while the beam moves along the x-axis. A single nozzle and an array of them can be seen in Figure 14.

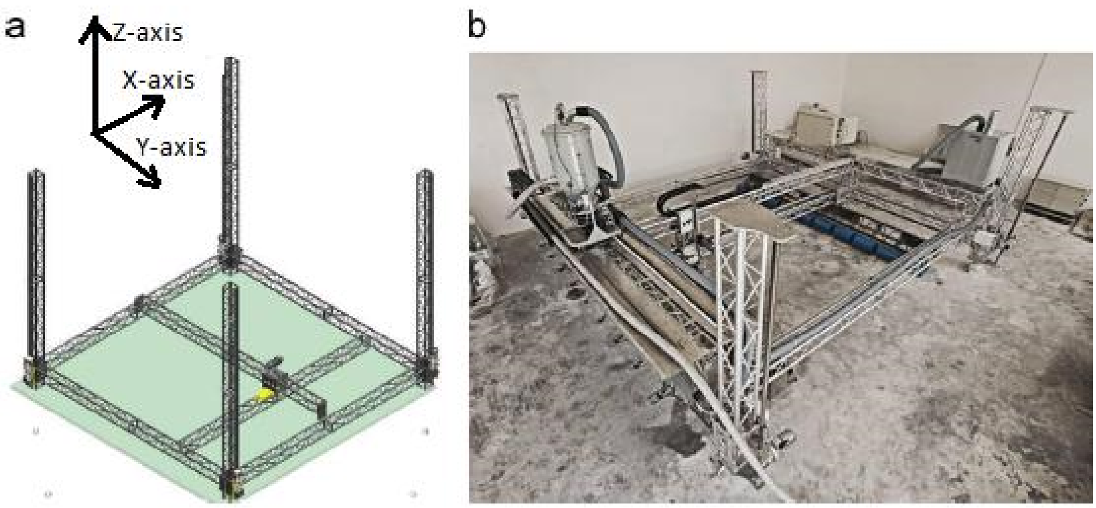


Figure 13. Representation of D-shape technology in a 3D printer. (**a**) Schematic drawing of the material depositing unit. (**b**) Complete D-shape printer [48]. More details on the components of the setup can be found in [48].

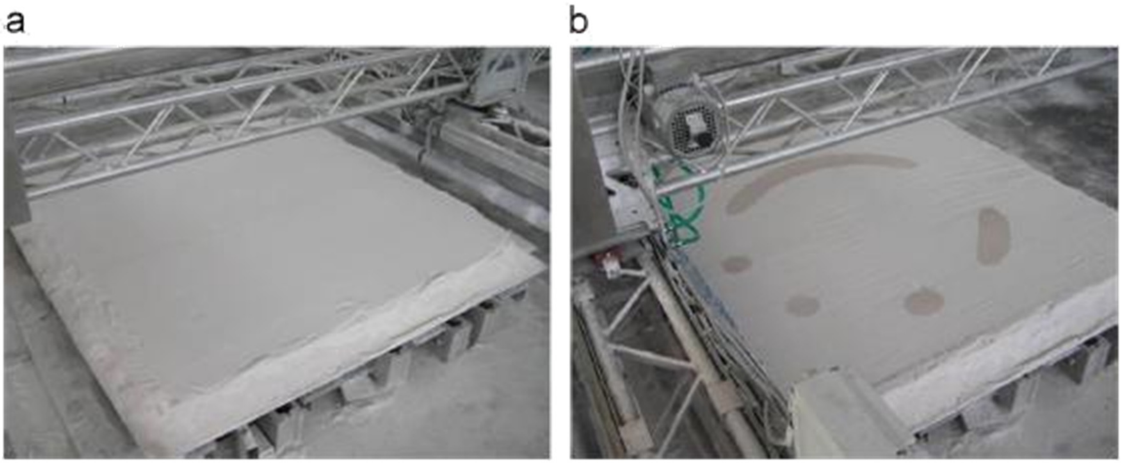


Figure 14. Printing process of the D-shape printer. (**a**) Sand layer prepared for binder deposition. (**b**) A sand layer with the binder deposited according to software directions [48].

The printing process for D-shaped printed parts is as follows:

- The shape of the desired item is modeled in CAD software.
- The modeled item is separated into layers parallel to the x-y plane with a set thickness (usually 5 mm).
- The sequence of layers, starting from the bottom up, is imported into the printer software.
- The material is deposited on the printing platform. Layer thickness after roller pressure is equal to the selected layer pitch. This step can be seen in Figure 14a.
- The printing head moves along the x-axis, spraying binding liquid in the designated places. To overcome the nozzle pitch, movement on the y-axis occurs between the x-axis paths, ensuring complete coverage of the material with binding liquid. This step can be seen in Figure 14b.
- The frame with the mounted printing head is lifted up along the z-axis, and a new layer of material is deposited on top of the bound one.
- The previous two steps are repeated until the programmed modeling sequence is complete.
- The excess material (that is not bound) is removed, and the part is complete.

