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Design and fabrication of the Martian habitat prototype, WATER

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Abstract

This research focuses on the design of a scaled prototype for a Martian habitat on Earth.

On Mars each structure has to withstand an outward pressure that is several orders of magnitude greater than conventional structural loads due to gravity and environmental loading on Earth. Therefore, the structure will be mainly subjected to tensile stresses instead of the compression induced in Earth-bound structures under gravity loading. Consequently, this research focuses on inflatable structures as main architectural solutions for designing extraplanetary habitats.

The project arose from the vision of using trees as conceptual structures for designing shelters for humans on another planet. The tree is chosen by its ability to extract water from its roots, that is a vital resource for life, and spread it, along its branches, to the exterior leaves. On Mars water is available as ice that can be extracted from the substrate of the local regolith.

The Water shielded Architectural Tree for Extraplanetary Resiliency (WATER) project has been algorithmic-based designed in order to be analyzed and optimized from an architectural and structural point of view. The number of branches as well as their final shape are chosen by their intrinsic feature of containing a thick layer of flowing water, that helps balancing the internal pressurization load of the habitat and shielding against cosmic radiations.

The final configuration of the WATER prototype is composed by an inflatable outer membrane that is anchored to the base along its perimeter and through the internal branch structure that works in tension, as on Mars. The branches have different diameters at each iteration like a real tree. Therefore, a custom computational study was required to automatize their entire design process.

The scaled prototype has been realized using a combination of different digital fabrication techniques, such as 3D printing, Computer Numerical Controlled (CNC) drag knife and pen.

In detail, the CNC pen and CNC drag knife were used to mark and cut the inflatable membrane in clear vinyl of the outer structure. Instead, the 3D printing has been used to fabricate the custom made joints for each iteration of branches. The branches have been cut out of transparent polycarbonate tubes. The entire structure has been fixed on a plywood box and connected to an air compressor for enabling the inflation and simulate the Mars environment.

Keywords: Mars living module conceptual design, prototype, digital fabrication, structure optimization.

1. Introduction

This research focused on the development of a prototype for a Mars architecture that could host 50 people [1]. The main concept of the project arose when designing a “forest” as a future city on a Martian crater, the Elysium depression.

The forest symbolizes the potential for expansive, outwards growth across Mars and the possibility of having an interconnected habitat through different levels, above and below ground.

The settlement unit, called Redwood Forest [2], is planned to be located in a circular depression in order to nurture up to 10.000 people thanks to the presence of underground ice, below the first layer of regolith.

The main transportation network will be an underground connection system modeled after rhizomes – a subterranean element present in various plant species. Mimicking the structure of trees, the habitat will exist both above and below ground. The public spaces will be on the Mars surface, in enclosed structures which filter daylight down the root network. Within the root network, residents will have their private spaces protected from cosmic radiations, micrometeoroid impacts and extreme thermal variations. The root network will also house most of the machines that process, store and distribute vital resources for everyday life.

The habitat will place a strong focus on recycling and using in-situ resources, especially water. The plan is to use the 580.000 cubic meters of regolith dug for the initial root system to extract the 46.000 tons of water within, and have it flow through transparent membranes inside the domes, letting the sunlight through but blocking harmful radiation.

The water – life-blood of each Redwood Forest unit – will circulate through swimmable cisterns, enchanting fountains, tranquil canals, swim-through water locks, hydroponic farms and lakes within the pressurized structures. We will then process the regolith to extract other resources for manufacturing and construction.

Figure 1: Redwood Forest habitat and conceptual design for the Water shielded Architectural Tree for Extraplanetary Resiliency (WATER) module [2].

The Martian structure will be a life-supporting closed environment with an internal pressure of 6.9×10^4 to 10.3×10^4 Pa. The tree structure and its branches are defined through a form-finding optimization process, the Force Density Method, and verified with a structural Finite Element analysis that considers the internal pressurization, the reduced gravity and the weight of the radiation shielding made mainly of water as loads.

