Multi-layered 3D Printed Mars Habitat Proposal, Analysis of Habitability Requirements and Autonomous Building Technologies from the NEST Team's Design at the NASA Centennial Challenge.

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The NEST project was one of the top thirty finalists of the 2015 NASA 3D Printed Habitat Challenge, to propose habitat construction ideas using additive manufacturing based on in situ resources utilization (ISRU) and promoting sustainable housing solutions. NEST stands for Nested Environment Settlement Technology, which highlights the most important aspect of the proposal: distinct layers that progressively create adequate environmental conditions for human habitation. However, current advancement of space research has updated life support considerations and construction knowledge. Specifically, a Mars habitat floor plan configuration and 3D printing for the exposed shell. This paper presents an analysis of the multi-layered approach considering the current advancements in autonomous building technology. It is shown that the multi-layer approach is a feasible solution for providing an incremental building scheme with redundant layers and enhanced living conditions. This updated research presents an opportunity for further development of multi-layered solutions as a way of combining habitability requirements with current automated construction technology for space and Earth settlements.

Nomenclature

3DPC	= 3D Printed Concrete
3DPH	= 3D Printed Habitat
N3DHC	= NASA 3D Printing Habitat Centennial Challenge
MM3DP	= Multi-Material 3D Printing
NEST	= Nested Environment Settlement Technologies
ECLSS	= Environmental Control and Life Support System
Exolayer	= Exterior Layer
Mesolayer	= In Between Layer
Endolayer	= Internal Layer
ESA	= European Space Agency
ISRU	= In Situ Resource Utilization
MMOD	= Micrometeoroids and Orbital Debris
mSv	= Millisievert
PLA	= Polylactic Acid
FFF	= Fused Filament Fabrication

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I. Introduction

The 3D Printed Habitat Centennial Challenge was a part of the NASA Centennial Challenges program to promote public awareness and encourage private actors to develop products and services for the agency[1].The program specifically aimed to "foster the development of new technologies necessary to additively manufacture a habitat using local indigenous materials with, or without, recyclable materials, in space and on Earth." (Harbaugh, 2015). Consequently, the program engaged professionals to rethink their potential contribution for the development of processes and technologies that can make a transformative impact in both the aerospace and construction industries.

As a team of young Chilean architects, we saw an opportunity in this assignment to develop a proposal for a Mars settlement, and to innovate on fabrication strategies and architecture concepts that would be applicable for the inhabitation of extreme environments on Earth, like the Atacama territory on northern Chile[2]. Therefore, our proposal aimed to expand the competition requirement of building an outer exposed layer, to the development of the inner zones to encompass living conditions. This is central to our concept of a Nested Environment Settlement Technology (NEST): nested layers fabricated with in situ resource utilization (ISRU) by using diverse and autonomous 3D printing technologies aimed at satisfying different user requirements.

In this paper we will revisit the proposal considering current information about the 3D printing technologies and space habitation. The method chosen for this paper is comparative analysis. We are assessing three topics from our NEST proposal: architectural concept, habitability, and fabrication strategy. Identifying differences and relationships between them and comparing it to updated bibliography. The goal is to explore new insights and deepen our understanding, while defining the next steps for a new iteration of the project.

In section II we will describe our design process and the different options explored. Section III will be an overview of our final design in the light of new advancements regarding the architectural concept, habitability and fabrication strategy. Finally, in Section IV we offer a conclusion of the full process while identifying future goals and constraints for a prototype implementation.

II. NEST Design Process (background)

Architecture blends art and science to create spaces that transform thoughts into reality. In space, architecture faces challenges but also opens multiple possibilities. Mars exploration missions have provided information about the environment, atmosphere, geology, and landscape for designing habitats. For Martian architecture, the task is to establish a permanent independent settlement that considers both immediate operations and future expansions criteria.

The case study for this paper is the NEST proposal, formulated in response to NASA's design brief and design parameters for phase I of the 2015 competition. The most important aspects of the model being the safety of the explorers and the redundancy of the structure, considering worst-case environmental conditions. We designed NEST as the habitation subsystem of a Mars exploration base. As one entry of the NASA 3D Printing Habitat Centennial Challenge (N3DHC), this project was required to accommodate four inhabitants for six months while enduring extreme conditions posed by the Martian environment: low gravity (0.3 G), lack of breathable air and surface liquid water, as well as elevated levels of harmful solar and cosmic radiation[3]. In addition, the teams were asked to use ISRU for the main materials for the 3D printing, while also integrating recycling from the mission, like plastics, metals, or prefabricated parts. Consequently, the judges evaluated the 165 submissions for their design process: architectural concept, habitability, 3D printed constructability, and Mars site selection. Our team reached the top thirty finalists of phase I.

