50th International Conference on Environmental Systems
12-15 July 2021

ICES-2021-398

Design of an Autonomously Deployable Mars Habitat

Rudolf Walther Erdem Neumerkel[1], Miruna Vecerdi[2] and Sandra Häuplik-Meusburger[3]
TU Wien, 1040, Austria

This paper presents a proposal for the design of an autonomously deployable habitat for a long-duration manned mission on Mars. Key drivers in the design were the payload and volume constraints of Starship, the heavy launch vehicle developed by SpaceX and addressing habitability challenges implied by Martian conditions. The habitat is conceived to be transported in compacted form and to expand to a habitable volume by autonomously deploying after being placed on the Martian surface. For this, the integration of several different kinetic structures is proposed: a protective casing, a vertically sliding core, radially expanding girders and an inflatable membrane. A digital parametric model was made with the Rhinoceros3D Grasshopper Plugin and used to compose and analyze the kinematic behavior of the structures. The form-finding and deployment process of the membrane was developed using the Kangaroo physics engine. The deployment choreography of the habitat is presented as the outcome of the kinematic investigation and the resulting architectural quality of the final deployed habitat is described.

Nomenclature

a = area
CAD = Computer Aided Design
g = dead load
i = index
ISRU = in situ resource utilization
ISS = International Space Station
MMOD = micrometeoroid / orbital debris
NASA = National Aeronautics and Space Administration
P = pressure
Rhino = Rhinoceros3D by Robert McNeel & Associates
t = thickness
TransHab = Transit Habitat
ρ = density

I. Introduction

THE Martian environment offers a challenging and unusual bed for the creation of a human enclosure. It is characterized by extremely low atmospheric pressure with no breathable air, low gravity, extreme temperatures, micrometeoroid and orbital debris (MMOD) impacts and permanent heavy energy radiation. These aspects have to be addressed in order to design a functional habitat to sustain a manned mission. Another major parameter governing the design of an extra-terrestrial habitat is its transportation. The planned habitat has to fit within the constraints of the available transportation vehicle. In order to make long-duration habitation on Mars possible it is important to have knowledge of heavy launch vehicle payload capabilities and integrate this in the design from the beginning.

A solution for dealing with the restricted fairing dimensions of the currently developing vehicles is making use of a deployable habitat architecture. We propose a design that, on one hand, has to fit within the fairing of the rocket and withstand launch, ascend and landing loads. On the other hand, once placed on the Martian surface, it has to autonomously expand to a habitable volume. In its deployed and final state, the habitat should provide a pressurized enclosure, thermal management and radiation protection.

---

[1] Student, TU Wien, Karlsplatz 13, 1040 Vienna, Austria, rudolf.neumerkel@gmail.com
[2] Student, TU Wien, Karlsplatz 13, 1040 Vienna, Austria, miruna.vecerdi@gmail.com
[3] Dipl.-Ing. Dr.-Ing., Senior Lecturer, TU Wien, Karlsplatz 13, 1040 Vienna, Austria, haeuplik@hb2.tuwien.ac.at

One way of achieving this would be making use of a soft good structure attached to a rigid structure, as has been proven by TransHab.[1] This concept was adapted and applied to the conceptual design of extra-terrestrial habitats for the moon and Mars[2,3], usually in combination with a 3D printed regolith shell, to make use of in situ resources (ISRU) for additional radiation protection. As an alternative to this energy an time intensive method for radiation protection, we decided using ground up regolith to fill the outer layer of the inflatable.

Our design proposes a deployable system that contains all principal necessary elements to make a habitat livable, while also being extremely compact for transportation. The compacted state of the design fits in the fairing of the Starship rocket developed by SpaceX. The Starship features an estimated payload to Mars of 100t and a fairing with a diameter of 8m and a height of up to 22m.[4] Two stacked compacted habitats would fit within the cylindrical part of the described volume, while the remaining space can be filled with the additional necessary fixtures that will be required for habitation, such as technical equipment, flooring, interior outfitting, etc.

II. Design Method

This paper focuses on the development of an integrated deployment mechanism that fulfils transportation constraints as well as addressing the habitability issues imposed by the Martian environment. For this, several different elements were integrated: a protective casing(1), a telescopic core structure(2), radially expanding girders(3) and an inflatable membrane(4). The configuration of the proposed systems is shown in Figure 1. Each system plays a role during deployment and also fulfils a function that is required for habitation in its deployed state. Each element, as well as their interconnectivity are described below.

