

3D Printed Martian Habitats and Challenges to Overcome

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Abstract

In exploring the potential design and construction of Martian habitats, one of the key factors that need to be taken into account is the environmental condition on the surface of Mars, which is drastically different from that of Earth and poses unique challenges. Innovative designs and construction technologies must be utilized to overcome these obstacles. In addition, the building materials should be those that can be locally obtained and must possess the properties and characteristics that would ensure the safety and longevity of the structures. This paper presents an overall portrayal of various Martian habitat designs, 3D printing technologies, and construction materials that have been proposed in recent years including the award winning Martian habitat proposals presented at the NASA's 3D-Printed Habitat Centennial Challenge. Also presented are discussions on some of the important considerations that must be thought of in order to successfully establish the human presence on Mars.

Keywords: Mars; habitat, Martian Concrete, 3D printing, Environmental challenges.

INTRODUCTION

In recent decades, Mars has attracted considerable attention as NASA plans to send the first human to Mars orbit in the early 2030s, followed by trips to the Martian surface coming sometime after that. Unlike the previous extraterrestrial missions that aimed at a flyby or simple planetary exploration, the ultimate goal this time is to establish a successful human presence on Mars. With the fast advancing scientific and engineering technologies, survival on a distant planet within a hostile environment seems no longer infeasible. Many believe that one of the key technologies that would make this mission successful is automated 3D printing. The idea of building structures using 3D printing technologies on Mars has been heavily explored by NASA, academia and other organizations alike [1]. In 2015, NASA launched a three-phased competition to encourage scientists and engineers around the world to develop suitable concrete mixes, 3D printing methods, and conceptual habitat designs

(Phase I and II) that could theoretically be constructed on Mars [2]. The habitat design required the use of indigenous materials available on Mars, and recycled materials that can potentially be salvaged from the initial mission. Following the completion of the first two phases, Phase III of the competition took place in 2019 at Bradley University [3] and consisted of the printing and testing of scale models of Martian habitats [3, 4]. Each participating team was required to 3D print a self-supporting, one-third scale model of a Martian habitat, and was evaluated based upon the overall design as well as the strength and durability of their 3D printed structure. The first place winner of Phase III was "AI SpaceFactory" with their "MARSHA" model

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Received Date: May 16, 2022

Accepted Date: June 02, 2022

Published Date: June 15, 2022

Citation: Yoon-Si Lee, Courtney Keys, Saratu Terreno. 3D Printed Martian Habitats and Challenges to Overcome. Research & Reviews: Journal of Space Science & Technology. 2022; 11(1): 29–39p.

shown in Figure 1 [5]. Their mix was composed of melted basaltic rock with basalt fibers and renewable polylactic acid (PLA) bioplastics that could be produced from plants preliminarily grown on Mars. The team utilized a stationary 3D printing machine with a robotic arm to craft a multi-floor, egg-shaped habitat with a dual-shell design that separated the habitable space inside from the outer, protective shell [6]. The runner up, the team “Penn State” designed a concrete mix made primarily from river sand having similar properties to Martian soil. The team implemented a printing method very similar to that of “AI SpaceFactory” and utilized it to print a final habitat comprised of two connected cylindrical structures with closed conical roofs as shown in Figure 1 [5].



Figure 1. One-third-scale 3D printed Martian habitats constructed during Phase III of NASA’s 3D-Printed Habitat Challenge: MARSHA (left) by AI SpaceFactory and Den@Mars (right) by Penn State (source: Staedter [5]).