We defined the design process as a sequence of decisions that changed our proposals and showed degrees of improvement over time in lieu of our problem understanding. Moreover, "in terms of space architecture, it corresponds to the idea that at every design level, all elements are considered, roughly at the beginning and more detailed at a later stage" (Häuplik-Meusburger and Bannova, 2016). In other words, our approach arose from making decisions, modelling prototypes, evaluating the tradeoffs, and keeping the learnings for the next iteration. This process aligned with distinct delivery stages at the N3DHC, including feedback from the judges.

In Table 1, we are presenting a summary of the factors, concepts, and decisions that guided the design process through each protype (Figure 1). In terms of environmental factors, we considered the site selection, ease of surface transportability, and deployment[4], atmospheric, radiation hazard, micrometeorites, and sandstorms. The architectural concept responded to mitigate these environmental hazards by creating baseline dome geometry. The fabrication strategy considered the domelike structure feasibility with 3D printing technology, ISRU material, and prefabricated modules. In each prototype competition, we trade off the learnings and implications of our decisions.

In prototype a, the main environmental factors considered were the cosmic and solar radiation health hazards and the need to provide a solution for the unbreathable atmosphere. Additionally, we considered the selection of the location as another layer of protection, such as choosing a shallow valley where the territory would provide shadow and protection from the environmental factors. Our first architectural concept considered a glass dome structural external layer (exolayer) that would accommodate a prefabricated habitable module transported with the fabrication machines, capable of providing breathable air and the array of needed subsystems and crew quarters. We considered that the glass transparency would reduce the need for artificial light, help the crew to acclimatize to the Martian day schedule, and observe the Martian landscape from inside the quarters. This means that the prefabricated module must be in place before the 3D printing process starts. The fabrication process embraced a 3DPH technology of heat and silicates from Martian regolith for the 150mm glass structure. This technology exists today, for example the Massachusetts institute of technology - Media Lab has researched this since 2015[5]. This technology would minimize

Table 1. Summary of factors, concepts, and decisions.

Concepts	Prototype a)	Prototype b)	Prototype c)
Environmental factors	Cosmic and Solar radiation. Unbreathable atmosphere.	Cosmic and Solar radiation. Unbreathable atmosphere. Micrometeorites.	Cosmic and Solar radiation Unbreathable atmosphere. Micrometeorites. Sandstorm seasons.
Architectural **concept**	Territory as a radiation shield. Glass dome and internal inflatable habitat.	Multi-material exterior layer with internal inflatable. A growth garden for food and PLA production.	Nested layers, external regolith, an intermediate in glass/ice and an internal inflatable and 3d printed
Fabrication strategy	Interior Habitat module prefabricated. Exterior layer (exolayer) in glass.	Exolayer in Glass with iron reinforcements. PLA 3d printed for equipment and furniture.	Exterior layer in regolith in between layer (mesolayer) in glass with ice to improve internal light and radiation mitigation. Internal layer (endolayer) inflatable.
Trade off & learnings	3D print glass would need large amount of heat. Single glass layer is dangerous due to possible projectiles perforations and other impacts.	A reinforced dome would help projectiles and radiation protection. However, glass and iron layer would present different thermal expansion and additional 3D print complications.	Separate layers in different materials would improve security, and redundancy. However, would increase fabrication complexity

Figure 1. Design process outputs: a) prototype, b) prototype, and c) prototype

water consumption; however, it implies the use of a sustained and large amount of power to generate heat to melt the material. Additionally, a single glass layer is vulnerable to projectile perforations from micrometeorites, debris from landing sites, or collisions from rover approaches and accidents. On top of that, more thickness was necessary to address proper radiation protection, as detailed below. In brief, with these considerations we moved to the next iteration.

Secondly, prototype b embraced the learnings from the previous cycle increasing the thickness for more radiation shielding and adding an iron layer to increase strength. The environmental factors were updated, the background radiation was considered as 240-300mSv per year[3], and the presence of micrometeorites[6] and other possible jumping debris from the mission operation were considered. Therefore, our architectural concept expanded to generate a multilateral dome by integrating iron, mud, and glass in a 3D printed additive fabrication scheme. Thus, defining the section with a 10mm iron plus a 150mm glass layer would potentially reduce in half the intensity of a 500 KeV radiation doses[7]. In addition, the prefabricated habitable module was intended to be partially completed on site with 3D printing polylactic acid (PLA) machines, for smaller to medium size items like furniture, tools and internal finishings like closeouts. Moreover, maintaining this fabrication system would require locally grown corn, as PLA is a bio renewable resin made from corn dextrose. Therefore, a garden zone was added to the floor plans to grow corn alongside other consumables. After finishing this iteration, our tradeoffs and learnings were that a glass and iron layer would present different thermal expansions exposed to the Martian environment. These two dissimilar materials would pose the risk of fracturing the exolayer as they are exposed to temperature variations. Further research would clarify the integration of these two materials as well as their thermal performance.