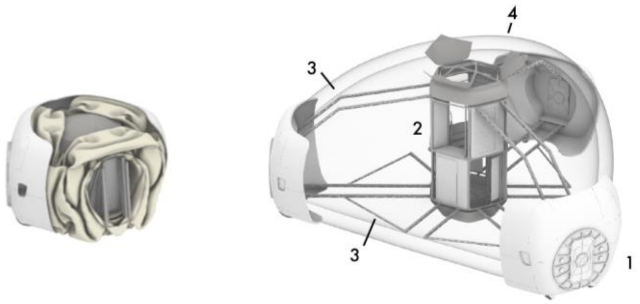


Figure 1. Model overview in compacted state (left) and in deployed state (right).
1. Casing part, 2. Core with technical units and cupola structure, 3. Girders, 4. Membrane

A. Casing

A protective rigid shell encloses and contains the compacted elements of the habitat. It is divided into 3 identical parts that are interlocked during transportation. This division is inspired by the triangular configuration described by Bannova in Ref. 4. It enables a compact footprint and possible egress loops.[5] Moreover, the expansion into a larger base can be achieved either with a triangular or hexagonal tiling of the habitats on the Martian surface. Each casing part has a docking interface that will allow for egress and ingress in deployed state, providing a connection to other modules via additional airlocks. This will enable the habitat to be part of a larger system of different modules (such as green houses, different dockings for surface vehicles, suit ports and other technical modules).

The casing should withstand launch and landing loads and protect the inner elements from dust and debris when placed on the Martian surface. Ski pads mounted on the bottom of the casing parts will reduce the friction area with the surface and ease the outward movement during deployment. Each casing element has two 1m deep windows on the sides. These elements are significant to maintain the psychological wellbeing of the inhabitants allowing them to have a view of the Martian landscape and also to let some natural light in.

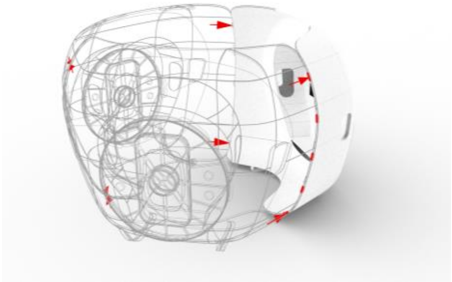


Figure 2. Casing. *It is divided into 3 identical parts, each containing a hatch for ingress/egress. During transportation and until placement at the final location these parts are connected and interlocked (markings in red) forming a protective shell*

Integrating openings such as windows in the rigid structure of the habitat would be a simpler solution in comparison to interrupting the weaving structure of the enclosing membrane.[6,7]

B. Telescopic core

The core is the primary rigid structure of the habitat. The bottom has a hexagonal base with rounded corners that will carry the waste and water management equipment and is foreseen with pads on the bottom face to allow it to be placed on the ground. As extrusions of the hexagonal base outline, two metal frames contained within one another form the telescopic structure. The outer frame is attached to the base and the inner frame slides vertically allowing the core to double in height (Figure 3). A structure similar to the cupola module on the ISS is mounted on top of the inner frame. It contains a water tank. This structure will act as a translucent window, allowing for natural lightning from above. Even though this element will be translucent, it will still ensure radiation protection due to the mass of water present in the water tank, since hydrogen rich materials are known to be well suited for this.[8] The technical units, such as sanitary fittings and small hydroponic greenhouse modules are attached in between the frames. The core has a hollow atrium space at its center that allows the habitants to pass through. In its deployed state, the core will act as the central part of the habitat and also as a circulation distributor horizontally as well as vertically. These aspects are presented in more detail below in II.E and IV.

Figure 3. Telescopic core in compacted and deployed state

C. Expanding girders

Radially oriented foldable girders connect the core to the casing elements. In the stowed state the girders are completely folded together, minimizing their volume. They have extending parts that can retract within the beams to keep in line with the dimensions of the core while in compacted state. They initiate the deployment of the habitat by unfolding and pushing the casing elements radially outward with the use of torsional and compressive springs. In this way, a controlled movement of the deployment process can be achieved. In their deployed state they extend to their full length to achieve the necessary floor area. The bottom girders create a grid onto which the floor plates can be mounted. The upper girders provide a rigid structure throughout the upper membrane surface that can be used for cable suspensions for second level flooring and other fixtures.

Figure 4. Extending girders in compacted and deployed state. *The extended parts are marked in red. More on the necessity of these parts can be found in section E.*

D. Inflatable membrane

Inflatables have been proven advantageous for space habitation: They can be stowed in an efficient manner for shipment, are suitable for creating a pressurized environment and can integrate several different functions by the use of respective separate layers[9]. Furthermore, they can be attached to rigid structures forming a hybrid system.[10,11] In this way advantages of both types of systems can be combined.

However, not any arbitrary shape can be selected for inflatable structures - certain geometric and physical constraints, such as the necessity of single or double curvature, have to be met. Hard edges or planar surfaces cannot be achieved by inflated shapes without the use of additional structural elements.[12] In order to develop a valid inflatable geometry the physics engine Kangaroo was used. By simulating the membrane behavior in this way, the formation of wrinkles in the fully pressurized state can be prevented and an optimal shape for given boundary conditions can be found.

Figure 5. Membrane section in folded and inflated state.

