Martian Modular Shielding Optimization Prototype

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Abstract. An ionizing radiation resistant structure is proposed to complement an inflatable habitat on the surface of Mars. The proposal is based on a modular construction system using in-situ resources (ISRU) such as regolith-based concrete and high-density polyethylene (HDPE). These materials are proposed to develop a series of modular multi-layered structural components to mitigate the radiation received by the habitat. Simultaneously, a site selection criterion and a shielding optimization algorithm are proposed as radiation mitigation measures. To test these measures, several radiobiological analyses were performed on the OLTARIS platform to evaluate the measured dosimetry inside the habitat in different configurations. The shielding modules are interconnected by snap or friction connections to facilitate the assembly and disassembly process. Overall, the combined radiation shielding measures showed a reliable performance alongside the structural results of the finite element analysis (FEA), suggesting acceptable radiation dosimetry and construction feasibility.

Keywords: Programming Cultures, Modular construction, Radiation optimization, Catenary shell, Martian habitat.

1 Introduction

Autonomous 3D printing technology presents important challenges in its current state (*MARSHA by AI SpaceFactory*, 2020), so for an extreme scenario like Mars, a more basic construction solution with a lower technological level is proposed, complementary to the use of inflatable habitats to protect them from ionizing radiation on the planet's surface. It is proposed in a scenario of intermediate colonization with industrial capacities for mass production (concrete and masonry) and plastics production, in addition to the use of construction methods with teleoperated robotic assistance (Dubbink, 2001; Dyskin et al., 2007; Handmer, 2018).

The main feature of this construction system is its modular composition and the use of plastic as the main material for the creation of structural HDPE modules filled with mass, either processed regolith or “Ferrock” extruded by robotic systems. This idea derives from the fact that Ferrock is not a suitable load-bearing construction material when combined with a Martian regolith simulant (Achey, L. et al., 2018), and is also based on radiation transport experiments using layers of HDPE and Martian Ferrock, which proved effective in mitigating ionizing radiation (She et al., 2018). Modularity could contribute to assembly and disassembly processes, maintenance and repair, and the possibility of relocating the settlement based on the possible needs of its users, without losing the shell that protects them from cosmic radiation.

2 Methodology

2.1 Location selection

The cylindrical projection map of the presence of water-ice under the surface of Mars (NASA, 2019) was used as base information, the ideal area of water-ice extraction was superimposed with areas of scientific interest proposed by various workshops in the Evolvable Mars Campaign (EMC) program, resulting in 5 sites near the ice-water area; Phlegra Dorsa, Amazonis Planitia, Acheron Fossae, Erberus Montes and Tempe Terra.

2.2 Algorithm

The JMARS platform was used to obtain 3D maps of each of these areas, which were then evaluated using a grasshopper algorithm that measured the slope at multiple points on each map.

The algorithm divides the 3D map into a regular grid mesh with multiple vertices at different heights, which are evaluated among their immediate neighbors to calculate the slopes between them. Greater levels of terrain variability would be beneficial to provide passive mitigation of ionizing radiation.

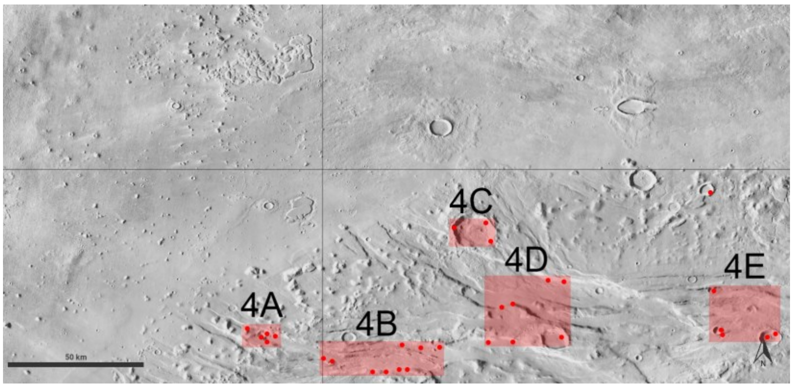

Figure 1. Satellite image of Acheron Fossae area (Site 4) overlayed with graphical representation of the grasshopper algorithm, showing areas with the greatest slope variability. Source: JMARS, 2020

Our algorithm determined that the site with the highest standard deviation corresponds to the 4D subzone in Acheron Fossae (Figure 1), however the native resolution provided by the JMARS platform is low, so an exaggeration of 50% of its geometry in the Z axis was applied. This feature is natively offered by the platform.