Lastly, with prototype c, we reconsidered the fabrication strategy and environmental factors. For the cosmic and solar radiation, unbreathable atmosphere, and micrometeorites, we also considered the sandstorm seasons and dust as design drivers. Our architecture evolved into a nested layer concept with different materials and functions to ensure better environmental response and additional safety for cosmic radiation. This means an exolayer 3D printed with regolith with a specific design shape to settle dust storm particles as another layer of mitigation for micrometeorites. An in-between layer (mesolayer) in mixing glass and ice to improve internal light and radiation mitigation, a portion of this layout would be directly exposed to the Martian landscape. An internal layer (endolayer) consisted of a prefabricated inflatable habitat with ready-made subsystems (like an access gate and breathable air machinery), and locally produced PLA parts and items. Producing these separate layers in varied materials would improve thermal performance, radiation protection, and operation performance while adding redundancy for safety. This would also increase complexity by separating into different 3D printed devices and subsystems. However, this idea helps organize the internal spaces for the crew living conditions and machine operations.

In brief, at the end of the design process our architecture concept distilled on the nested layers in a way to both increase protection and organize the habitable zones and fabrication process (Figure 2). This was named NEST, which stands for Nested Environment Settlement Technology, to summarize the relationship between these factors. These concepts and the NEST project will be outlined and discussed in the following sections.

Figure 2. Nested habitable volumes as the architectural concept.

III. Overview of NEST

A. Architectural Concept

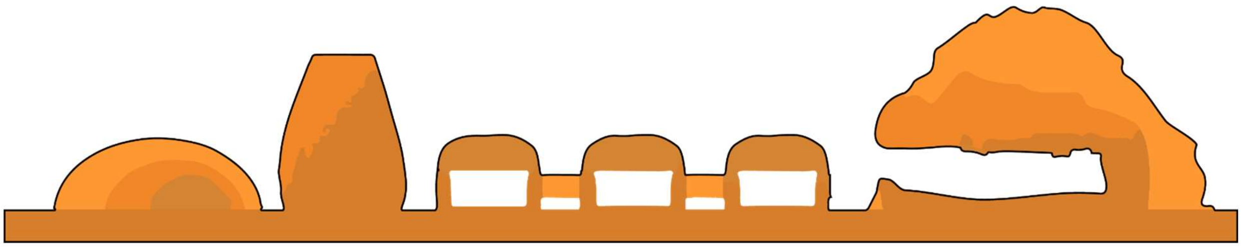

Figure 3. Different Martian architectural concepts – dome, tower, modular, lava tubes.

An architectural concept is a fundamental idea that guides the design process of a building. This concept can take multiple forms, such as specific features, materials, or environmental factors. NEST is a dome composed of nested layers defining habitable volumes and redundant protection for occupants and machinery operations.

In recent years, there has been considerable discussion and exploration of various concepts related to Martian space architecture research (Figure 3). Some of them are:

Dome or geodesic forms: the structural integrity of the curved geometry, effectively distributes loads to the ground. However, certain spaces could be underutilized due to the arch shape. For instance, closer to the ground is hard to operate because of the low ceiling height; and the zenith space could remain unused due to the tall height. This issue was addressed by SEArch+ team on the "icehouse," the design phase winning project of the *N3DHC*. The multiple story platform inside the ice domelike shape allows to increase the habitable space vertically[1]. Additionally, the semitransparent ice external layer performs as a radiation barrier while adding natural light into daily activities[22].

Tower shaped structures: allow optimal space utilization and ease of 3D printing. As described by AI space factory for the MARSHA project[23], the extruded egglike tall form minimizes construction timelines and corridor areas by vertically distributing the different zones. At the third phase of the *N3DHC,* all the final prototypes from the different teams gravitated toward a tower configuration[1] as they were loaded vertically until collapse. The winner of this phase was the MARSHA project, using a mix of material of basalt fiber and bioplastics the team was able to support the

Underground structure or lava tubes: provide better shielding during times of increased solar activities and radiation; however, these spaces could become dangerous for unknown Martian factors, like quakes or partial collapse of the structure[4]. Also, limited access would increase the difficulty for construction and installation of the pressurized volumes, as well as increase the difficulty of operation. Nevertheless, there is benefit in locating a secondary cavern or lava tube habitat as an emergency shelter, due to the possibility of operational accidents during increased solar activity.