The binding process behind D-shape printing is based on Sorel cement chemistry. The material, namely regolith, contains Magnesium Oxide (MgO), as can be seen from the composition in Table 3. Upon being mixed with the ink, which contains Magnesium Chloride ($MgCl_2$) and water, the multiphase system is formed within several hours. This system consists of brucite ($Mg(OH)_2$), Phase-3 ($3Mg(OH)_2.MgCl_2.8H_2O$), and Phase-5 ($5Mg(OH)_2.MgCl_2.8H_2O$). In order to ensure higher-quality cement, regolith needs to be enriched in Magnesium Oxide content, as the initial content is not sufficient. Overall, the resultant cement has good mechanical properties and a relatively fast setting time, which is important in the context of the expected slower curing rate in low-temperature conditions.

Before deploying a D-shaped printer to Lunar conditions, it has to be confirmed that it can operate in a space environment. Namely, this means the ability of the binder to react with Lunar soil (regolith) and evaporate in conditions of near vacuum and low temperature. The technology was successfully tested on Earth using regolith imitation. In the conditions of an artificial atmosphere, which is expected to be generated inside the habitat, it is expected to operate normally. However, the habitat has to be constructed first. In order to reduce the amount of equipment that needs to be transported to the Lunar surface, it is more optimal to ensure that the printing process is viable at a lower temperature, at the cost of the process being considerably slower. In conditions of low pressure and low temperature, the main danger is boiling and rapid vaporization of the deposited ink, which leads to eventual freezing and hence not binding the material. This can be prevented by enclosing ink particles between small enough material particles, which induces high internal pressure and forces the liquid ink to behave in a capillary fashion.

In the samples of an actual regolith, it was found that the particles are small enough to prevent this process, and hence Lunar soil can be used for this process without additional processing as soon as it is deposited in the intended fashion.

Another issue that had to be tested was operating vacuum conditions. Printing on Earth in normal atmospheric conditions was thoroughly tested, but in vacuum or close-to-vacuum conditions with low gravity, the ink would not necessarily reach the material directly. This issue can be solved by directly depositing the ink inside the bulk material during the manufacturing process. It was possible because the printing layers are considerably thick (typically 5 mm), and hence the nozzle needle could be inserted without issues. To ensure equal spreading of the material as the needle moves along the x-y plane, flat disks slide along the surface as well, applying pressure and smoothing the material. The image of the nozzle needle and vacuum testing setup is presented in Figure 15 [59,60].

Table 3. Compositions of Lunar regolith determined in DNA-1, JCS-1A (both are simulants), and Apollo samples [61].

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	0.213	0.24	0.1
Cr_2O_3	0.0	0.03	0.2
P_2O_5	0.341	0.63	0.0
Total	98.9	99.0	99.8

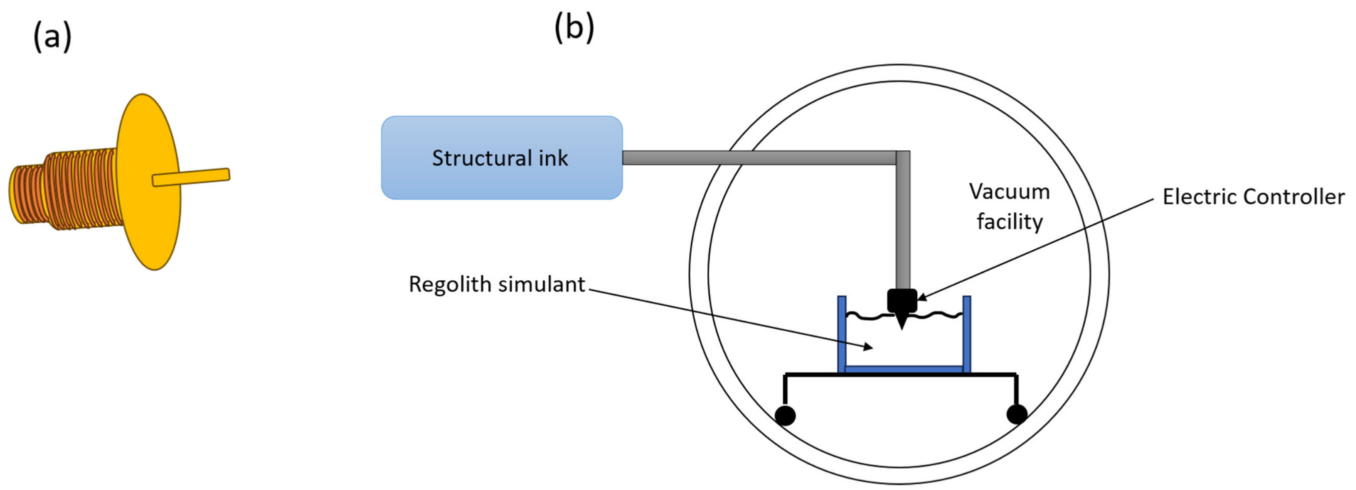


Figure 15. (**a**) Nozzle attachment for the vacuum printing conditions. (**b**) Printer setup for vacuum conditions. Imaged drawn based on [48].