Apart from containing the overpressure of 1 bar and the resulting high stresses, the membrane also has to fulfil several other functions including: sufficient radiation protection, puncture and flammability resistance, MMOD impact and dust protection. Similar to the construction method developed by NASA with the TransHab project[7], the habitats multi-layered membrane is divided into 3 different layer groups, with each group attached separately and fulfilling different functions. The material configuration of these layers and the connection to the rigid structure are adapted from TransHab[13–15] and are proposed as follows:

1. The interior layer has an interior finish made of Nomex, as a puncture and flame-resistant layer, followed by redundant air bladders made of CepacHD200, which are separated by Kevlar felt layers. This ensures air tightness and thermal insulation. This layer is not supposed to take any loads and therefore, its surface area will be slightly larger than the structural layer.[9]
2. The middle part is the restraint layer consisting of woven Kevlar belts that takes the pressure loads.
3. Additionally, on the outside a dust protection and a fillable chamber layer is provided, with the latter one being able to be filled with ground up loose regolith to a thickness of up to 100cm to provide radiation and MMOD protection.

The resulting mass of the filled regolith would easily be held up by the internal pressure of 1 bar, as the latter would be much larger than the resulting dead load pressure of the regolith with a maximum at the horizontal areas of the membrane of up to around 0.07 bar, as shown in (1). Typical Martian regolith density lies at 1300kg/m3. However, due to different grain configurations this number can vary, as the void ratio changes. A higher bulk density can be achieved by applying external load and or subjecting the regolith to vibration. Densities of 1910kg/m3 can be achieved in this way, further improving radiation protection and resulting in a shielding thickness of 191g/cm2.[16]

$$P_{regolith} = \rho_{bulk,max} * t_{regolith} * a_{Mars} = 1910\,{}^{kg}\!/_{m^3} * 1m * 3.721\,{}^{m}\!/_{s^2} = 7107.11\,Pa$$

$$P_{atmosphere} = 651.8\,Pa$$

$$P_{deadweight,membrane} = g_{membrane} * a_{Mars} = 2.95\,{}^{kg}\!/_{m^2} * 3.721\,{}^{m}\!/_{s^2} = 10.98\,Pa$$

$$\sum P_i = 7769.1\,Pa$$

$$P_{internal} = 100000\,Pa \tag{1}$$

Atmospheric and dead weight pressure are only 7.8% of the internal pressure as can be seen from calculations showcased above (1). Thus, the regolith layer can easily be supported and its thickness even be increased if needed.

A detailed interface of the connection of the membrane with the rigid structure of the telescopic core can be seen in Figure 6.

Figure 6. Model overview from the outside with detail position marked in red (left). Connection detail of the membrane with the upper core structure (right). *This is an abstracted example showcasing a possible construction approach. The other connection points can be adaptations of the one showcased above. 1. interior layer with air bladders separated by Kevlar felt layers and interior finish; 2. restraint layer made up of Kevlar belts; 3. outer layer made up of chambers filled with regolith.*

E. Design Workflow

In this project all constraints and system components are closely related to one another. Therefore, the habitat had to be designed and analyzed in both stowed and deployed states simultaneously. A CAD model using the Rhinoceros3D Grasshopper Plugin was made from the beginning of the design process.

The cargo volume and human factors posed input variables from which the core with its sanitary fittings and functional units, as well as the coarse casing element geometries were created. The hexagonal base of the core is offset inwards to create the necessary space for the sanitary fitting units. Their inside volume allows for a minimum movement diameter of 90 cm for the inhabitants.[17] The resulting inner atrium space of the core allows for three inhabitants to simultaneously pass through.

The system height is based on a study[18] on ergonomics for Mars that takes the Martian gravity into consideration. As suggested in this study the door height is set at 2.3m. From this a floor height of 2.75m with a respective 5.5m total height for the core is determined. The floor area and perimeter were determined by having a minimum distance of at least 3m from the core structure to the outer boundary. This way it is ensured that crew quarters with the minimum necessary depth of 2.15m and a passing way of 0.8m, as described in Ref. 6, can be installed. With the previously described boundary conditions set, an approximate geometry of the membrane was modeled as a base for the inflation simulation. This approach is similar to the one in Ref 17. Due to the 6-axis symmetry of the design only a sixth of the membrane was taken for the inflation simulation to reduce simulation time. This allowed for faster design iterations. Boundary conditions for the inflation were anchors at the openings in the membrane (Figure 7) and having no bending stiffness for the simulated geometry in order for it to behave as a textile. The final inflated part was then mirrored along the 6 symmetry axes to obtain the full geometry of the inflated membrane.

The final inflated geometry of the membrane determines the actual dimensions of the floor and walkable area within the habitat. The full length of the expanding girders is based on the outline of the resulting floor. The lower girders connect the base of the core with the casing parts. The upper girders connect the base of the cupola structure with the upper part of the casing and follow the curvature of the membrane. To make the girders fit in their folded state within the casing, the difference in length between the casing height and half of the girder length is determined for the expanding parts. These parts are contained within the girders in compacted state and slide axially outwards during deployment until full length is achieved. In compacted state, the membrane should be contained within the casing and should fold to fit between the folded girders and the casing inner boundary. All of the systems are modeled dependent of one another, thus enabling the simulation of their simultaneous movement. First the movement of each system was studied individually and adapted until the desired control could be achieved. After this, an overarching parameter from 0 (stowed configuration) to 1 (deployed configuration) was set to control the movement of all elements. In this way the stowed, interim and deployed states of the system could be evaluated and adapted. The integrated simulation of all elements was iterated until the desired compacted state was achieved without collision between the elements. The deployment steps and their key visualizations can be seen in Chapter III.