2.3 Basic inflatable habitat module

The chosen volume corresponds to the one used in NASA's Minimum Acceptable Net Habitable Volume (MANHV) (Whitmire et al., 2015). This volume corresponds to a cylindrical habitat with a radius of 3 meters and a length of 15 meters, providing 25 m3 of usable space for a crew of 6.

Curving the cylindrical habitat to form a torus implies additional radiological protection for the crew, since the thickness of the walls increases for the particles coming from lower angles. This is advantageous from a radiological point of view because it increases the amount of mass protecting the occupants without necessarily increasing the thickness of the walls (Slaba et al., 2013).

2.4 General shell design

The initial shell is conceived from an inverted catenary rotated from the center of the torus, forming a vault. This geometry is chosen for 2 reasons:

Structural behavior

The inverted catenary is the optimal form of an arch since vertical loads are transferred in the same direction as its shape. Applied to the case, the catenary-torus vault behaves as a highly efficient structure.

Radiological behavior

Given two 5 cm deep shell cross-sections with a set of cosmic rays placed every 15° from -30° to 210° pointing to the center of the habitat module, the sum of the thicknesses that cosmic rays traverse is greater in an inverted catenary arch cross section (93.08 cm) than in a regular circular cross section (85 cm), meaning that the former could theoretically absorb slightly more energy than its circular counterpart.

2.5 Ray evaluation

Sub zone 4D is subdivided into a grid mesh, where each grid vertex represents the surface center of the torus habitat, evaluated by a series of radial rays projected from 0° to 28° upwards, coinciding with the top of the catenary arch. We established parameters that count the number of hits of the rays with the terrain, selecting the point of the grid that has the most hits, therefore, the one that is most protected by the surrounding topography.

The intersection of the highest rays that hit the terrain with the surface of the shell draws an approximation of the surrounding terrain in the outer face of the shell, defining a safe horizon that will help define the openings.

2.6 Lateral Openings

Since the shell is composed of 64 arches, a support is proposed every 4th arch, leaving 3 arches in between supports to create an opening. The projected horizon line serves as the height limit for the openings. Therefore, it is possible to project inverted catenaries using the shell supports as anchors and the projected horizon line as an upper limit. All triangles whose geometric centers are within the area delimited by the projection of the catenary curves on the shell are eliminated. In this way, an approximation of catenary voids is built based on triangulated modules (Figure 2).

2.7 Surface Folding

We proposed that radiation mitigation could be increased by folding the shell's surface, tilting the shell's modules at lower angles in relation to the incoming particles, thus increasing the module length through which they would pass.

Folding degree

This parameter directly affects the overall mass of the structure, along with its radiation attenuation capacity. It corresponds to the distance between the original smooth shell and the furthest points of the folded surface in the same segment. Folding degrees of 1, 2 and 3 meters with respect to the original shell were evaluated. As the degree of folding increases, the angles between arches decrease, which can negatively affect the application phase of Ferrock or regolith, making it difficult for a robotic arm to reach required areas.

2.8 Radio-biological evaluation using OLTARIS

The Online Tool for the Assessment of Radiation in Space (OLTARIS) is an online platform developed by NASA to assess the effect of various radioactive space environments on humans and electronic components present in habitats, aircraft, rovers, and space suits.

This tool can simulate a cosmic radiation environment on the surface of Mars, considering the effects of its atmosphere and topography.

In this case study, a period of minimum solar activity has been chosen, which means that the intensity of cosmic rays is at its peak, without considering solar flares. An "equivalent effective dose" figure was used, which shows the radiation received by all the organs of a computerized anatomical human, adding up to the total dose received by the whole body, expressed in mSv.

Preliminary tests were carried out with cylindrical and toroidal habitats with different combinations of rays and materials. In addition, information from the Acheron Fossae 4D area was included in the tests that included terrain (Table 1).

Table 1. Dosimetry results of different shell configurations using OLTARIS.

Terrain	Rays	Surface	Materials	Straight Cylindrical (mSv/day)	Torus (mSv/day)
No	42	Smooth	5 cm HDPE	0.4065	0.4058
No	42	Smooth	5 cm HDPE + 25 cm regolith	0.3804	0.3858
No	42	Folded 1 m	5 cm HDPE	0.4045	0.4041
No	42	Folded 1 m	5 cm HDPE + 25 cm regolith	0.3750	0.3642
No	1002	Folded 1 m	5 cm HDPE + 25 cm regolith	0.3592	0.2775
Yes	1002	Folded 1 m	5 cm HDPE + 25 cm regolith	-	0.0640
Yes	1002	Folded 2 m	5 cm HDPE + 25 cm regolith	-	0.0562
Yes	1002	Folded 3 m	5 cm HDPE + 25 cm regolith	-	0.0516

2.9 Surface subdivision

Initially, a mesh subdivision is designed in Rhinoceros Grasshopper, consisting of 64 “V Count” segments and 20 “U Count” segments that constitute the initial surface mesh. The number associated with “V Count” determines the number of shell folds, while the number associated with “U Count” determines the number of segments that make up a catenary arch.