Modularity and urban addition: aggregation strategy to connect new modules. Allowing to expand and compartmentalize the base into parts. An example of this is the Sprout Project[8], where the team projected interconnected habitation and productive units, concentric to a bigger central building called the "green powerhouse". The configuration is branched, meaning that is possible to transit from the peripheral modules to the center thought the other modules while in a pressurized atmosphere.

Future work will integrate and reference ideas behind the architectural concepts presented in this section.

B. Habitability

Habitability in an architectural plan refers to the design and provision of adequate living conditions for the occupants of a building. It encompasses a wide range of factors that contribute to the comfort, quality, and planned distribution of zone; aiming to enhance the daily conditions of its inhabitants. A space habitat integrates these factors with the increased complexity of maintaining internal conditions that ensure the life and well-being of the occupants by deploying different hardware throughout the structure. NASA identifies some of these technologies as Environmental Life Support systems (ECLSS), grouping by function of water recovery and management, atmosphere revitalization, waste management and environmental monitoring[24]. Martian habitat will integrate these systems to ensure habitability, addressing the local conditions like lack of breathable air, high radiation, low gravity, scarcity of water, power, and food production.

Our NEST proposal focused on the habitability plan while considering these systems. On a future iteration, these will further be defined and integrated into the plan.

The habitability proposed for NEST is a sequence of zones from public to private areas following a nested pattern (Figure 4). From the outside towards the inner part of the plan: an arrival platform, a drone area or garage, a core or access gate, a work and gathering zone, a crew quarters and resting zone, a gallery for producing vegetables with a recreation area. These zones correspond to a pressurized atmospheric strategy determined by the access gate (Figure 5). These areas are determined by the positions of the different built elements and layers.

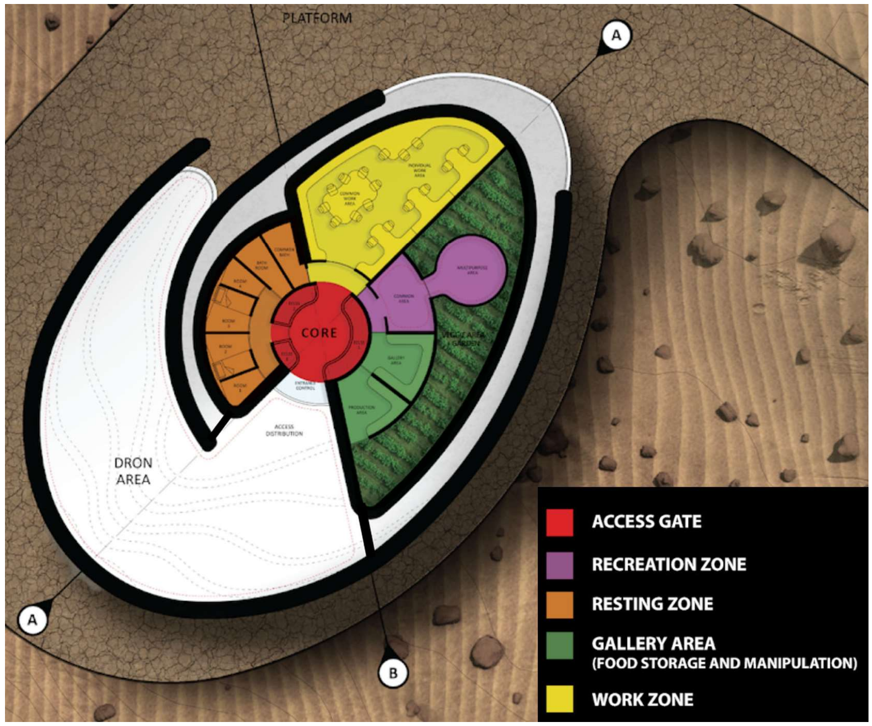

Figure 4. NEST Habitable zones.