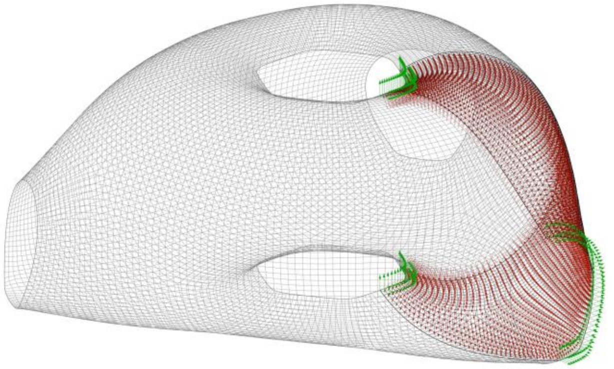


Figure 7. Simulation of the inflation. *Due to the 6-axis symmetry of the design only a sixth of the membrane (marked in red) was simulated to reduce simulation time. Boundary conditions for the inflation were anchors at the openings in the membrane topology: the connection to the casing as well as the upper and lower boundary of the core (marked in green). The movement of the naked vertices along the naked edges of the membrane part was limited to the respective symmetry plane.*

III. Arrival and Deployment Choreography

The compact design of our habitat enables the transportation of two units within the cargo space of the Starship. They can be transported in stacked configuration, one being mounted on the payload adapter, while the other can be mounted with support on the sidewalls and nose.[4] Transporting two units would allow for the necessary redundancy, while also letting additional cargo space available in the nose of the fairing. This space can be used for the transportation of other necessary fixtures, such as technical equipment, floor plates, partition walls, furniture etc. (Figure 8). Table 1 showcases a listing of components, with an estimative massing of the principal elements of the habitat. The volume of each part is calculated from the digital model. The mass is estimated by multiplying the volume with the density of the material chosen for each part. The total weight of the habitat lies at approx. 28t. This fulfills the cargo space restrictions of 100t of Starship and enables the transportation of two units.

Two habitat units are conceived for a long stay mission of 2 years and should fit 4-6 crew members. We assume that multiple robotic missions were carried out before enabling manned ones.[20] During these missions, the necessary infrastructure would have already been installed to make a manned mission possible at the point of crew arrival. The habitat could be transported during one of these robotic missions at a point where the required infrastructure to unload, carry and place the habitat at its final location would be present on the Martian surface.

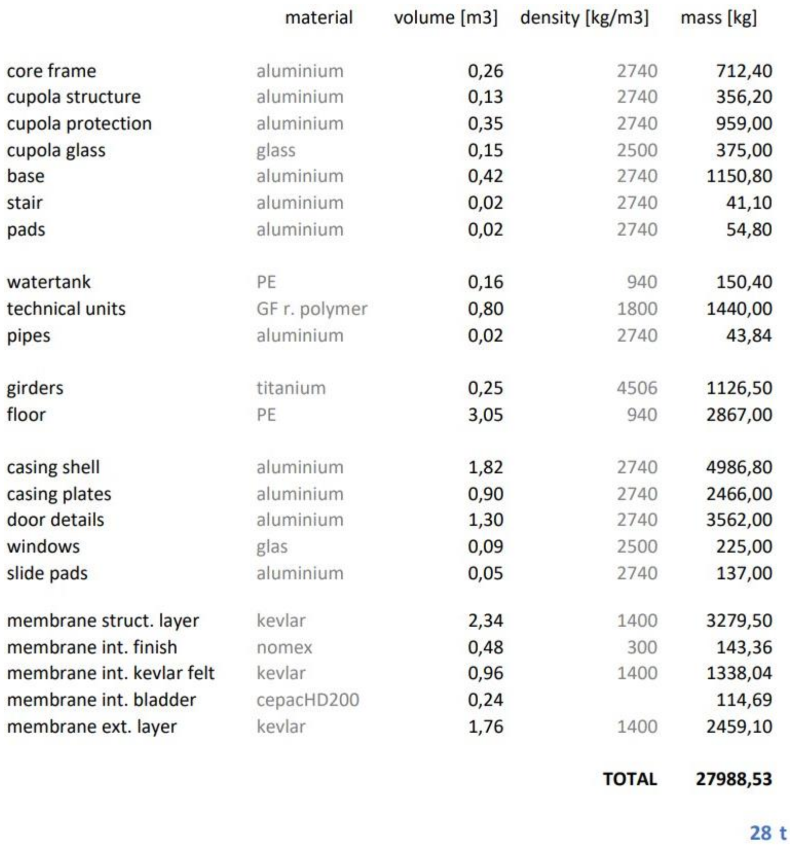
The habitat will be transported in its compacted form and placed at the selected location (Figure 9). The 3 casing elements unlock and the deployment sequence is initiated. The compressive springs of the girders are released pushing the casing elements radially outwards. The membrane starts to inflate (Figure 10). The pressure that builds up further pushes the casing parts outwards and initiates the vertical sliding of the interior core frame (Figure 11). This process continues until the maximum pressure of 1 bar is reached and the core frame has doubled in height. (Figure 12).