Based on structural stability reasons we decided to subdivide each face using the triangulation method instead of using faces made from 4 vertices.

Subdivision depth

The side faces are designed to guarantee a depth of 25 cm in the narrowest part of the module. With the subdivisions of the main mesh and the subdivisions of the side faces, the final mesh is obtained, which will be evaluated for its static behavior in the next step.

2.10 Finite Element Analysis FEA

The FEA was performed using the Karamba 3d plug-in for Rhinoceros Grasshopper. The points of the final mesh are defined as supports of the structure, with points regularly distributed on the inner perimeter of the shell, while on the outer perimeter they are located at the base of the supports.

The Ferrock mixture corresponds to 3423.64 Earth tons of material, which is equivalent to 1295.12 tons of mixture in Martian gravity. Combining this data with the total surface area of the shell with openings gives a distributed load of 0.45 ton/m2, which is equivalent to 4.41 kN/m2 (Figure 2).

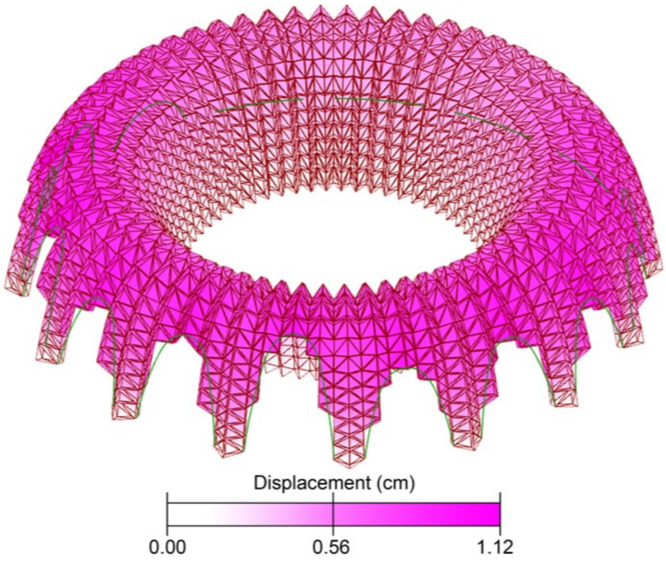

Figure 2. Total displacement of plastic structure considering Ferrock.

2.11 Joints design

The openings on the outer face of the envelope are subject to tensile stress.

We propose a combination of snap-fit and friction plastic joints that could hold the modules together; especially in the case of those modules that make up the openings and that do not have lower supports to transfer their own weight directly to the shell's supports.

Based on the foregoing, it was decided to use a combination of continuous annular-type cantilever snap-fit joints in the vertical direction of the modules, added to lateral friction joints of each module, so they could hold unsupported modules in place and restrict sliding movements between arches, respectively.

2.12 HDPE production sequence

Given the possibility of expansion, it is suggested that the ideal method of manufacturing HDPE modules corresponds to injection molding. This process becomes viable when there are more than 1000 pieces to reproduce, in this case there are 80 modules with different dimensions, so 80 different molds are needed. Figure 3 describes a general diagram of plastic parts production.

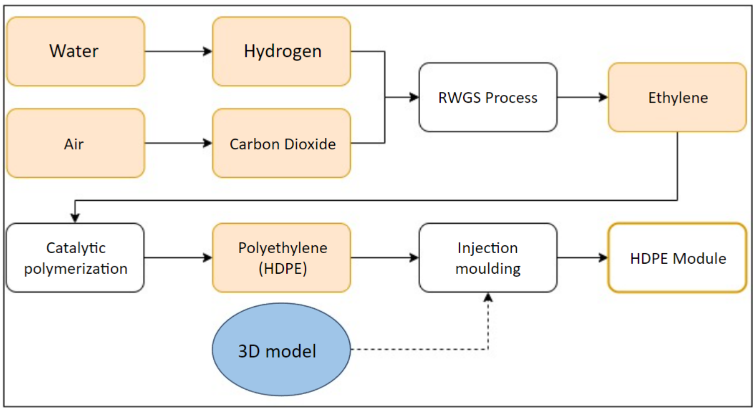

Figure 3. Production sequence of HDPE (Flynn & Rosenberg, 2005; Zubrin et al., 2011), and fabrication based on 3D data.