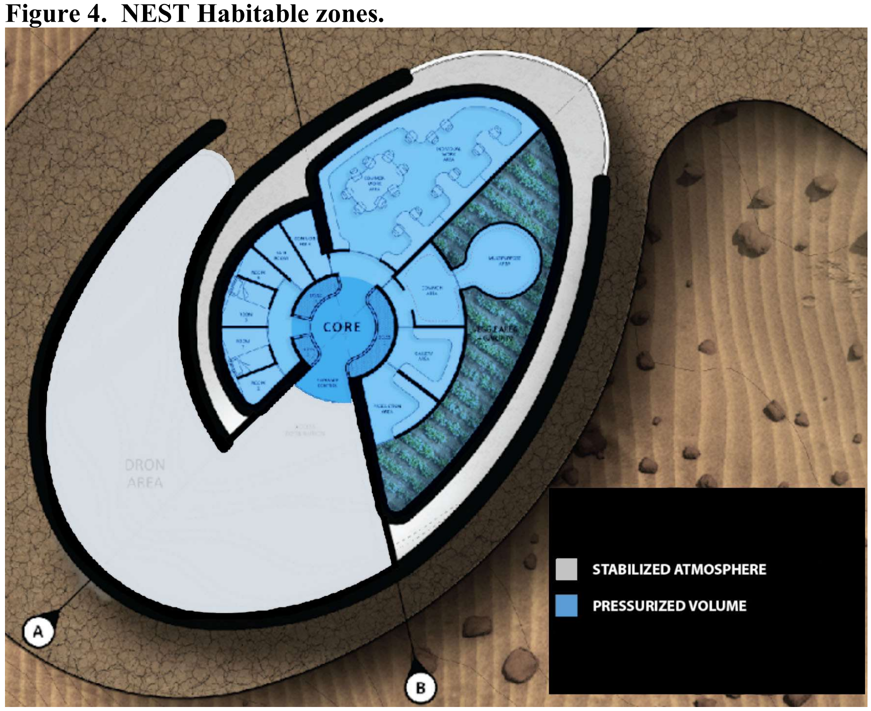

Figure 5. NEST Atmospheric zones.

Firstly, the arrival platform was designed as a stabilized ground for both the access area and docking pressure port for the explorer from the launching pad, allowing easy surface transportability of elements and materials and serving as the building site to fabricate the rest of the structural elements. This is the foundation of the building and the access to other areas of the site. As per recent literature discussions[9], the entrance should have wider and continuous access-egress for ease of operation. Therefore, a separate ingress and exit strategy is preferred. However, this would double the need for additional barriers from dust and sandstorms (Figure 6). For the next NEST iteration, the team is considering this new plan diagram and addressing the increased complexity.

Secondly, the drone area is where the crew could store and repair the exploration vehicle and other sensitive mobile technologies. This area is the entry to the habitat and acts as another protection measure for the habitat from environmental hazards like winds, dust, and sandstorms. This zone should be ground stabilized and dust-controlled, becoming another layer of protection for explorers as they access the habitat. For a better dimensioning of this space, a review of the possible machines must be made for eventually separating the entries by type and size of machines, for instance, having one for small aircrafts, another for larger wheeled vehicles and a quick exit for humans in suit.

Thirdly, the core gate is a pressurized unit that acts as an air lock and includes a hatch for sample airlock and access to the rest of the zones, with the machinery necessary to provide continuous pressurized breathable air for the explorers. Additionally, this unit works as the connector to the rest of the areas by providing another layer of security. This will mark the entrance to the prefabricated and inflatable section of the habitat, the endolayer. In combination with the exolayer, and mesolayer, the levels of redundancy are increased for crew safety. A better understanding of the subsystem technology is needed to possibly have a double gate.

Fourthly, the work zone is thought to be a collaborative multiuse space for the crew. In this area tables and chairs are allocated for individual and collaborative work. We envision this area to face the mesolayer, made of glass and water. Hence, having indirect light and views of the Martian territory, which helps with psychological well-being of the crew. More research is needed to integrate specific functions and research equipment, like rock analysis. Additionally, this space will become the communal space for eating, coordinating, and celebrating. Having a list of possible crew uses will help refine its design. Next to the work area is the resting zone or crew quarters. Located at the center of the building, it is envisioned to have extra shielding by increasing the layered thickness to isolate the