As the first step in the long journey to Mars the idea is to design a habitat that can address the needs of Martian society at various scales. Redwood Forest will support the emergence and sustenance of a strong sense of community that will be required to ensure that a long term society – not only a habitat – is created.

2. The WATER Martian habitat prototype.

In this paper, a scaled prototype of the WATER module is taken into account to investigate the design and fabrication strategies for maximizing the use of in-situ natural resources when designing a Mars exploration habitat and developing Earth-independent structural designs that use local ice/water as a possible solution for long-term extraterrestrial sustainability.

On Mars each structure has to withstand an outward pressure that is several orders of magnitude greater than conventional structural loads due to gravity and environmental loading on Earth. Under gravity loading, therefore, the structure will be mainly subjected to tensile stresses instead of compression induced in Earth-bound structures [2]. Consequently, this research focuses on inflatable structures as main architectural solutions for designing extra-planetary habitats [3] [4].

The project developed from the vision of using trees as conceptual structures for designing shelters for humans on another planet [5] [6]. The tree is chosen by its ability to extract water from its roots, that is a vital resource for life, and spread it, along its branches, to the exterior leaves. On Mars water is available as ice that can be extracted from the substrate of the local regolith.

Therefore, the final configuration of the WATER prototype is composed by an inflatable outer membrane that is anchored to the base along its perimeter and through the internal branch structure that works in tension, as on Mars.

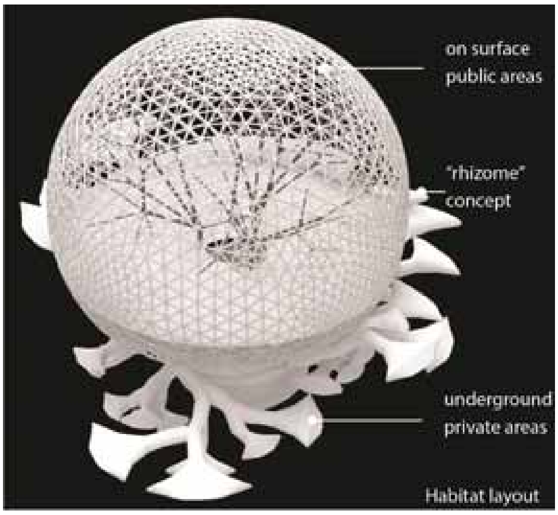

Figure 2: WATER habitation module and underground root system conceptual design.

3. Computational design

The computational design method applied to the project involved a script entirely developed in Grasshopper in order to biomimicry the tree growth. The parameters of this design approach are the branch densities for each generation. Figure 2 shows the different morphologies that are obtained varying the number of branches: the third number affects the inner generation, the second number the intermediate one while the first number relates to the outer part of the structure that is connected to the external dome. The final structure presents the following values for the three generations of branches: 96.4 – 98.9 – 99.75.

The geometry of the branches is also optimized through the Force Density Method in order to have pure tension stresses inside the tree structure. The goal is to optimize the cross sections and, therefore, reduce the use of local material to have a more efficient and sustainable architecture.

1st generation of branches

2nd generation of branches

3rd generation of branches

Figure 3: Computational design of the WATER branch structural system.

The final overall structure is consequently analyzed through a Finite Element Model in Grasshopper – Karamba considering the internal pressurization load inside the dome and the weight of the water for the radiation shielding [7]. The analysis of the deformation is reported in Figure 4 and highlights the organic shape that will allow the water to flow inside the branches and will spread all over the dome in order to protect the inhabitants from cosmic radiation (the detailed analysis of the radiation shielding is reported in Sumini *et al.* [8]).

4. Digital fabrication

The digital fabrication process for the final prototype considered two main methods: 3D printing and CNC (Computer Numerical Control) machining [9] [10].