5.2. Habitat Printing-Mars

Just like in the case of Lunar habitat, Martian habitat needs to be preferably built in situ using local materials and equipment. It is considerably more important to be able to utilize Martian resources, as the distance that needs to be covered by the spacecraft from Earth to Mars is about 142 times greater than the distance to the Moon. While the Moon has abundant regolith to work with, Mars offers an abundance of both regolith (of a different composition than the Moon) and basalt, which is mostly composed of Silicon Dioxide and other glasses, as can be seen in Table 4 [62].

For dealing with basalt, it is convenient to employ the FDM printing technique. The melting temperature of basalt is high (984 °C to 1260 °C), but it is still possible to have an FDM printer that can operate at such temperatures without being damaged. Furthermore, Martian conditions do not affect the FDM process much, as printing is performed by heating up and then cooling down the material, which does not involve any chemical reactions. Layer deposition and solidification require temperature control and gravity, both of which are available. FDM is a relatively slow printing technique, but the structure generated by it can be almost immediately used, as cooling down and hence solidification are quite fast as the deposition is performed [63]. The proposed printing setup is presented in Figure 16, where a large FDM printer is housed inside the dome. The components for this printer are brought from the Earth, and the printer is assembled using robotic units, which also gather basalt for printing purposes. When the printer is assembled, it has to print the dome mentioned first for protection from possible environmental hazards. It is carried out by printing individual triangles, so the robots can perform the assembly. As this primary dome is completed, more printers, dome connecting units, and smaller domes can be printed in a similar fashion. The arrangement of the domes can be performed as proposed in Table 2 for Lunar habitat, as the associated risks are similar for the Moon and Mars. After the majority of printing is completed, the initial dome can be converted into an agricultural unit used for growing plants. For this, either bringing soil from Earth or terramorphing is required. Furthermore, some of the printed triangles can be replaced by transparent glassy triangles, the material for which can be obtained on the Martian surface as well.

Table 4. Composition of the Martian regolith [64].

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
MgO	7.0	3.4
Na_2O	2.1	2.4
Total	83.8	98.2

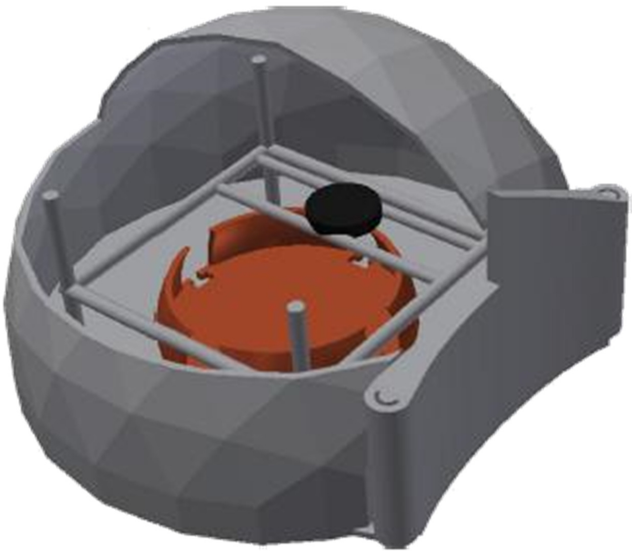


Figure 16. Rendering of the FDM printer inside the dome [63].

The basalt printing concept on Mars still has to undergo extensive testing, including optimization of the printer itself and the structure of the printed habitat components. An alternative to the FDM technique using basalt is binder deposition using Martian regolith, similar to the D-shape printing discussed before. The composition of Martian regolith is presented in Table 4. As a binder, it is possible to use polyethylene (PE), which can actually be synthesized in situ by performing a series of chemical reactions with CO_2 from the atmosphere and H_2O from the soil [64,65]. These reactions require complex equipment, but for a long-term mission, it is more convenient to bring or even print this equipment and have a constant source of binder material.

The regolith/PE composite material was extensively tested for impact strength, radiation shielding potential, thermal expansion, and other mechanical properties, and the results were promising. However, this material was not manufactured using additive manufacturing; hence, research has to be performed in this area. Overall, regolith/PE composite seems to be suitable for 3D printing purposes, similar to D-shape printed Lunar habitats.

5.3. Spacecraft Parts and General Tools Printing

For long space missions, it might be convenient to have a way to manufacture spacecraft parts in case unexpected damage occurs. Installing a 3D printer and taking a variety of raw materials significantly increases the costs of the mission but also reduces the risks involved with the spacecraft being critically damaged without the possibility of repair [66,67]. This becomes even more crucial with the presence of humans in the spacecraft.

FDM is one of the printing techniques that works with a variety of materials and is relatively simple to deploy. One of the issues with this technique is its high energy consumption, as the material has to be partially molten during the printing process. One of the proposed mechanisms for overcoming this issue is installing a solar ray concentrator. It consists of a system of mirrors that focus the incident solar light on the melting area and the nozzle. If those parts are non-reflective, they absorb the intense incident light and heat up. The intensity of the beam can be regulated by changing the mirror orientations. This can ensure optimal processing temperatures for the material used. The same mechanism can be used for heat-treating the printed part if it is made from metal to enhance its mechanical properties.

