September 25th - 28th, 2017
INTERFACES
architecture . engineering . science IASS 2017 hamburg

Proceedings of the IASS Annual Symposium 2017
"Interfaces: architecture . engineering . science"
September 25 - 28th, 2017, Hamburg, Germany
Annette Bögle, Manfred Grohmann (eds.)

Form finding of deep exploration surface habitats

Valentina SUMINI*, Caitlin T. MUELLER[a],

*Massachusetts Institute of Technology
Department of Civil and Environmental Engineering
77 Massachusetts Ave, 02139 Cambridge, MA, United States
vsumini@mit.edu

[a] Massachusetts Institute of Technology
Department of Civil and Environmental Engineering
77 Massachusetts Ave, 02139 Cambridge, MA, United States
vsumini@mit.edu

Abstract

This research aims to explore form finding strategies for deep space exploration habitats on extraplanetary surfaces such as the Moon and Mars. In this paper, a new sphere packing form finding approach has been studied, trying to optimize the location of different system and subsystems inside a space habitat and respond to the high pressure differentials required in these environments. Typically the organization of the interior layout follows the functional needs of the crew, such as working, hygiene, preparing and eating food, etc. To respond to relationships between such functional areas, including sizing, adjacencies, and approximate shapes, architects traditionally have used bubble diagrams and adjacency matrices as design aids. The research presented here combines and digitizes these approaches with a sphere packing algorithm powered by dynamic relaxation, which allocates all required activities and respects all analyzed linkages between functions and subsystems. Furthermore, the obtained functional diagram is readily translated in architecture through a transformation into a tension-only pressurized surface using form-finding tools. The resulting habitat design is evaluated, in terms of its structural performance, through FE analysis tools. In summary, this paper presents a new computational design method for space surface habitats that responds to both functional and physical requirements, offering new ways to support future space exploration.

Keywords: Space architecture, sphere packing, dynamic relaxation, form finding, Finite Element analysis

1. Introduction

A renewed interest in space exploration, mainly proved by the recent funding that NASA received for sending human to Mars by 2030, led to new challenges in architecture and structural engineering. Space architecture is deeply interdisciplinary and connects different fields of research such as aerospace engineering, architecture, design, space science, medicine, psychology and art. It combine together the accuracy of technical systems, human needs for working and living, the interface design for the relationship between humans, and the built and natural environment. In addition to traditional knowledge of planning and building processes, special knowledge is needed regarding how to design for humans in extreme environment and how to do so creatively, narrowing down to every specific detail of the construction system.

Unlike structural engineering for the built environment on Earth, there are virtually zero rules of thumb or design precedents to draw on for construction on Mars and on the Moon. There is exciting potential to shape this discussion with fundamental structural engineering principles and forward-looking material and fabrication strategies.

The basic requirements of future space habitat structures are defined by their ability to protect their occupants and provide usable space to live and work [7].

The idea of Moon colonization originated far before the age of actual space exploration, as the Moon is the only Earth's natural satellite. Recent discoveries of considerable amounts of water close to the Lunar poles as well as the need to optimize space exploration by exploiting Moon bases and thus reducing the amount of fuel required for take-off (thanks to the fact that the Lunar gravity is far lower than the Earth's one) makes this opportunity more concrete and appealing [14]. However the establishment of a manned human colony on the Moon (or on Mars) will need some form of infrastructure to shelter the astronauts and scientific instrumentations from a very harsh environment.

2. Structural requirements due to internal pressure

Structural systems for space habitats must be designed for four main loading types: internal pressure, reduced gravity (one-sixth on the Moon and one-third on Mars), thermo-elastic loads and micrometeoroid impact [1].

The most significant of these loads is pressurization. Due to the absence of atmosphere on the Moon, a pressure differential of 100 kPa (0.99 atm) across the habitat enclosure is required to sustain Earth level pressures inside, resulting in outward pressures on the structure that are several orders of magnitude greater than conventional structural loads due to gravity (one sixth on the Moon and one third on Mars), wind, etc. Consequently, the structure will be mainly subjected to tensile stress instead of compression ones (as it happens for Earth structures).

According to NASA reports, the lunar and Mars Habitats are recommended to use both 55 kPa and 52.4 kPa atmospheres for normal operations. After extended acclimation of the surface habitat crewmembers, the lower pressure can be used.

However, these recommended atmospheres involve oxygen volume concentrations slightly greater than 30% (for Mars and Lunar surface habitats is 32 %) which is the maximum non-metallic materials flammability certification level used by current operational human space flight programs. It is relevant to note that these recommendations for surface habitats has to be examined more closely prior to development of requirements for those elements.

For highly pressurized structures, inflatable or pneumatic membranes are a compelling solution because then can be easily transported and use little material.

3. Literature review of inflatable structures

Over the years, the idea of inflatable structures as space habitats began to catch on [13]. Several important NASA reports, such as the Synthesis Group Report, identified inflatable structures as an enabling technology that would allow NASA to accomplish lighter weight structures at a lower cost. NASA has been experimenting pneumatic or inflatable structures, which resist tensile forces due to internal pressure with flexible membranes, since the 1960s for space exploration. The reasons are connected to their main features to reduce mass during the launch and to be folded and compacted in smaller volumes. Other key features are reduced loads while landing on the Moon or Mars and shorter manufacturing time.