All participating groups in this competition were required to present their plans on how to utilize locally available materials on Mars, and how to overcome the challenges caused by the environmental conditions that are still unknown or significantly different from that of Earth. For example, the gravitational acceleration on Mars is approximately 3.71 m/s^2 (12.17 ft/s^2), almost a third of that felt on Earth. The surface temperature ranges between -140°C and 30°C (-220°F and 86°F) with an average surface temperature of approximately -63°C (-81°F), as compared to that of Earth at 14°C (57°F) [7]. This correlates to the thinner atmosphere of Mars, which is composed of 96% carbon dioxide [7]. The thinner atmosphere offers less protection from harmful radiation in the form of galactic cosmic rays and solar proton events [7, 8]. The radiation, as well as the composition of the atmosphere, could potentially have deteriorating effects on materials used to construct the habitats [9]. Mars also experiences dust storms with wind speeds of about 30 m/s (67.1 mph) [8]. Though the wind forces themselves have less impact due to the thinner atmosphere, the planet’s dry surface allows for the winds to pick up loose soil, creating abrasive dust storms [10, 11]. Other critical concerns on Mars that need to be accounted for include micrometeorites, seismic activity, depressurization, and low availability of water. These environmental differences pose unique challenges that must be overcome. Therefore, the most efficient and economical designs and methodologies should be utilized in order to successfully build Martian habitats that can safely protect the human crews from the extremely hostile conditions of Mars. The subsequent sections present an overall portrayal of various Martian habitat designs, 3D printing techniques, and construction materials that have been proposed in recent years. Also discussed are some of the challenges the mission crews will have to face as well as plausible solutions to overcome these challenges including how to keep the inhabitants safe and secure in the extreme conditions of Mars.

MARTIAN HABITAT DESIGN

The establishment of “habitat” on Mars does not just mean a shelter for a short-term structural and environmental survival. Rather, its longevity should be considered in the design process since ultimately the goal is to have human presence on Mars over a prolonged period. Commercially available software such as Building Information Modeling (BIM) and 4D site logistic planning can be utilized to simulate and analyze various options and scenarios through algorithmic problem formulation, and optioneering [12] to come up with a most suitable habitat design. Martian habitat must be structurally and architecturally viable and sustainable for an extremely hostile environment and, simultaneously, provide human crews with a feeling of “home” and a healthy environment for both physiological and psychological conditions within a confined structure. As the term denotes, a “habitat” is considered more than just a shelter, but a dwelling that simulates an environment that is closest to the conditions of earth, where the astronauts consider as “home” [13].

Martian habitats can be constructed either ‘below’ ground (underground) or ‘above’ ground with a possibility of a combination of both. When the 2001 Mars Odyssey orbiter found evidence of underground caves across the red planet that might have the potential to be closed off and converted into shelters [7], the ‘below’ ground option was initially considered more logical and beneficial in terms of protecting the inhabitants from the harsh environment. The layer of land above and around the caves seemed thick enough to shield the inhabitants from radiation, cold, atmospheric toxins and abrasive dust storms. One of the major concerns with the ‘below’ ground shelter is that the natural shape of the cave walls makes it difficult to fully seal the structure. In addition, 3D printing the walls in such a confined space is much too difficult to be effectively executed. A plausible solution may be to print the walls in pieces outside of the base and make them light enough to be transported into the caves for assembly. For example, the wall pieces can be printed hollow with a corrugated structure on the inside to reduce weight while retaining its strength [7].