FDM as a technique can also be used on planetary missions due to the versatility it offers. A huge advantage it has over other techniques is that it is possible to perform self-repair, as having multiple printers allows you to replace faulty components by being able to print up to 57% of the components for that printer [68]. Having multiple FDM printers, which are usually not very large, introduces enough redundancy such that one of the printers is always available, making it a reliable source of tools for the mission. One of the possible uses of this technique is manufacturing a variety of tools, in particular the surgical tools shown in Figure 17 [68]. Surgical tools were printed with ABS polymer, tested in actual surgeries, and deemed to have acceptable quality for short-term use. Due to the possibility of thermoplastic being recycled after one or several surgeries and reprinted into the same tool afterwards, it is a good option to generate a sustainable source for a variety of tools, not only surgical. The disadvantage of long printing times can be bypassed by preplanning and having spare parts available, while the disadvantage of inferior mechanical properties can be bypassed by recycling the used parts. The high-power consumption of the printers can be fulfilled by using readily available solar energy in space [69].

There are three major polymers that have been tested in FDM space printing: ABS ($(C_8H_8)_x .(C_4H_6)_y. (C_3H_3N)_z$), PET ($C_{10}H_8O_4$), and PEI ($(C_{37}H_{24}O_6N_2)_n$). Of course, all three of these polymers are thermoplastic and hence can be reused, making it possible to have a small amount of the material taken into space and used for multiple purposes. All these polymers have a relatively low cost and are hence widely used for 3D printing purposes. ABS and PEI are similar to each other when it comes to mechanical properties but have quite a difference in chemical composition, which might be important when looking at potential in-situ synthesis. PEI has considerably better thermal stability compared to both ABS and PET and superior mechanical properties, making it well suited for printing external spaceship parts and potentially other components that have to be mechanically reliable. The downside of PEI is a higher price than its counterparts and a more complex synthesis process [70–72].

Figure 17. Schematic of a variety of metal and thermoplastic surgical instruments, manufactured via the FDM 3D printing technique. Image drawn based on [66].

5.4. Other Techniques

Thus far, only binder deposition and FDM techniques have been covered in this literature review. However, there are many other 3D printing techniques available for use [20,21,73]. There are multiple limitations that prevent other 3D printing techniques from being used in space:

- Non-recyclable materials: As was mentioned many times in this paper, the recyclability of the material is a major concern when it comes to space tool printing. The limited amount of material and low durability of the 3D-printed tools absolutely requires recyclability. This effectively eliminates stereolithography from the list of possible printing techniques, as photopolymers are essentially thermosetting in nature; once they are cured, they cannot be recycled. The same reasoning is used in eliminating the material jetting method, as photopolymer is used there as well.
- Size of printed parts: Items like habitat walls have to have a large size, meaning that it is inconvenient to use controlled environment printing chambers, as those would have to be very large and require a lot of energy to maintain. This makes controlled-environment printing methods like stereolithography and SLS difficult to use for large items, while binder deposition and partially FDM can easily operate in open areas.
- Material state required: In space, where energy is limited and humans are not always available, the material needs to be processed as little as possible before the printing process. This makes SLS not a good option for space manufacturing, as it requires the material to be milled in a powder state. On the contrary, FDM can simply reuse a damaged tool after being melted and reshaped into filaments, and binder deposition machines can perform printing with regolith gatherers, which only need to be placed in layers and rolled.

6. Conclusions

In this review article, the challenges and advances of 3D printing in space and habitats on other celestial bodies were reviewed. Several potential additive manufacturing techniques, such as FDM, SLA, SLS, Material jetting, and Binder jetting, were described. The needs for space habitats were reviewed. Moreover, the important aspect of differences between manufacturing on Earth and Mars/Moon was reviewed. Finally, the current progress on habitat printing on Mars, habitat printing on the Moon, and printing spacecraft parts and general tools was reviewed. In summary,

- While there is a wide selection of materials that can be used for 3D printing on Earth, only a very limited amount can be reasonably transported into space. Taking enough material to build one or multiple habitats seems unrealistic, especially considering the fact that the walls have to be thick and strong to protect humans from dangerous environments. Hence, it is necessary to use in-situ resources when constructing the habitat and potentially utilize in-situ resources for the synthesis of usable binders. By exploring the underground of the planets, it could be possible to dig and construct an underground shelter that offers high protection from meteoroid strikes and radiation due to the potentially high wall/ceiling thickness. However, for this to become possible, more exploration is required. If the raw resources are not usable, perhaps the possibility of synthesizing printing material will open once more information about the availability of those resources is known. This would require extra energy and possibly complex equipment, but the result might make the Martian colony independent from Earth.
- The danger of meteoroid impact persists not only for potential humans and habitats on Mars but also for 3D printing equipment and unfinished habitats. Printing equipment itself can contain vulnerable components that might get damaged by smaller strikes. Initial stages of printing, which are expected to be most vulnerable due to unfinished structures and exposed printing equipment, are expected to be carried out without supervision by humans, eliminating the possibility of easy repair. Material for building the habitat should also have enough impact resistance to withstand small strikes.
- Temperature affects 3D printing and material cure to a very large extent, and therefore printing machines, processes, materials, and habitat location have to be established together as they affect each other closely. Near-vacuum conditions due to the thin atmosphere make the problem worse, especially if the binder that is used to solidify Martian regolith is a liquid. On Earth, the evaporation behavior of liquids is governed by the presence of water vapor in the atmosphere. However, the atmosphere is nearly absent on Mars, and hence no water vapor is present. This would result in the deposited liquid rapidly evaporating into the atmosphere and, immediately afterwards, freezing due to low temperatures.