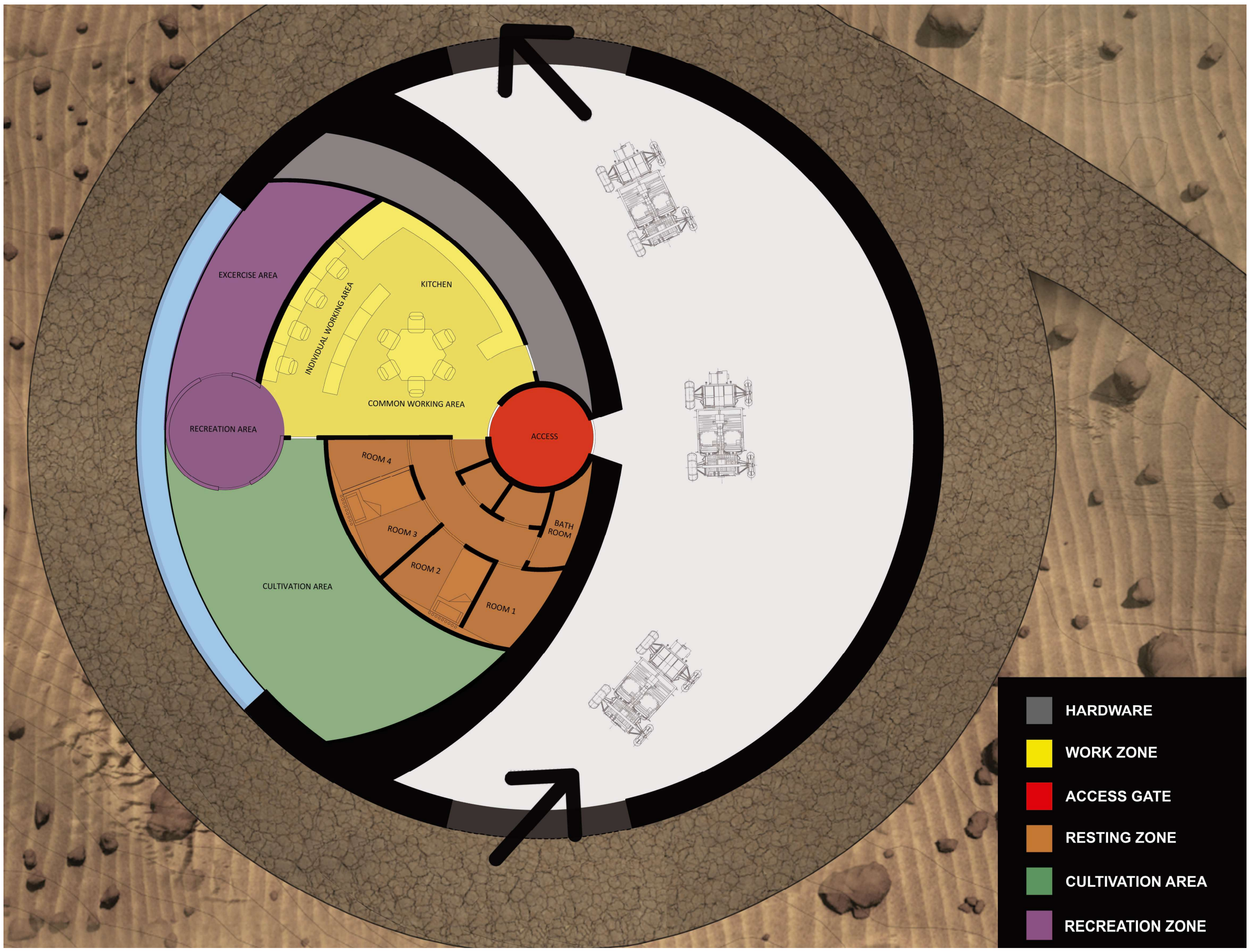

Figure 6. Concept plan for a circular mobility flow. Adapted from Design Analysis for Lunar Safe Haven Concepts. (Wong et al, 2023)

crew as much as possible from the radiation during sleeping hours. This configuration includes four closed rooms for crew comfort, lavatories, and stowage.

Finally, the gallery area and the recreation zone are tied together in a combined area. On one side, this zone would serve as food production by growing plants, and on the other side, recreation, and exercise. We believe this would help the crew's morale and lower stress levels. More research is needed to understand how crops should be produced on Mars while integrating additional features for wellbeing.

In brief, this nested habitation strategy provides increasingly more private areas towards the center of the layout to insulate the crews both physiologically and psychologically from the environment and mission. All activities being on the same level also give better visual connectivity, which reduces the sense of isolation, adds a sense of comfort, encourages social interaction, and allows for some flexibility of functions based on future needs that come up as the astronauts continue their mission. Overall, the design of a habitable Martian architecture requires careful attention to the needs of the human occupants for the high intensity of the mission.