The printing of pieces, transportation concerns and other physical constraints associated with the ‘below’ ground shelter can be avoided with the ‘above’ ground option. There can be countless, various habitat design ideas that can be thought of for the ‘above’ ground option, but all would have the same end goals: withstanding the tensile forces caused by the internal pressure, holding up to the surrounding environment in the long term, and safely protecting the inhabitants. One of the important considerations that should be accounted for in the design and construction of Martian habitats is Martian gravity. Since Martian concrete will be subjected to much less gravitational force when compared to that of Earth, the primary forces that need to be accounted for will likely be tensile forces caused by the pressurization of the interior living space of the habitats [14]. Numerous Martian habitat designs proposed in recent years utilize rounder shapes such as a dome, torus, cylinder, cone, hyperboloid, or egg-like shape because of these tensile forces [8, 15]. Unlike traditional boxy, rectangular building structures that are designed primarily to withstand the compressive forces caused by gravity, a rounder shape, if designed properly, offers effective distribution of the tensile forces of the internal pressure [8, 15]. Moreover, a rounder shaped structure is known to effectively divert the wind during possible abrasive dust storms, lessening its impact on the integrity of the structure’s exterior walls [10, 11] by redirecting the wind dust. The ‘above’ ground option, however, does not provide the level of a natural protective barrier that the underground case walls do. Therefore, additional measures will need to be taken to protect the inhabitants against the harsh Martian environment. Basalt and Martian regolith comprising walls are known to provide sufficient radiation shielding [8]. Adding a plastic layer to these walls would provide extra protection. An alternative approach to protecting the habitat’s interior from radiation and other harmful aspects of the Martian environment would be an implementation of an outer shell structure separate from the livable interior. A simply shaped outer structural shell would provide an additional shield for more complex interior living spaces, allowing for the interior structure to not be directly exposed to the strain of the extreme temperature fluctuations. This also keeps the inhabitants safe if the outer shell becomes damaged or breached. One possible redundancy strategy in the case of a wall failure without the use of an outer

shell would be to include a basement underneath the structure. The use of additional resources for this basement can be avoided or minimized with careful construction planning. For example, large amounts of Martian land will be excavated to gather the construction materials necessary to form the concrete to build a habitat, and the resulting holes can be converted into basements with the rest of the habitat built on top of them [15].

Amongst the numerous contests participated by researchers and engineers throughout the world, Phase III of the 3D-Printed Habitat Centennial Challenge was the ‘On-Site Habitat Competition’ [3, 4]. It consisted of five levels of competition (three construction levels and two virtual levels) requiring participants to create sub-scale habitats. For the virtual modeling competition, participants were tasked with BIM software tools to design a habitat that “combines allowances for both the structure and systems it must contain,” according to [4]. The habitat must include 93 square meters (1000 square feet) of living shelter constructed with a 3D printer and equipped to house four astronauts for at least one year, in addition to planning for configuring life supporting systems such as spacesuit, rover hatches, plumbing, mechanical and electrical. Each design was evaluated based upon the habitat layout, spatial efficiency, programming, scalability, and constructability. The construction levels involved the 3D printing of elements of their design that eventually resulted in a one-third scale printed model of the habitat. After three stages and four years of the 3D-Printed Habitat Challenge, NASA and partner Bradley University selected five finalist teams: Zopherus, AI SpaceFactory, Kahn-Yates, SEArch+Apis Cor, and Northwestern University [4]. The winning teams’ Martian habitat proposals are briefly described subsequently.

Team Zopherus’s model (Figure 2) is a modular shelter that consists of multiple latticed domes. The team proposed to utilize a lander that houses the 3D printer and concrete mixer for constructing habitats, and autonomous robots for collecting locally available construction materials such as Martian rocks, calcium oxide, ice, etc. that will be used to produce Martian concrete. The resulting modular habitats will be a series of hexagonal structures that are optimized to withstand the harsh Martian environment.



Figure 2. Team Zopherus’s Martian habitat design proposal (source: NASA [4]).

The ‘Marsha’ habitat by the team AI SpaceFactory (Figure 3) is a double-shell, cylindrical structure constructed with a 3D printer that utilizes a vertical telescoping arm. The outer shell, made out of biodegradable, reusable thermoplastic mixed with indigenous rock fibers for reinforcement, will provide an extra protection from the harsh Martian environment to the inhabitants housed inside the inner shell. Its cylindrical shape is intended to maximize pressurization efficiency and usable floor area.

Team Kahn Yates’s design (Figure 3) utilizes a prefabricated core that is plopped down from the lander. Once landed on the ground, the core extends a five-axis 3D printing arm from its top for constructing the habitat’s foundation and perforated walls using locally collected materials. Secondary nozzles will simultaneously 3D print a protective layer made out of high density polyethylene (HDPE) thermoplastic for protecting the habitat from the red planet’s climate and dust storms.