The results of this literature study are not only useful to shed light on the necessities, considerations, and challenges of future missions to Mars and the Moon and 3D printing on them, but they are also beneficial for the colonization of other celestial bodies in the Solar System, which is likely to happen in a few decades. The results of this study are also readily helpful for considerations that need to be taken into account for 3D printing in extreme Earth environments, such as Antarctica, deserts, and mountain tops.

Author Contributions: Conceptualization, R.H.; methodology, R.H. and V.S.; software, R.H. and V.S.; validation, R.H. and V.S.; investigation, R.H. and V.S.; writing—original draft preparation, R.H. and V.S; writing—review and editing, R.H.; visualization, R.H. and V.S.; supervision, R.H.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data is contained within the article.

Acknowledgments: We would like to thank Sybrand van der Zwaag for their support during the project.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

ABS	Acrylonitrile, butadiene, and styrene
PE	Polyethylene
AI	Artificial intelligence
PEEK	Polyether ether ketone
AM	Additive manufacturing
PEI	Polyetherimide
CAD	Computer-aided design
PET	Polyethylene terephthalate
DLP	Digital Light Processing
PLA	Polylactic acid
FDM	Fused Deposition Modeling
SLS	Selective Laser Sintering
PCL	Polycaprolactone
UV	Ultraviolet

References

1. Gale, A.; Ramachandran, N. Space colonisation. *Aerosp. Am.* **2008**, *46*, 77.
2. Burelle, A. Mining the moon: A first step in harnessing extraterrestrial resources. In Proceedings of the 61th International Astronautical Congress IAC, Prague, Czech Republic, 27 September–1 October 2010; pp. 6914–6918.
3. Homeck, G.; Bhim, V.; Gitelson, J.I. Opportunities and constraints of closed man-made ecological systems on the moon. *Adv. Space Res.* **1994**, *14*, 271–280.
4. Akins, F.R.; Connors, M.M.; Harrison, A.A. Living Aloft: Human Requirements for Extended Spaceflight. NASA SP-483; NASA: Washington, DC, USA, 1986.
5. Jozuka, E. 3d Printing in Space Is Really Hard. 2015. Available online: https://motherboard.vice.com/enus=article=4x3pzn=3d-printing-in-space-is-really-hard (accessed on 13 June 2018).
6. Raval, S. Exploration colonization resource extraction and utilization of moon and mars. In Proceedings of the International Astronautical Congress IAC, Cape Town, South Africa, 3–7 October 2011; Volume 9, pp. 7845–7851.
7. O'Connor, G.W.; Trigwell, S.; Bose, S.; Bandyopadhyay, A.; Balla, V.K.; Roberson, L.B. First demonstration on direct laser fabrication of lunar regolith parts. *Rapid Prototyp. J.* **2012**, *18*, 451–457.
8. Gannon, M. 3d Printer Could Transform Moon Dirt into Lunar Base. 2012. Available online: https://www.space.com/18694-moon-dirt-3d-printing-lunar-base.html (accessed on 13 June 2018).
9. McGregor, W.; Pope, R.D.; Bodiford, M.P.; Fiske, M.R. In situ resource-based lunar and martian habitat structures development at nasa/msfc. In Proceedings of the 1st Space Exploration Conference: Continuing the Voyage of Discovery, Orlando, FL, USA, 30 January–1 February 2005.
10. Reichert, M.; Rettberg, P.; Seboldt, W.; Manzey, D.; Comet, B.; Maillet, A.; Preiss, H.; Schauer, L.; Dussap, C.G.; Poughon, L.; et al. Humex, a study on the survivability and adaptation of humans to long-duration exploratory missions, part ii: Missions to mars. *Adv. Space Res.* **2006**, *38*, 752–759.
11. Liacouras, P.; Schmid, J.R.; Parsons, M.; Kondor, S.; Grant, G. On demand additive manufacturing of a basic surgical kit. *J. Med. Devices* **2013**, *7*, 030916.
12. Gao, W.; Zhang, Y.; Ramanujan, D.; Ramani, K.; Chen, Y.; Williams, C.B.; Wang, C.C.L.; Shin, Y.C.; Zhang, S.; Zavattieri, P.D. The status, challenges, and future of additive manufacturing in engineering. *Comput. Aided Des.* **2015**, *69*, 65–89. [CrossRef]
13. Leach, N. 3D printing in space. *Archit. Des.* **2014**, *84*, 108–113. [CrossRef]
14. Hedayati, R.; Ghavidelnia, N.; Sadighi, M.; Bodaghi, M. Improving the accuracy of analytical relationships for mechanical properties of permeable metamaterials. *Appl. Sci.* **2021**, *11*, 1332. [CrossRef]
15. Roudbarian, N.; Jebellat, E.; Famouri, S.; Baniasadi, M.; Hedayati, R.; Baghani, M. Shape-memory polymer metamaterials based on triply periodic minimal surfaces. *Eur. J. Mech. A/Solids* **2022**, *96*, 104676. [CrossRef]
16. Hedayati, R.; Güven, A.; Van Der Zwaag, S. 3D gradient auxetic soft mechanical metamaterials fabricated by additive manufacturing. *Appl. Phys. Lett.* **2021**, *118*, 141904. [CrossRef]
17. Wong, J.Y. 3D printing applications for space missions. *Aerosp. Med. Hum. Perform.* **2016**, *87*, 580–582. [CrossRef] [PubMed]
18. Zhou, X.; Ren, L.; Song, Z.; Li, G.; Zhang, J.; Li, B.; Wu, Q.; Li, W.; Ren, L.; Liu, Q. Advances in 3D/4D printing of mechanical metamaterials: From manufacturing to applications. *Compos. Part B Eng.* **2023**, *254*, 110585. [CrossRef]
19. Shahrjerdi, A.; Karamimoghadam, M.; Bodaghi, M. Enhancing Mechanical Properties of 3D-Printed PLAs via Optimization Process and Statistical Modeling. *J. Compos. Sci.* **2023**, *7*, 151. [CrossRef]
20. Pingale, P.; Dawre, S.; Dhapte-Pawar, V.; Dhas, N.; Rajput, A. Advances in 4D printing: From stimulation to simulation. *Drug Deliv. Transl. Res.* **2023**, *13*, 164–188. [CrossRef] [PubMed]