The 3D printing was used to perform an initial mock-up of the overall geometry in a very small scale, in order to evaluate in detail the architectural characteristics and analyze all the possible fabrication issues. The final branch geometry was then simplified in linear elements in order to be divided in joints and beams while the membrane remained a dome like structure to be inflated.

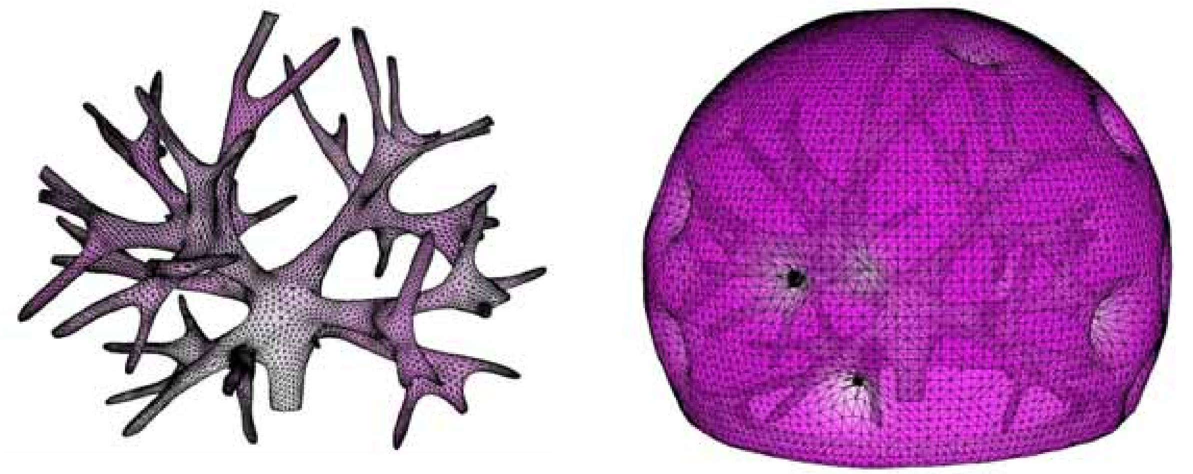

Figure 4: Final configuration of WATER pavilion.

In Figure 5, the numbering of the external joints, that connect the outer branch generation to the inflated dome, allowed to inform the membrane unfolding, performed in Rhinoceros-Grasshopper, of the position of the nodes. Therefore, using the CNC drag knife and pen, it was possible to respectively cut the membrane, according to the cutting pattern shown in Figure 6, and mark the numbers of the nodes on the vinyl. Marking the unfolded membrane played a key role in order to assemble the transparent dome in a precise and quick way.