To ensure radiation protection and MMOD shielding, our design uses ground up regolith to fill the outer layer of the membrane, in the final deployed state. We assume that unmanned robotic missions would have already set up the necessary infrastructure for a human mission. At the point of the arrival of the habitat, the necessary regolith would have been gathered and prepared at the site location. The filling process will begin when the habitat is fully deployed and will be done robotically (Figure 13). This would allow for a more simple and fast protection method compared to the rather time consuming and very energy intensive method of 3D sintering a regolith shell. However, this strategy can be considered additionally to the mentioned method in the event of an even longer stay mission. With the regolith shielding completed the crew can enter the habitat (Figure 14). They will install the additional necessary interior fixtures such as technical equipment, flooring, crew quarters etc. (Figure 15).

The design has in its compacted state a bounding volume of approx. 180m^3 that can expand to a habitable pressurized volume of 921m^3. This results in an expandability factor of approx. 5.

Figure 8. Starship cargo space with two stacked habitats in compacted state. *The remaining space (marked in blue) can be used to transport the remaining necessary fixtures.*

Table 1. Listing of components. *An estimation of the total mass of the habitat, showcasing the principal elements and materiality.*



	material	volume [m3]	density [kg/m3]	mass [kg]
core frame	aluminium	0,26	2740	712,40
cupola structure	aluminium	0,13	2740	356,20
cupola protection	aluminium	0,35	2740	959,00
cupola glass	glass	0,15	2500	375,00
base	aluminium	0,42	2740	1150,80
stair	aluminium	0,02	2740	41,10
pads	aluminium	0,02	2740	54,80
watertank	PE	0,16	940	150,40
technical units	GF r. polymer	0,80	1800	1440,00
pipes	aluminium	0,02	2740	43,84
girders	titanium	0,25	4506	1126,50
floor	PE	3,05	940	2867,00
casing shell	aluminium	1,82	2740	4986,80
casing plates	aluminium	0,90	2740	2466,00
door details	aluminium	1,30	2740	3562,00
windows	glas	0,09	2500	225,00
slide pads	aluminium	0,05	2740	137,00
membrane struct. layer	kevlar	2,34	1400	3279,50
membrane int. finish	nomex	0,48	300	143,36
membrane int. kevlar felt	kevlar	0,96	1400	1338,04
membrane int. bladder	cepacHD200	0,24		114,69
membrane ext. layer	kevlar	1,76	1400	2459,10
			TOTAL	**27988,53**
				28 t

Figure 9. Section of habitat placed at location

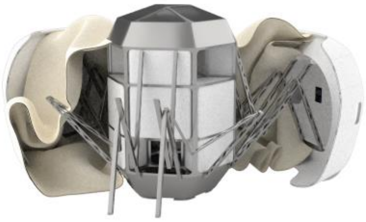


Figure 10. Section of habitat at the beginning of the deployment sequence

Figure 11. Section of habitat during deployment process

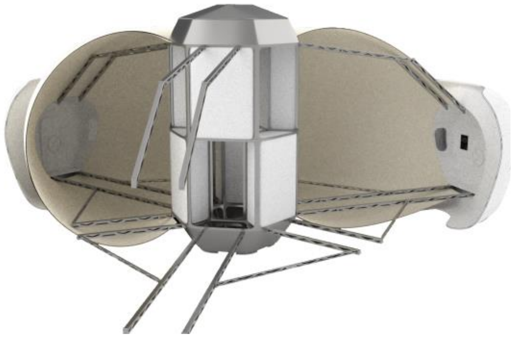


Figure 12. Section of habitat in equilibrium and final state

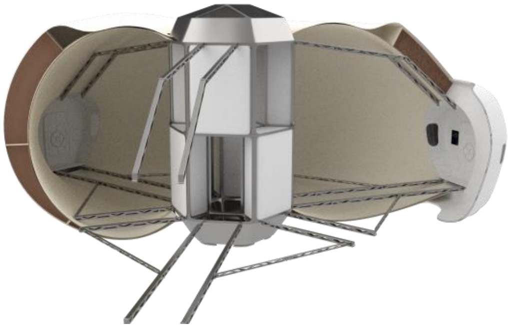


Figure 13. Section of the habitat while regolith is being filled into the outer membrane chambers

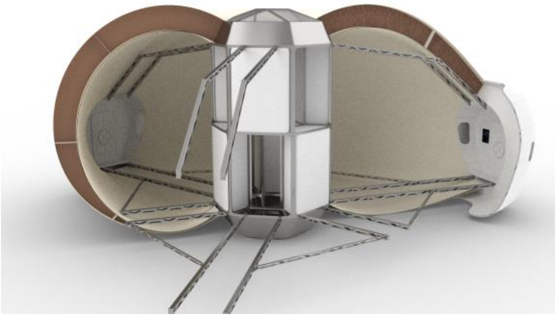


Figure 14. Section of habitat with filled regolith. *Pressurized Volume = 921m*^{3}