Figure 3. Habitat designs by AI SpaceFactory (left) and Team Kahn Yates (right) (source: NASA [4]).

Mars ‘X-House V1’ proposed by the team SEArch+Apis Cor (Figure 4) is a dual-shell housing module constructed from locally harvested materials including thermoplastic, fibrous, and cementitious materials. It features a pair of interior “inflatable volumes” that can be deployed to the Martian surface prior to the arrival of human crews and a 3D printed shell for shielding the inflatable habitats from radiation. Its innovative design allows natural light to filter into the interior to support inhabitants’ physiological and psychological wellbeing in a long duration mission.

A team from Northwestern University proposed a 3D printable ‘housing pod’ (Figure 4), which is an inflatable, dome-shaped pressure vessel featuring an inner spherical living space and a protective outer parabolic shell to shield the habitat from the harsh Martian climate. The team’s intuitive floor plan attempts to maximize private and common spaces, and resource efficiency. In order to minimize the resources needed for construction, the team places all ‘wet rooms’ (bathroom, lab, kitchen) along one side of the shelter.



Figure 4. X-House V1 (left) and Housing Pod (right) (source: NASA [4]).

3D PRINTING TECHNOLOGY

Though the idea of 3D printing has been around since the 1980s, its adaptation and usage are still considered to be at an early stage [1]. Yet, efforts to develop and advance the 3D printing technologies have continued, and the list of 3D printable materials has grown from plastics to some heavy duty materials such as metal and concrete. For a 3D printer to be used in building Martian habitats, it must be heavy-duty and capable of enduring the extreme environment on Mars. It would also require a compound system consisting at least of an end nozzle and a mix-pump for 3D printing and for supplying the concrete mixture, respectively. In terms of its delivery system and printer apparatus, there are two types of 3D printing modes that can be considered: a frame-type, and a mobile robotic-arm-type. The frame-type printer (Figure 5) consists of a basic set of a static platform (or a frame structure), similar to a gantry system, that supports a printer head and electrical and

mechanical components. A printer head is typically attached to rails on the frame and moves around in three axial plains to 3D print a preprogrammed object. The frame-type printer has the advantage of quickly printing the framework for the structure with high precision, allowing for simpler design, construction and operation. However, its tradeoff is that it requires a large space for installation due to the physical footprint of the system, takes longer to setup and teardown, and has a limited printing capability, only capable of three degrees of freedom to handle complex geometries. In addition, the effective area or size of the structure it can print is limited to the inside dimension of the gantry system.

An alternative to the frame-type system is a mobile compound robotic-arm 3D printer, which can take the form of a conventional six-axis robotic arm or a custom-made system. This type of printer has a concrete extruder mounted on the robot arm effector that can move in six axes to position the nozzle for material deposition. Because of more achievable geometric complexity and the system's mobile capability, the robotic-arm-type 3D printer appears to offer more benefits for building Martian habitats when compared to the frame-type printer [16]. Its six-axis robotic arm allows for depositing complex out-of-plane layers in sections rather than printing the entirety of the layer at once. In addition, by placing a robotic arm and a concrete mixer-pump on a movable platform with all-terrain wheels or tracks and legs (e.g., caterpillar tracks, robotic legs, etc.), its ability to 3D print in terms of speed and range will dramatically improve. An example of such a system is a compound robotic 3D printing system developed by a research team at Massachusetts Institute of Technology (MIT). The MIT team's prototype shown in Figure 5 consists of a track-driven vehicle with a pair of robotic arms and a flatbed that can carry metal tanks or a concrete mix-pump system [17]. The system features compound arm systems, known as micro-macro manipulators, which utilize an industrial hydraulic robotic arm for gross positioning and a smaller electric arm, attached at the end of the larger arm, for fine-positioning and 3D printing [17]. If needed, it can additionally be equipped with a scoop for mining local resources or for surface preparation of a construction site. The entire system can be powered by solar energy and operated electrically. The research team's ultimate goal is to make the system automated and self-sufficient so that it can be deployed to a remote place like Mars to construct structures rapidly [17].