21. Nazir, A.; Gokcekaya, O.; Billah, K.M.M.; Ertugrul, O.; Jiang, J.; Sun, J.; Hussain, S. Multi-material additive manufacturing: A systematic review of design, properties, applications, challenges, and 3D Printing of materials and cellular metamaterials. *Mater. Des.* **2023**, *226*, 111661. [CrossRef]
22. Karamimoghadam, M.; Dezaki, M.L.; Zolfagharian, A.; Bodaghi, M. Influence of post-processing CO_2 laser cutting and FFF 3D printing parameters on the surface morphology of PLAs: Statistical modelling and RSM optimisation. *Int. J. Lightweight Mater. Manuf.* **2023**, *6*, 285–295. [CrossRef]
23. Tan, K.C.; Teoh, S.H.; Zein, I.; Hutmacher, D.W. Fused deposition modeling of novel scaffold architectures for tissue engineering applications. *Biomaterials* **2002**, *23*, 1169–1185.
24. Zein, I.; Ng, K.W.; Teoh, S.H.; Tan, K.C.; Hutmacher, D.W.; Schantz, T. Mechanical properties and cell structural response of polycaprolactone scaffolds designed and fabricated via fused deposition modeling. *J. Biomed. Mater.* **2001**, *55*, 203–216.
25. Odell, D.; Roundy, S.; Wright, P.K.; Ahn, S.-H.; Montero, M. Anisotropic material properties of fused deposition modeling abs. *Rapid Prototyp. J.* **2002**, *8*, 248–257.
26. Sathies, T.; Senthil, P.; Anoop, M. A review on advancements in applications of fused deposition modelling process. *Rapid Prototyp. J.* **2020**, *26*, 669–687.
27. Hedayati, R.; Lakshmanan, S. Pneumatically-actuated acoustic metamaterials based on Helmholtz resonators. *Materials* **2020**, *13*, 1456. [CrossRef] [PubMed]
28. Cano-Vicent, A.; Tambuwala, M.M.; Hassan, S.S.; Barh, D.; Aljabali, A.A.; Birkett, M.; Arjunan, A.; Serrano-Aroca, Á. Fused deposition modelling: Current status, methodology, applications and future prospects. *Addit. Manuf.* **2021**, *47*, 102378. [CrossRef]
29. Roudbarian, N.; Baniasadi, M.; Nayyeri, P.; Ansari, M.; Hedayati, R.; Baghani, M. Enhancing shape memory properties of multi-layered and multi-material polymer composites in 4D printing. *Smart Mater. Struct.* **2021**, *30*, 105006. [CrossRef]
30. Wallace, J.; Wang, M.O.; Thompson, P.; Busso, M.; Belle, V.; Mammoser, N.; Kim, K.; Fisher, J.P.; Siblani, A.; Xu, Y.; et al. Validating continuous digital light processing additive manufacturing accuracy and tissue engineering utility of a dye-initiator package. *Biofabrication* **2014**, *6*, 015003. [CrossRef]
31. Grinevich, O.V.; Mejiritski, A.; Neckers, D.C.; Specht, K.G. Method for Forming Polymeric Patterns, Relief Images and Colored Polymeric Bodies Using Digital Light Processing Technology. Patent US 6200646 B1, 13 March 2001.
32. Beaman, J.; Marcus, H.; Barlow, J.; Agarwala, M.; Bourell, D. Direct selective laser sintering of metals. *Rapid Prototyp. J.* **1995**, *1*, 26–36.
33. Williams, J.M.; Adewunmi, A.; Schek, R.M.; Flanagan, C.L.; Krebsbach, P.H.; Feinberg, S.E.; Hollister, S.J.; Das, S. Bone tissue engineering using polycapro-lactone scaffolds fabricated via selective laser sintering. *Biomaterials* **2005**, *26*, 4817–4827. [CrossRef]