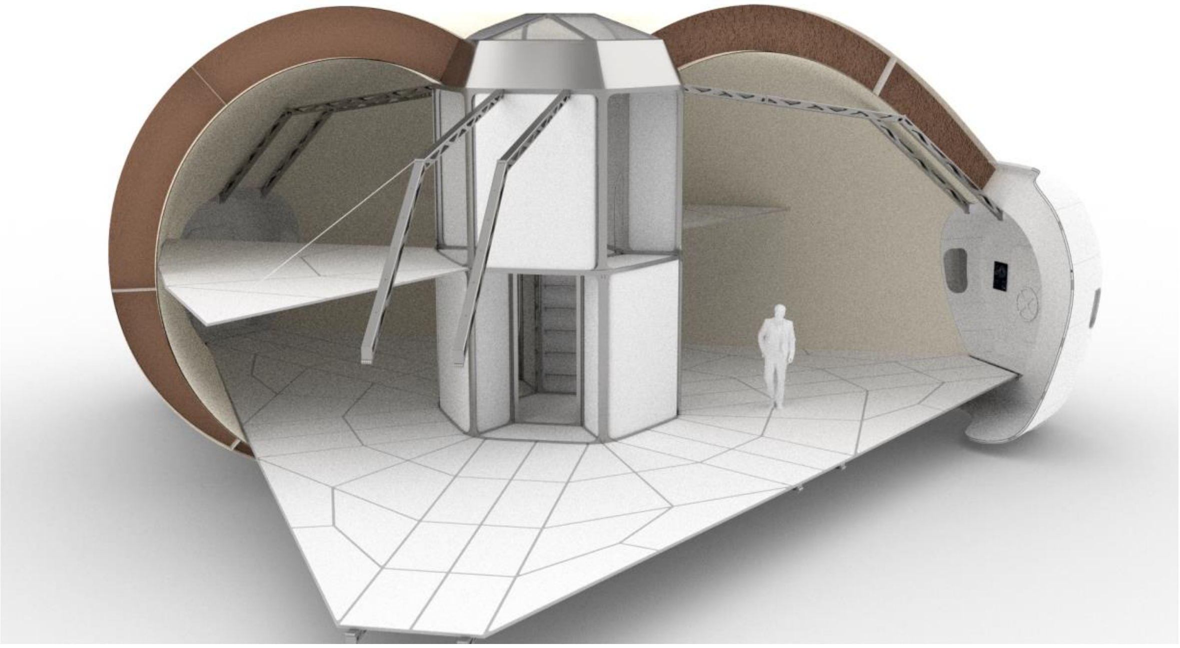


Figure 15. Section of habitat with additional fixtures. *After the regolith is filled in the outer membrane chambers the crew can enter the habitat. They will install the necessary technical equipment and aditionar interior fixtures*.

IV. Architectural Quality and Benefits to the Life on Mars

Living on Mars comes with great challenges: no breathable air, no atmospheric pressure, permanent heavy radiation and extreme temperatures. A habitat should not only address these given issues, but also provide a comfortable and safe environment for the crew.

Enclosing the habitat with a continuous membrane allows for MMOD and radiation protection and enables the creation the necessary pressurized environment. Necessary technical equipment such as power cables and pipes can be installed under the lower girders. Flooring plates and partitioning walls can be mounted onto the girders. Due to the symmetrical geometry of the habitat, the layout of the compartments is reconfigurable. One habitat is laid out for a 4-person crew, with the possibility of housing up to 6 crew members in case of damage to one of the two habitat units. The floor area provides the necessary space for 4 crew quarters and additional space for recreational and social activities. The ceilings of the crew quarters can be used as flooring to a second level, that could be used as a work space.

The core acts a circulation distributor horizontally and vertically. It contains the sanitary units, such as a shower cabin, a toilet, and a small kitchen unit within the lower part (Figure 17). The upper frames hold the hydroponic greenhouses for the necessary food production (Figure 18). The central atrium allows the inhabitants to pass through the center of the enclosure and use the sanitary fittings without the need of passing through a compartment. This space will be naturally lit during the day. The core also has incorporated stairs, that would allow the crew to move also vertically, making use of the full height of the habitat.

The floorplan can thus be divided into two zones. A more generous space for social interaction, medical interventions etc. could be facing the kitchen unit. The other half of the space can be used for crew quarters, resulting in a more intimate quiet area (Figure 16).

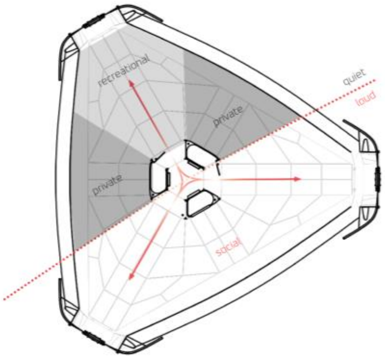


Figure 16. Floor plan diagram.