2.13 Construction sequence

Arch assembly

In case of not having a controlled environment for the assembly process, the arch can be assembled in a horizontal position. Since the HDPE material is highly resistant to impacts, it would not be harmful for the modules to rest on the natural ground.

The Martian equivalent to the weight of the modules does not exceed 35 kg. So, in theory two people could assemble an arch manually. However, it is recommended that the transport and handling of modules is assisted by special equipment.

Once assembled, the arch can be lifted with a crane and placed in its final position, shimming its ends with the previously excavated trenches. The successive arches must undergo the same process of horizontal assembly and final location, but they must be joined to the previous arch by means of the lateral friction joints previously indicated. This process will be repeated until the length of the available inflatable habitat section is finished.

Fill extrusion

It is recommended to use a robotic extruder arm capable of reaching the maximum height of the shell, which is possible using an ATHLETE mobile base that loads a crane with a robotic extruder arm at the end of its mast (*AI SpaceFactory - MARSHA - Our Vertical Martian Future - Part One*, 2018).

Ideally, this process should be performed by two robots simultaneously to avoid stressing the structure with unevenly distributed loads. One robot should work on the inside of the torus while another on the outside, both extruding material at the same rate from the base to the apex. This process should be repeated for each arc.

3 Results

The combination of HDPE material and Regolith were satisfactory in the experimental configurations. Based on initial studies (Achey, L. et al., 2018; She et al., 2018), it can be concluded that the application of an HDPE container of at least 5 cm thickness in conjunction with a 25 cm thick Regolith element that forms a complementary torus shell to a habitat on the surface of Mars is sufficient to provide a 37.8% reduction in radiation to the interior of the habitat.

The sub-hypothesis of shell geometry optimization based on its surface folding was verified. It was possible to conclude that the three folding degrees contributed to the additional reduction of radiation inside the habitat. In addition, our results recommend a stay of up to 53 years inside the shell before reaching the radiation dose limit, without considering additional mitigating effect of equipment and materiality of the habitat. Furthermore, the effects of passive radiation mitigation were quantitatively demonstrated through the developed terrain selection algorithm.

Based on FEA, it is possible to conclude that the general HDPE structure of the shell can resist its Martian weight and that of the additional load of Ferrock.

Additionally, the results obtained by the FEA of arches composed of mass-loaded HDPE modules suggest that the deformations and displacements produced by the modules are acceptable to be used in a real scenario on Mars.

Furthermore, the designed snap fit joints performed well under FEA. Although it is estimated that the force necessary to assemble the HDPE modules that have these joints exceeds human strength, it is not considered a major inconvenience since the installation of the shell would be carried out by teleoperated robotic work, in any case.

The design of the snap fit joints enables the possibility of disassembling defective or damaged modules due to human or environmental emergencies, and even disassembling all or part of the shell for a possible planned or emergency relocation.

4 Discussion

The conception of the Martian Modular Shielding Optimization Prototype unlocks an entirely new opportunity for sustainable and shielding habitats on Mars. The advantages of the proposed approach aligned with an efficient application of ISRU principles for a notable reduction in radiation exposure. A key finding is the promising reduction in radiation exposure enabled by HDPE and regolith shielding, which achieved 37.8% reduction during simulation, having substantial implications for long-term human habitation on Mars.

The successful application of our modular architecture delivers important advancements in the construction and assembly processes, providing flexibility and adaptability for the Martian environment. This also allows for the efficient replacement or repair of components that can extend the lifespan of the habitat. For this, it is essential to note the robustness of the HDPE structure under Martian gravity. Our simulations show that the structure can withstand the additional load of Ferrock.

Regardless of the significant findings of this study, numerous areas require further investigation. While the designed snap-fit joints performed well in the FEA experiments, further research is needed to understand how these materials and geometries would perform under the extreme conditions on Mars, including temperature variations, Martian dust, and radiation levels. In addition, integrating the habitat with other necessary life-support systems remains unexplored in this work. The promising results of this study suggest that this approach has substantial potential for the successful creation of long-term human settlements on Mars. Future research should aim to refine the design approach through prototyping, address the identified challenges, and explore its integration within the broader scope of Martian colonization missions.

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