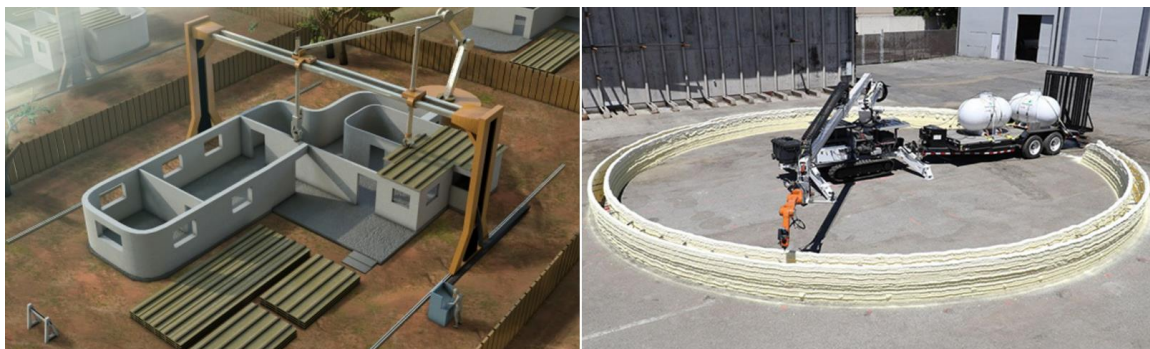


Figure 5. Rendering of a gantry-type 3D printer (left) (source: Lee et al. [1]) and a robotic-arm-type 3D printing system (right) (source: Murray-Nag [18]).

CONSTRUCTION MATERIALS AND MARTIAN CONCRETE

Martian concrete mix and its composition should be carefully designed such that Martian concrete possesses the properties and characteristics needed to ensure the safety and longevity of the structures including structural stiffness, durability, radiation blockage, and insulation. Due to the limited payload the rocket can carry from Earth, the majority of construction materials should be those that can be locally obtained and/or recycled. Amongst the numerous materials that can be locally extracted on Mars, sulfur and basalt have received considerable attention in the recent decades. Martian concrete can be created in the form of melted-basalt, sulfur-regolith, or utilizing both materials. Sulfur is among the fairly widespread resources on the surface of Mars with a concentration level of

approximately 4% atomic sulfur by weight [19]. Once extracted, sulfur can be mixed with indigenous Martian regolith and melted down at approximately 121°C (250°F), acting as a binder to produce Martian concrete. Sulfur-based Martian concrete can be fabricated to become impermeable, and has properties that naturally block radiation [20]. In addition, it has a low thermal conductivity and a high frost resistance, allowing it to function more effectively in low Martian temperatures. Although sulfur-based Martian concrete does not experience shrinkage like conventional concrete does, it can experience thermal contraction when it cools from a working temperature of 116°C (240°F) to -63°C (-81°F) on the surface of Mars [20]. Since fluctuating temperatures may cause damaging effects on the overall strength of the concrete, temperature control must be administered with care during the curing process to achieve its maximum strength with minimal to no cracking.

Basalt is another abundant material on Mars that was produced as a result of magma extrusions from lava flows on the planet [15]. As a stone, basalt has natural properties of low permeability and high strength. It has a low permeability constant of approximately 10-11 and 10-13 depending on the conditions it is formed under [15, 21]. Basalt concrete can be produced by mining basalt rocks, melting them at approximately 1100°C (2012°F), and extruding the material out of a 3D printing device, where it would act as the main concrete [15]. If the walls of a Martian habitat are made of basalt, its low permeability would allow for the walls to keep out the majority of the toxic atmosphere and retain the interior pressurization. However, it cannot yet be concluded that the printed materials alone will be sufficiently impermeable because the exact composition of the basalt native to Mars is presently unknown. Therefore, a plan to add a secondary layer of protection may be necessary to ensure that the interior is completely protected.