C. Fabrication Strategy

Developing a fully automated 3D printing system for constructing Martian habitats using ISRU presents several challenges. By utilizing local resources, the mass and cost of interplanetary manned missions can be significantly reduced, as well as the need for on-site logistics[10]. This approach also reduces the need for mission-critical spare parts by relying on on-site fabrication for replacements and repairs. Still, building an automated construction system requires a significant advancement in the robustness of the printing systems, to be able to operate in a remote and adverse environment without human intervention[11]. While several efforts have advanced the technological readiness level of automated large-scale 3D printing technologies[12], these technologies are still in an early stage of development. On Earth, applications for building construction are divided into prefabrication and on-site construction. While prefabrication allows higher complexity and higher quality control, in-situ construction presents several challenges related to uncontrolled environmental conditions and uncertainty in the process. In fact, the case of Mars may represent the most extreme case of a remote environment for 3D printed construction[13]. The system would need to withstand the harsh environment and be able to address failure and changing conditions autonomously. The use of 3D printing is not restricted to the establishment of a settlement prior to the arrival of the first human inhabitants, but it would play a major role in repairing and maintenance.

Additive manufacturing, commonly known as 3D printing, encompasses several different techniques[20]. The main types used in construction are those based on material extrusion, material jetting, and binder jetting. In the early years of the development of large-scale printing techniques for space exploration, there was a focus on two competing technologies[14]. On one side, the application of binder jetting (presented as D-shape) was backed by the European Space Agency (ESA). On the other side, NASA presented a proposal based on material extrusion (presented as Contour Crafting) in partnership with one of the earliest proponents[15] of what is today known as 3D Concrete Printing (3DCP)[16], which has become the dominant technology for large-scale additive manufacturing in the construction sector.

A variety of materials have been proposed for a space habitat on Mars, with two main types of concrete having been identified as potential building materials[17]. Magnesium silica concrete is a composite made of magnesium oxide and silica sand. It can reach very high compressive strength but has large water requirements. Additionally, several critical components and additives are uncertain to be able to be produced on Mars. On the other hand, sulfur concrete is created by heating sulfur and aggregates that form a solid and durable concrete. As sulfur is used as a thermoplastic binding agent, it does not depend on the cement and water reaction as in ordinary concrete. While normally sulfur concrete consists of up to 80% aggregate, research has shown that the optimal mix for Mars is a 1:1 sulfur to aggregate ratio[18]. Another remarkable advantage of sulfur concrete is that it is a recyclable material, although the integration of sulfur concrete and 3D printing would also be based on extrusion. The heating necessary to melt the sulfur would make the application closer to 3D printing with thermoplastics, commonly known as Fused Filament Fabrication (FFF).

Shielding the crew from space radiation has been one of the main requirements for the construction. For this reason, the NEST proposal creates distinct construction layers with different materials to provide increasing levels of protection. However, recent studies have shown that the required thickness for diminishing cosmic radiation to acceptable levels is probably much higher than expected due to the creation of secondary particles within the regolith19. This would imply that several different composite layers are a much more effective approach to the overall building of the habitat. This is aligned with the architectural concept of nested layers. As depicted in Figure 7, The NEST schematic layer composition for prototype c can be summarized as:

I. **Endolayer:** Given the need of creating an air-tight environment and generating the necessary support for structuring the dome, the internal layer is proposed as an inflatable membrane deployed from Earth. This could be covered with a Micrometeoroids and Orbital Debris (MMOD) fabric shield made of Kevlar to strengthen the pneumatic membrane. Additional parts and items, such as closeouts and furniture, should be locally 3D printed with PLA.

II. **Mesolayer:** This was thought of as a silicate-glass scaffolding with a water-ice layer as a radiation shield. As per recent studies, it is noted that hydrogen, water, and polyethylene are among the optimal shielding material to reduce secondary radiation for astronauts on long during missions in deep space[25], but the containment of hydrogen is largely incompatible with the pressurized endolayer and the internal use. Another possibility is adding hydrogen-rich plastics to improve their shielding effect. More research is needed to decide the final composition.

III. **Exolayer:** While the original proposal was based on molten regolith and silica, current advancements in sulfur concrete are much more promising as a feasible solution for space construction. The ribbed geometry of this layer would receive dust from the environment, creating another layer of protection for radiation and projectiles.

In brief, as the development of 3D printing technology and material sciences progresses, so does our understanding of their potential integration into the design process and future iterations. The building sequence would be largely dependent on the robustness of the building methods deployed on the Martian surface. While prototypes a) and b) relied on a multi-material 3D printing system capable of printing graded materials from silicate-glass and regolith, prototype c) considered independent meso- and exolayer fabrication, with an eventual exposure of the mesolayer for getting natural light into the habitat. This multi-layer strategy involves the integration of different printing techniques in multiple steps and the final amalgamation of different printing technologies will largely depend on their individual progress.