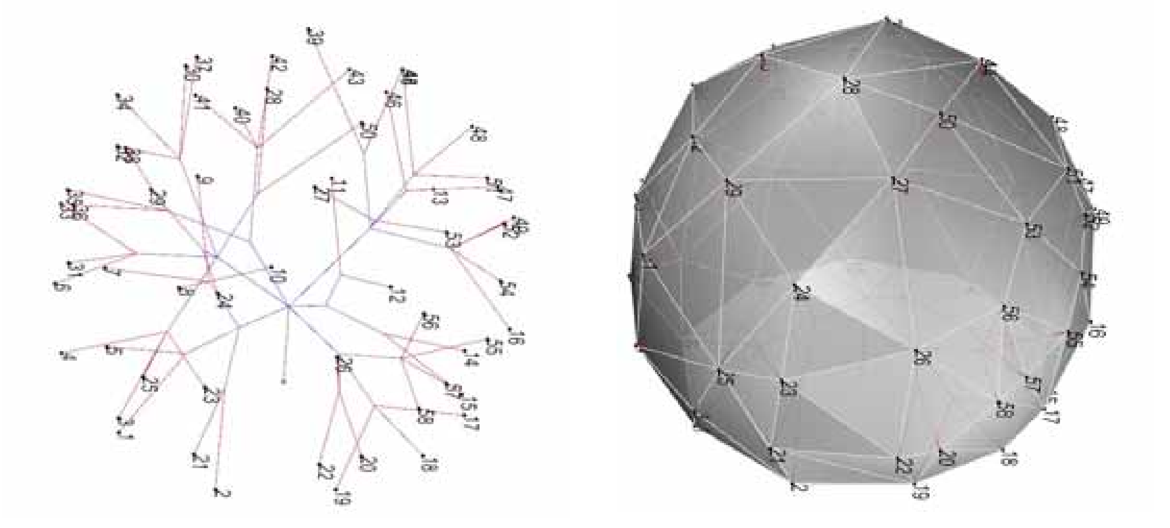

Figure 5: Beam configuration of the WATER pavilion and dome membrane.

In correspondence of each node a standard 3D printed joint is inserted through the membrane to generate the connection with the internal tree structure made of polycarbonate plastic tubes. In order to achieve the same variety of the original organic tree structure, four different tube diameters have been considered for the support beam and the three different branch generations: 2-1/4", 1-3/4", 1-1/4" and 3/4". Each tube presents also different thickness and, therefore, stiffness.

However, connecting tubes with different diameters and thicknesses led to a customized design of each joint. In order to automate the entire joints geometry an ad hoc script in Grasshopper has been implemented. The algorithm evaluates the type of tubes, and their corresponding length, that has to connect and performs Boolean operations to find the intersecting sections. Afterwards, a mesh relaxation through GeometryGym component is performed and transformed into a snap-joint. The protruding part of each joint depends on the tubes length, diameter and thickness.

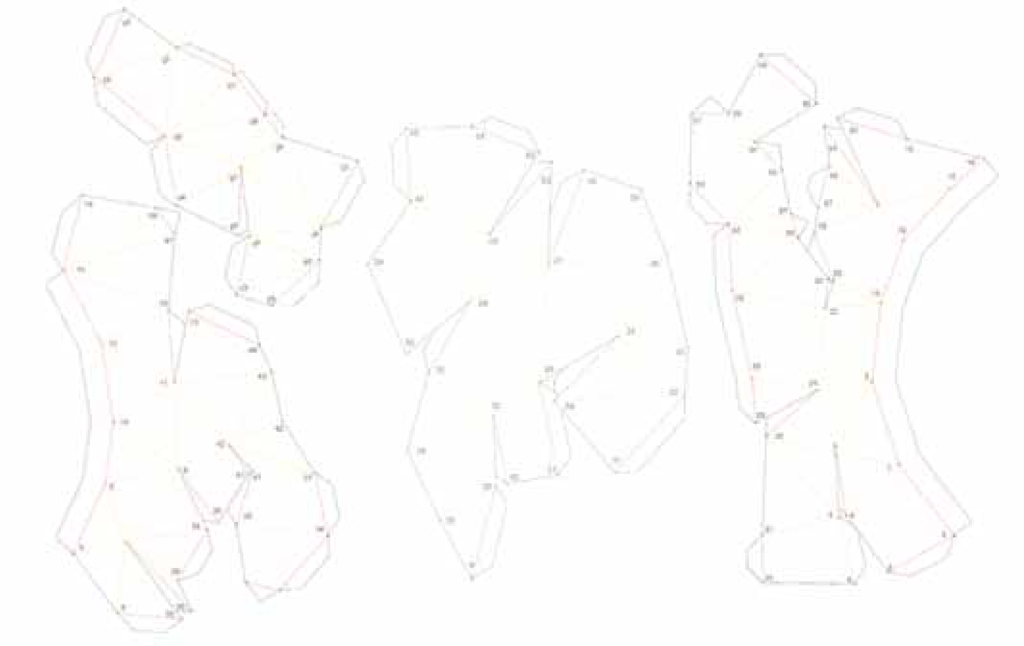

Figure 6: Dome membrane unfolding for CNC router machine.