Basalt can also be used in the form of basalt fibers, which can be incorporated into the concrete mix as reinforcement to obtain desirable properties. Basalt fibers can be created by melting and extruding basalt rock into fibers thinner than a human hair [7]. This extrusion method will allow the rock to take on a crystalline structure, making it much stronger than the amorphous structure of natural basalt. One of the benefits of using basalt fibers is its ability to withstand the considerable tensile force of a pressurized structure [22]. Basalt fibers have a tensile strength ranging from approximately 1600 to 2000 MPa (232 to 290 ksi) depending on the form of basalt and how the fibers are fabricated [23]. Its tensile strength is comparable to that of carbon fiber. Recent studies revealed that basalt fibers are 2.5 times and 1.5 times stronger than steel and glass fibers, respectively (Freitas 2018), and that they can be used in a wide range of temperatures, from -200 to 600°C (-328 to 1112°F) [23], which are well within the temperature range on the Martian surface. In addition, the use of basalt fibers would increase the concrete's resistance to abrasive dust storms [7]. Presented in Table 1 are the properties for different types of basalt fibers. In Table 1, SB denotes short basalt fibers; CB1, CB2, and CB3 are continuous basalt fibers from different manufacturers; and GF is E-glass fibers, which was included for comparison purpose.

Additional materials can be incorporated into the mix to increase the strength as well as to obtain other desirable properties of Martian concrete. Examples of such materials are high-density polyethylene (HDPE) and polylactic acid (PLA) plastics. Both HDPE and PLA can theoretically be produced on Mars and can be either used within the concrete mix itself, or applied directly to the structures to seal the walls and ensure that they are completely impermeable [14]. There are two different ways to obtain HDPE. It can be either supplemented with recycled materials from the missions or produced from scratch on the planet. To manufacture HDPE on site, methane fuel must be produced through a chemical reaction utilizing carbon dioxide and subsurface water resources. The methane fuel is then polymerized, resulting in a usable plastic. Adding the right proportion of HDPE would provide beneficial properties to the Martian concrete. Its use would improve the concrete's ability to block radiation and allow for a non-porous boundary layer to keep the habitat's interior airtight, and shield from potential toxic materials within Martian regolith itself. It can also help insulate the structure much better than the concrete alone would [14]. It is worthwhile to note, however, that locally producing HDPE will be energy intensive and would require the use of water.

Table 1. Properties and Tensile Test Results of Basalt Fiber (source: Deák and Czigány [23])

	Diameter	Cross-section	Maximum Force	Extension at failure	Tensile strength	Breaking strain	Elastic modulus	Density
Marking	D_{av} [μm]	A_f [μm^2]	F_{fs} [N]	Δl_{fs} [mm]	σ_{fs} [MPa]	ε_{fs} [%]	E_f [GPa]	ρ [g/cm ³]
SB	10.3 ± 3.1	90.2 ± 56.7	0.05 ± 0.04	0.32 ± 0.12	602 ± 295	1.29 ± 0.48	48.2 ± 20.6	2.66
CB1	14.2 ± 1.4	160.2 ± 30.3	0.32 ± 0.09	0.89 ± 0.22	2016 ± 434	3.56 ± 0.89	61.9 ± 3.5	2.56
CB2	12.7 ± 1.5	128.1 ± 31.5	0.21 ± 0.07	0.68 ± 0.17	1608 ± 350	2.72 ± 0.67	62.0 ± 3.6	2.64
CB3	14.1 ± 2.9	163.5 ± 63.3	0.30 ± 0.13	0.87 ± 0.18	1811 ± 331	3.47 ± 0.70	53.2 ± 7.4	2.63
GF	16.8 ± 1.6	223.4 ± 42.0	0.32 ± 0.08	0.68 ± 0.22	1472 ± 395	2.71 ± 0.86	57.0 ± 3.0	2.61