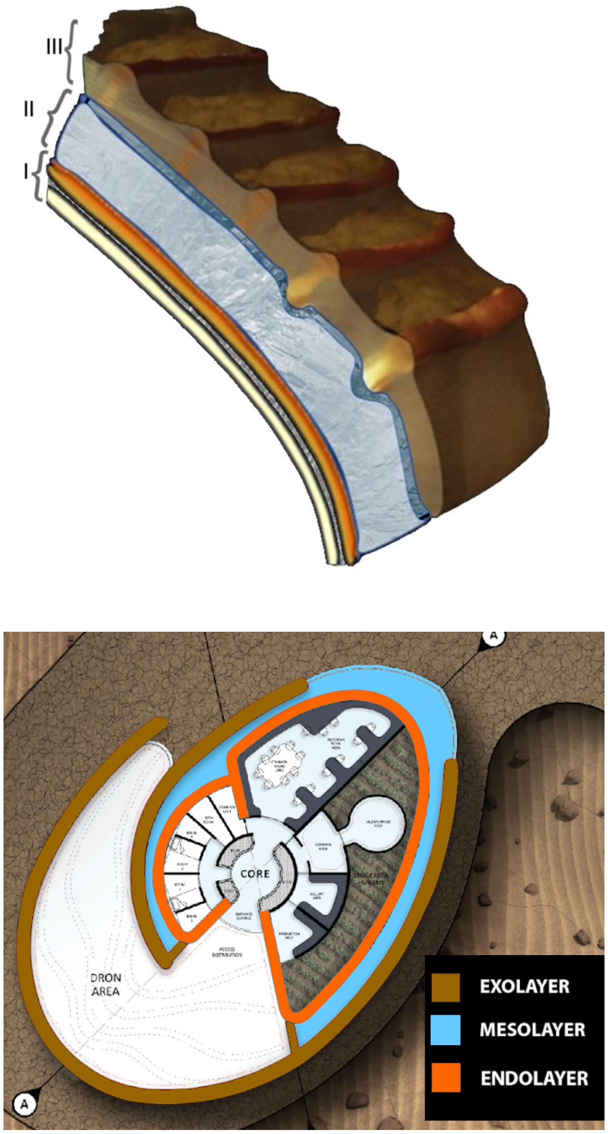

Figure 7. NEST layers.
i) Endolayer: Inflatable membrane.
ii) Mesolayer: Silica-glass and Ice.
iii) Exolayer: Sulfur concrete with dust sedimentation

IV. Conclusions

Space architecture provides a unique platform to reimagine the relationship between humans, environment, and

Figure 8. NEST architecture images, aerial and ground level.

technology, enabling the development of innovative design strategies and hardware for self-sufficient habitats. Our proposal, NEST, aims to establish a secure and sustainable base on the red planet. This paper showed an overview of the three key ideas: architectural concept, habitability, and fabrication strategy, with the goal of advancing the future iteration of the project.

The architecture concept is a series of nested layers in a dome shape, defining different habitable volumes for the occupants and machinery operations. The nested strategy benefits the habitat thus creating barriers from the outside and environmental hazards, towards a more protected interior. Additionally, it organizes the habitat functions and zones for activities. In exploration with other architectural concepts from the literature, as presented by the winning projects of the different phases at the N3SPCC, the “icehouse” by Search+ team and the AI Space factory with the MARSHA project, adopting a multi-story configuration would optimize the use of space, while a modular approach would facilitate the expansion or compartmentalization of the building.

The NEST habitability plan continued the dome shape concept with a circular array of the zones: an external unpressured volume for drones and rover arrival, a core with hatch for the entry, and a pressurized volume for the astronauts' dwellings. In the literature, a circular plan scheme[9] with double entry for rover operation will be adapted for a future iteration. Further research is needed to include and allocate ECLSS, and other crew systems such as lavatory and hygiene, food production, waste management/recycling and emergency systems.

The NEST fabrication strategy consists of three layers, two of them 3D printed on site and one prefabricated. The external layer or exolayer, while originally based on molten regolith and silica, current information suggest sulfur concrete is the best material for the future iteration, more research is needed to understand the potential fabrication automation. The in-between layer or mesolayer, considered as silicate-glass and ice mix would be maintained as it provides shielding radiation while permitting natural light to enter the structure, however further design is needed to maintain the ice captured during the 3D printing. The internal layer or endolayer, would be further iterated as a mix of a prefabricated structure completed with locally produced 3d printing PLA elements, such as hardware parts, pipes, and closeouts. A breakdown of these items is needed to understand what is possible to produce on site or need to be fabricated on earth.

Future work will integrate these ideas into an architecture that addresses the challenges and opportunities of a Martian habitat.

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