34. Van Vaerenbergh, J.; Froyen, L.; Rombouts, M.; Kruth, J.-P.; Mercelis, P. Binding mechanisms in selective laser sintering and selective laser melting. *Rapid Prototyp. J.* **2005**, *11*, 26–36.
35. Williams, C.B.; Moore, J.P. Fatigue properties of parts printed by polyjet material jetting. *Rapid Prototyp. J.* **2015**, *21*, 675–685.
36. Perry, N.; Zhao, Y.F.; Meteyer, S.; Xu, X. Energy and material flow analysis of binder-jetting additive manufacturing processes. *Procedia CIRP* **2014**, *15*, 19–25.
37. Karim, H.; Delfin, D.; Lin, Y.; Espalin, D.; MacDonald, E.; Wicker, R.B.; Gaytan, S.M.; Cadena, M.A. Fabrication of barium titanite by binder jetting additive manufacturing technology. *Ceram. Int.* **2015**, *41*, 6610–6619.
38. Cucinotta, F.A.; Hu, S.; Schwadron, N.A.; Kozarev, K.; Townsend, L.W.; Kim, M.-H.Y. Space radiation risk limits and earth-moon-mars environmental models. *Space Weather.* **2010**, *8*, S00E09. [CrossRef]
39. De Kestelier, X.; Benvenuti, S.; Cesaretti, G. Living on the moon: Topological optimization of a 3d-printed lunar shelter. *Nexus Netw. J.* **2013**, *15*, 285–302.
40. Kobayashi, S.; Yamashita, N.; Miyajima, M.; Sakurai, K.; Hasebe, N.; Hayatsu, K.; Hareyama, M. Radiation doses for human exposed to galactic cosmic rays and their secondary products on the lunar surface. *Biol. Sci. Space* **2008**, *22*, 59–66.
41. Li, Z.; Wang, Q.; Liu, G. A review of 3D printed bone implants. *Micromachines* **2022**, *13*, 528. [CrossRef]
42. Ghavidelnia, N.; Hedayati, R.; Sadighi, M.; Mohammadi-Aghdam, M. Development of porous implants with non-uniform mechanical properties distribution based on CT images. *Appl. Math. Model.* **2020**, *83*, 801–823. [CrossRef]
43. Honigmann, P.; Sharma, N.; Okolo, B.; Popp, U.; Msallem, B.; Thieringer, F.M. Patient-specific surgical implants made of 3D printed PEEK: Material, technology, and scope of surgical application. *BioMed Res. Int.* **2018**, *2018*, 4520636. [CrossRef] [PubMed]
44. Hedayati, R.; Yousefi, A.; Dezaki, M.L.; Bodaghi, M. Analytical relationships for 2D Re-entrant auxetic metamaterials: An application to 3D printing flexible implants. *J. Mech. Behav. Biomed. Mater.* **2023**, *143*, 105938. [CrossRef]
45. Reichert, M.; Rettberg, P.; Seboldt, W.; Manzey, D.; Comet, B.; Maillet, A.; Preiss, H.; Schauer, L.; Dussap, C.G.; Poughon, L.; et al. Humex, a study on the survivability and adaptation of humans to long-duration exploratory missions, part i: Lunar missions. *Adv. Space Res.* **2003**, *31*, 2389–2401.
46. Suedfeld, P. Historical space psychology: Early terrestrial explorations as mars analogues. *Planet. Space Sci.* **2010**, *58*, 639–645. [CrossRef]
47. Ferlazzo, F.; Kanas, N.; Weiss, K.; Schneider, S.; Whiteley, I.; De La Torre, G.G.; van Baarsen, B. Future perspectives on space psychology: Recommendations on psychosocial and neurobehavioural aspects of human spaceflight. *Acta Astronaut.* **2012**, *81*, 587–599.
48. De Kestelier, X.; Colla, V.; Pambaguian, L.; Cesaretti, G.; Dini, E. Building components for an outpost on the lunar soil by means of a novel 3dprinting technology. *Acta Astronaut.* **2012**, *93*, 430–450.