In Figure 7, the configuration of all snap joints required to assemble the WATER pavilion is shown. This parametric design allows to adapt their geometry almost automatically at given branch generation densities. The snap joints are consequently 3D printed in PLA in order to achieve an higher elasticity than in ABS and allow some deformations during the assembly.

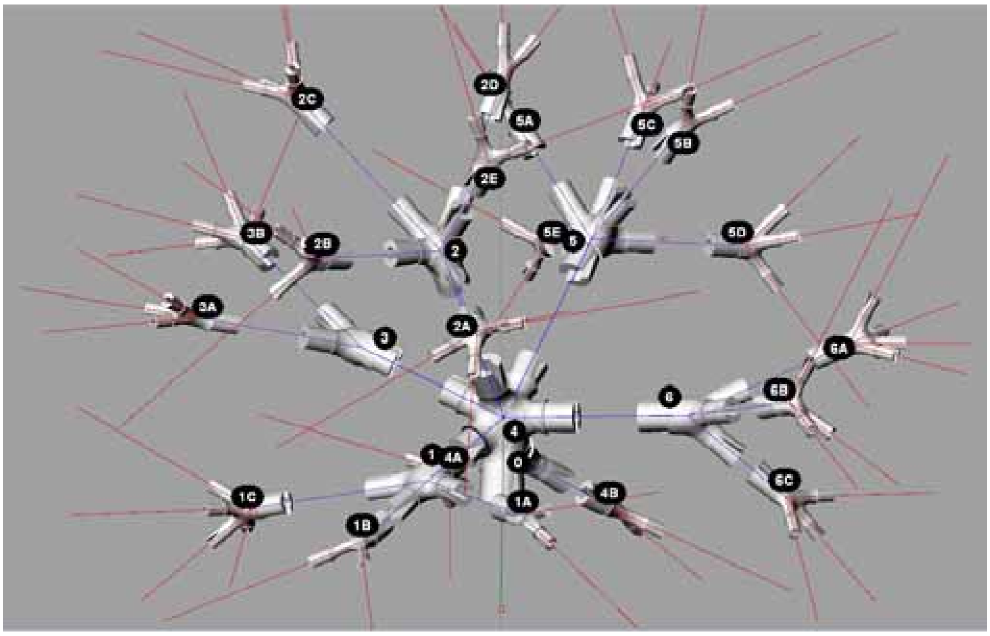

Figure 7: Parametric design of the structural joints of the WATER pavilion.