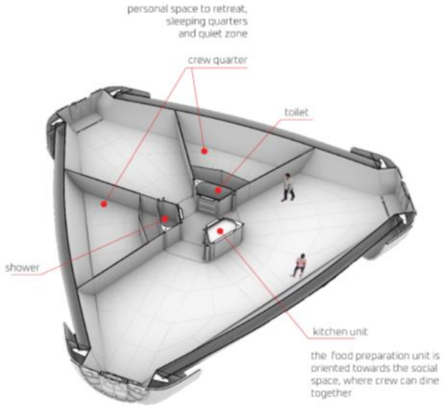


Figure 17. Floor plan – level 1

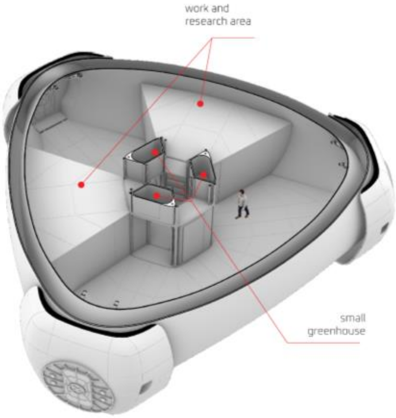


Figure 18. Floor plan – level 2

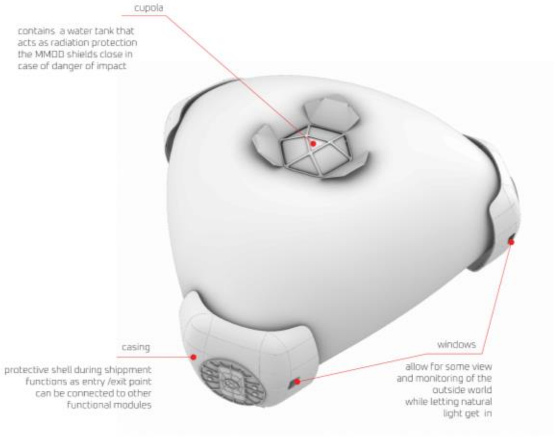


Figure 19. Overview

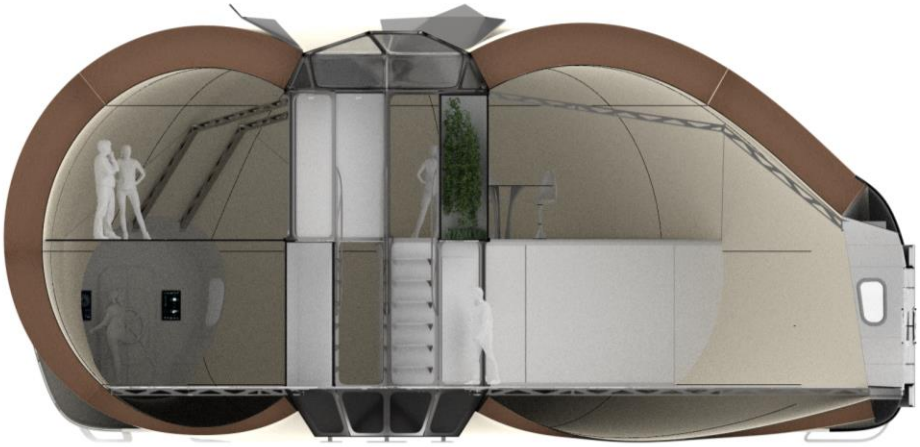


Figure 20. Section showing a possible internal outfitting of the habitat.

Figure 21. Interior Rendering – View from atrium towards the cupola

V. Conclusion

There is no question that planning a habitat for Mars is a tremendous challenge and requires extensive interdisciplinary knowledge. The main design parameters were the transportation constraints imposed by Starship and the necessary habitable volume for a longer stay mission. We propose a design that is compact for transportation and that can expand to a habitable volume once placed on the Martian surface. For this, a deployable structure consisting of a protective casing, a telescopic core, expanding girders and an inflatable membrane was designed. These elements actuate the deployment process and ensure habitability. A CAD model using Rhino and Grasshopper was made from the beginning of the design process in order to ensure that the previous mentioned design parameters are met. The kinematics of the deployment mechanisms was simulated using the Kangaroo physics engine. In this way, collisions could be avoided and the integrated movement of all elements could be controlled.

We believe that the deployment process should be further investigated and refined. This includes the initial stowed configuration, where more accurate transportation loads have to be taken into account, in order for all deployment actuators to be intact and ready for deployment on landing. Furthermore, the choreography of the deployment actuation should be simulated and tested in further detail.

Furthermore, our design also addresses the challenges that are implied by the Martian environment: no breathable air, extreme temperatures, MMOD impacts and permanent heavy radiation. The habitat ensures a protective environment for the crew, offering radiation and MMOD shielding, while also ensuring a breathable and pressurized atmosphere. The symmetrical geometry ensures a flexible layouting and a modular configuration of the necessary

Figure 22. Habitats on the Martian ground.

functions, such as crew quarters, dining, work spaces etc. Natural light is provided by the cupola similar structure containing the water tank at the top of the central core. Windows are placed on the sides of the egress/ingress areas to allow the view of the surrounding Martian environment. These elements are important for the psychological wellbeing of the crew.