PLA is a renewable bioplastic that be extracted from plants and is known to have the lowest coefficient of thermal expansion among all plastics, making it suitable construction material for the highly fluctuating temperatures of Mars [6]. Moreover, it has a low conductivity, which is a desirable property for effectively insulating structures. Though this material is very useful, it would be difficult to procure on Mars and would require a pre-planning and preliminary missions to grow the plants necessary to produce the plastics. To avoid the mass transport of raw PLA to Mars, plants would have to be brought to the planet to be grown and processed on Mars before the material can be effectively utilized.

CONCLUDING REMARKS

With the rapid advancement of scientific and engineering technologies, the establishment of human presence on Mars seems to have become within reach. Yet, there still exists too much of the specifics of the composition and conditions on Mars that are unknown or significantly different from that of Earth, posing unique challenges to overcome. Thus, the most economical construction materials, efficient 3D printing technologies as well as innovative habitat designs must be utilized to overcome these challenges. First, it is not viable to transport construction materials from Earth. Therefore, the use of locally available materials such as Martian soil and regolith must be extensively explored. In the event that some materials need to be transported from Earth, they must be a minimum amount, light weight and less space consuming. Considering the resources available on Mars, the use of sulfur, basalt, or a combination of both seems practical over other possibilities because Martian concrete can be produced without the need of water. Yet, because these options are hot-mix based and that Mars is known to have a high temperature swing, a mechanism by which the mix can be kept heated throughout the mixing and printing process must be incorporated into the 3D printing system.

When it comes to 3D printing technologies, different 3D printing technology offers different benefits, challenges and suitability for the varying applications and projects it is used for. For the Martian habitat project, however, a mobile compound robotic-arm type system appears to be a better alternative over a gantry-based system in terms of the system's achievable build volume, as well as its mobile capability with multi-dimensional extensions that allows for high kinematic flexibility to fabricate complex structures in varying construction environments. It is important to continue the effort to recognize the opportunities and limitations to further enhance the system's capabilities. These may include adding a secondary robotic arm with a multi-tool capability to allow automated placement of pre-fabricated reinforcing components into a structure being 3D printed, and integrating sensors for real-time monitoring of print quality and consistency.

Amongst the numerous Martian habitat designs that have been proposed through the NASA's 3D-printed habitat challenge, each design has its own benefits and drawbacks. Thus, further efforts should be made so that the most efficient design, featuring these various advantageous characteristics, can be developed before the actual mission takes place. In addition, one of the most important parts of the Martian habitat is the protection of the interior living space since no human can survive without a proper protection from the harsh Martian conditions including a high temperature fluctuation, abrasive

dust storms, and deadly solar and cosmic radiation. Thus, such a protective barrier must be designed and constructed completely airtight with a controlled indoor oxygen level, temperature and air pressure. Considering the deadly radiation exposure on the Martian surface, an underground habitat may look like a reasonable solution because constructing the habitat deeper into the Martian soil, the more efficient it will be in terms of protecting inhabitants from the radiation. However, it may be an extremely uneconomical and time-consuming construction process (e.g., underground 3D printing). A better alternative appears to be an 'above' (or semi-above) ground habitat that is easy to be 3D printed and has a safe interior living space with an efficient protective barrier. Sufficient transparent area should be incorporated in the exterior walls or in the protective barrier (e.g., windows) that would allow sunlight for growing crops as well as provide a visual connection with the surrounding landscape to the inhabitants. Another key feature that must be included in the habitat design is a feeling of 'home' that would provide inhabitants with physical and psychological comfort. Furthermore, other considerations that need to be accounted for include multifunctional space and possible expansion of the habitat. Finally, the Martian habitat should be designed completely sustainable. Once built, it must be capable of self-sufficient in energy production and conserving limited resources such as air, water and other materials with the highest recycling efficiency ever thought of.

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