49. NASA. Moon Fact Sheet. 2017. Available online: https://svs.gsfc.nasa.gov/4537 (accessed on 15 May 2018).
50. Barker, G.C.; Mehta, A. The dynamics of sand. *Rep. Prog. Phys.* **1994**, *57*, 4.
51. Bocam, K.J.; Bodkin, D.K.; Escalera, P. A human lunar surface base and infrastructure solution. In Proceedings of the Space 2006, San Jose, CA, USA, 19–21 September 2006.
52. Hedayati, R.; Sadighi, M. Effect of using an inner plate between two faces of a sandwich structure in resistance to bird-strike impact. *J. Aerosp. Eng.* **2016**, *29*, 04015020. [CrossRef]
53. Hedayati, R.; Ziaei-Rad, S. Foam-core effect on the integrity of tailplane leading edge during bird-strike event. *J. Aircr.* **2011**, *48*, 2080–2089. [CrossRef]
54. Malhotra, R.; JeongAhn, Y. The current impact flux on mars and its seasonal variation. *arXiv* **2015**, arXiv:1503.03885v1.
55. Jull, A.J.T.; Berry, F.J.; Bevan, A.W.R.; Cloudt, S.; Pillinger, C.T.; Bland, P.A.; Smith, T.B. The flux of meteorites to the earth over the last 50 000 years. *Mon. Not. R. Astron. Soc.* **1996**, *283*, 551–565.
56. Ivanov, B. Mars/moon cratering rate estimates. *Chronol. Evol. Mars* **2001**, *96*, 87–104.
57. space.com Staff. Pow! Mars Hit by Space Rocks 200 Times a Year. 2013. Available online: https://www.space.com/21198-mars-asteroid-strikes-common.html (accessed on 15 June 2018).
58. Frost, R. How Often Do Meteoroids Hit the Moon? *2016.* Available online: https://www.forbes.com/sites/quora/2016/12/29/how-often-do-meteoroids-hit-the-moon/23d478b86f2b (accessed on 15 June 2018).
59. D-Shape—Official Webpage. 2018. Available online: https://d-shape.com/ (accessed on 1 June 2018).
60. De Kestelier, X.; Colla, V.; Pambaguian, L.; Ceccanti, F.; Dini, E. 3d printing technology for a moon outpost exploiting lunar soil. In Proceedings of the 61st International Astronautical Congress, Prague, Czech Republic, 27 September–1 October 2010.
61. Laul, J.C.; Papike, J.J.; Simon, S.B. The lunar regolith' chemistry, mineralogy, and petrology. *Rev. Geophys. Space Phys.* **1982**, *20*, 761–826.
62. Wyatt, M.B.; McSween, H.Y., Jr.; Taylor, G.J. Elemental composition of the martian crust. *Science* **2009**, *324*, 736–739.
63. Straub, J.; Kading, B. Utilizing in-situ resources and 3d printing structures for a manned mars mission. *Acta Astronaut.* **2014**, *107*, 317–326.
64. Pillay, S.; Sen, S.; Carranza, S. Multifunctional martian habitat composite material synthesized from in situ resources. *Adv. Space Res.* **2010**, *46*, 582–592.
65. Wagner, R.; Zubrin, R. Exploring mars. In *The Case for Mars*, 1st ed.; Simon & Schuster: New York, NY, USA, 1997; Chapter 6; pp. 139–156.
66. Pfahnl, A.C.; Wong, J.Y. 3d printing of surgical instruments for long-duration space missions. *Aviat. Space Environ. Med.* **2014**, *85*, 758–763.
67. Hedayati, R.; Yousefi, A.; Bodaghi, M. Sandwich structures with repairable cores based on truncated cube cells. *Compos. Part B Eng.* **2022**, *243*, 110124. [CrossRef]
68. Sells, E.; Pejman, I.; Olliver, V.; Jones, R.; Haufe, P. Reprap—The replicating rapid prototyper. *Robotica* **2011**, *29*, 177–191.
69. Parsons, M.; Leake, S.; Straub, J.; McGuire, T.; Hirsch, M. Design of an in-space 3d printer. *Proceedings* **2016**, *9838*, 256–265.
70. 3D Hubs. Petg 3d printing. 2018. Available online: https://www.3dhubs.com/3d-printing/plastic/petg (accessed on 12 June 2023).
71. 3D Hubs. Abs 3d printing. 2018. Available online: https://www.3dhubs.com/3d-printing/plastic/abs (accessed on 12 June 2023).
72. Davies, S. Made in Space to Use pei/pc Polymer on International Space Station 3d Printing Platform. The Magazine for Design-to-Manufacturing Innovation. 2017. Available online: https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/made-in-space-peipc-polymer-international-space-stationm (accessed on 12 June 2023).
73. Kim, S.H.; Yeon, S.M.; Lee, J.H.; Kim, Y.W.; Lee, H.; Park, J.; Lee, N.K.; Choi, J.P.; Aranas, C., Jr.; Lee, Y.J.; et al. Additive manufacturing of a shift block via laser powder bed fusion: The simultaneous utilisation of optimised topology and a lattice structure. *Virtual Phys. Prototyp.* **2020**, *15*, 460–480. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.