With this project, we propose a habitat design, that can be deployed and ready to be inhabited in a relatively short time. This is based on integrated deployment mechanisms and lower risk approaches for ISRU. Furthermore, the reconfigurable and modular design of the habitat allows it to be adapted to specific use cases and also to expand to a larger system of units.

Acknowledgments

The authors would like to thank Jun.-Prof.Dr.-Ing Maria Matheou and Dr.-Ing. Walter Haase from the Institute for Lightweight Structures and Conceptual Design (ILEK) at the University of Stuttgart for assisting with the development of the project and providing expertise on the kinetic systems.

Special thanks are in order to Dr. Gernot Groemer, David Nixon, Gerhard Schwehm and Dr. Advenit Makaya, next to the other guests of the design studio ‘Mars Science City’ at the TU Vienna[21], who so wholeheartedly have shared their knowledge and time with us.

The authors would also like to thank Daniel Piker, the developer of the Kangaroo Physics engine, who provided insight regarding the membrane inflation and folding simulation.

References

[1] Kennedy, K. J. & Adams, C. M. International Space Station (ISS) TransHab: An Inflatable Habitat (2000).

[2] Adams, C. M. & Petrov, G. The Surface Endoskeletal Inflatable Module (SEIM). In *Earth & Space 2006,* edited by R. B. Malla, W. K. Binienda & A. K. Maji (American Society of Civil Engineers, Reston, VA, 2006), pp. 1–8.

[3] Hinkle, J. *et al.* Design Development and Testing for an Expandable Lunar Habitat. In *AIAA SPACE 2008 Conference & Exposition* (American Institute of Aeronautics and Astronautics, Reston, Virigina, 2008).

[4] Starship Users Guide. STARSHIP PAYLOAD GUIDE (2020).

[5] Bannova, O. Design Considerations for Exterior and Interior Configurations of Surface Habitat Modules. *Journal of the British Interplanetary Society* **60,** 331–338.

[6] Inocente, D. *et al.* Master Planning and Space Architecture for a Moon Village. In *70th International Astronautical Congress (IAC)* (2019).

[7] Seedhouse, E. *Bigelow Aerospace* (Springer International Publishing, Cham, 2015).

[8] NASA. Space Faring: The Radiation Challenge. Module 3: Radiation Countermeasures (2008).

[9] Valle, G. D., Zipay, J. J., Litteken, D., Christiansen, E. L. & Jones, T. C. System Integration Comparison Between Inflatable and Metallic Spacecraft Structures. In *2019 IEEE Aerospace Conference* (IEEE32019), pp. 1–14.

[10] Haeuplik-Meusburger, S. & Ozdemir, K. Deployable Lunar Habitation Design. In *Moon. Prospective Energy and Material Resources,* edited by V. Badescu (Springer Berlin Heidelberg, Berlin, Heidelberg, 2012), pp. 469–502.

[11] Häuplik-Meusburger, S. *et al.* Deployable and portable emergency shelter for mars (2013).

[12] Wagner, R. *Bauen mit Seilen und Membranen.* 1st ed. (Beuth Verlag GmbH, Berlin, Wien, Zürich, 2016).

[13] Valle, G. D., Litteken, D. & Jones, T. C. Review of Habitable Softgoods Inflatable Design, Analysis, Testing, and Potential Space Applications. In *AIAA Scitech 2019 Forum* (American Institute of Aeronautics and Astronautics, Reston, Virginia, 2019).

[14] Badhwar, G. D., Huff, H., Wilkins, R. & Thibeault, S. Comparison of graphite, aluminum, and TransHab shielding material characteristics in a high-energy neutron field. *Radiation Measurements* **35,** 545–549; 10.1016/S1350-4487(01)00271-2 (2002).

[15] Valle, G., Edgecombe, J. & La Fuente, H. de. Damage Tolerance Testing of a NASA TransHab Derivative Woven Inflatable Module. In *50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* (American Institute of Aeronautics and Astronautics, Reston, Virigina, 05042009).

[16] Morgan, P. *et al.* A Pre-Landing Assessment of Regolith Properties at the InSight Landing Site. *Space Sci Rev* **214**; 10.1007/s11214-018-0537-y (2018).

[17] Häuplik-Meusburger, S. & Bannova, O. *Space Architecture Education for Engineers and Architects* (Springer International Publishing, Cham, 2016).

[18] Flores, J. & Sasangohar, F. Human Factors Review of Space Habitat Feature Requirements. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* **61,** 62; 10.1177/1541931213601481 (2017).

[19] Petrov, G., Park, K. S. & Adams, C. Optimization of Inflatable Spacecraft Interior Volume Using Constraints Driven Design. In *40th International Conference on Environmental Systems* (American Institute of Aeronautics and Astronautics, Reston, Virigina, 2010).

[20] Hoffman, S. J. & Kaplan, D. I. *Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team* (1997).

[21] Haeuplik-Meusburger, S. *Mars Science City* (TU Wien, Wien, 2020).