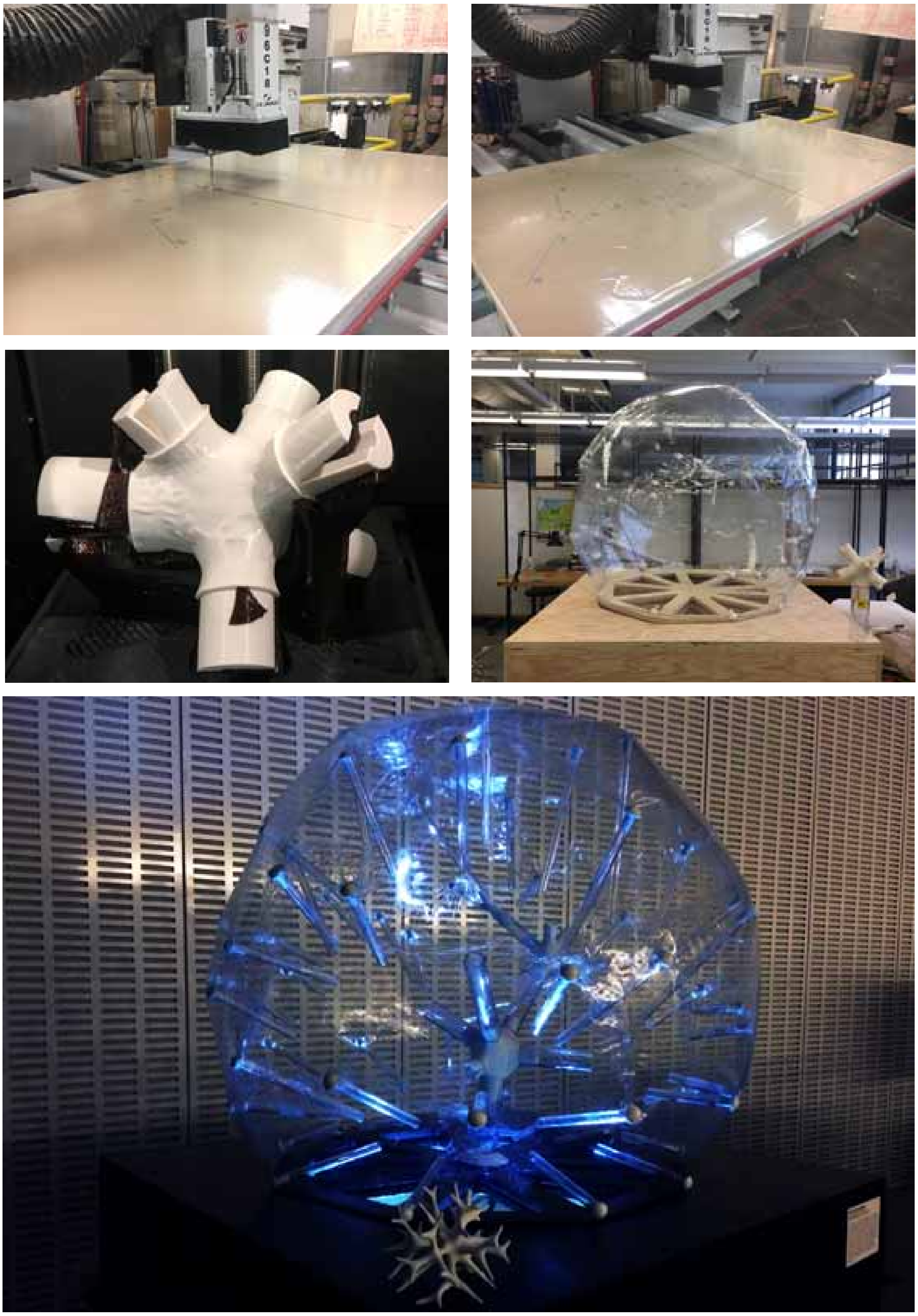

Figure 8: WATER pavilion fabrication process.

The assembly process of the WATER pavilion resulted quite quick. The entire structure has been fixed on a plywood box and connected to an air compressor for enabling the inflation and simulate the Mars environment. The most time consuming aspect of the construction is the 3D printing of the different snap joints.

5. Conclusions

The Water shielded Architectural Tree for Extraplanetary Resiliency (WATER) pavilion has been entirely algorithmic-based designed in order to be analyzed and optimized from an architectural and structural point of view. The density of branches as well as their final shape are the main parameter of the overall design. They are chosen by their intrinsic feature of containing a thick layer of flowing water, that helps balancing the internal pressurization load of the habitat and shielding against cosmic radiations.

The scaled prototype has been realized using a combination of different digital fabrication methods, such as 3D printing and Computer Numerical Controlled (CNC) machining. The CNC drag knife and pen were essential for fabricating the inflatable dome membrane while the additive manufacturing technique was used for generating the snap-joints of the internal tree structure.

This study showed how a computational design approach could lead towards an entirely automated design to fabrication process, that can be updated in real-time. Moreover, the ease in construction is one of the key elements for building in a harsh environment, such as the Martian one.

The overall algorithm could also lead to a multi-objective optimization design approach for a potential ecosystem architecture at the urban scale of Mars.

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