One of the first inflatable deployable space structures was developed by Goodyear for designing a radar antenna (late 1950s). The inflatable part was the lenticular parabolic reflector. The inflated structure was about 12 meters in diameter while the reflector itself was about 10 meters in diameter. Other projects include Echo Balloons (1960), the Cotraves Antennas and Sunshades (late 1970s), and NASA IN-STEP Inflatable Antenna Experiment (1996) [8], shown in Figure 1.

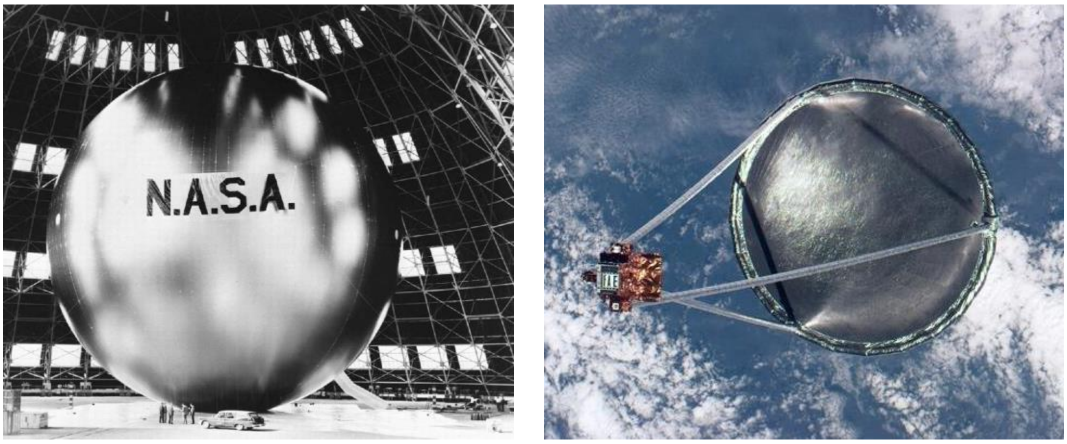

Figure 1: Echo Balloons project and Inflatable Antenna Experiment by NASA [8].

Beyond structures for space application, exploration into pneumatic structural design more broadly by Frei Otto in the early 1960s. Thomas Herzog, in his book *Pneumatic Structures: A Handbook of Inflatable Architecture* (1976), gives an excellent overview of historical inflatable architecture, such as the Expo ’70 in Osaka, where many pioneering pneumatic buildings were shown.

Another interesting Project is the Dyodon designed by Jean Paul Jungmann in 1967, shown in Figure 2. Jungmann carefully studied the laws of form of pneumatically stabilized structural elements made of closed membranes. A framework of tubes in the form of a polyedron is infilled by means of rigs and flexible filling elements. The building is stabilized against wind loads by a rope network [10].

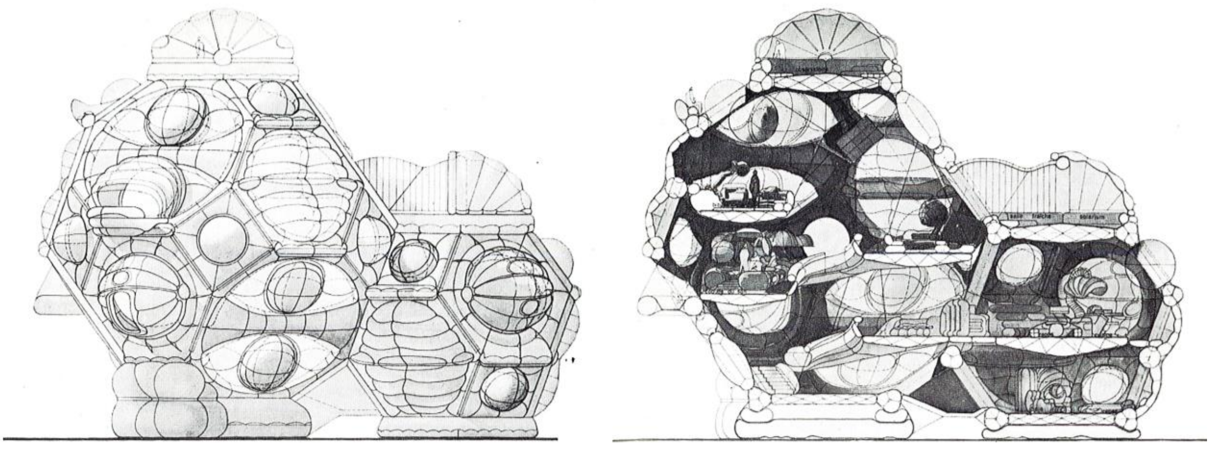

Figure 2: Dyodon project designed by Jean Paul Jungman in 1967 [10] [16].

Other inflatable architectural concepts, inspired by space applications, have been explored over time. In 1966, Archigram proposed the Living Pod project, a free-roving exploratory house inspired by the Lunar Modules that NASA was preparing for a moon landing. A few decades later, the architect Dante Bini developed two design proposals Lunhab and Lunit in collaboration with Harrison Schmitt, the twelfth astronaut to set foot on the Moon in 1971 during the Apollo mission. Lunit was essentially a kind of mechanical worm three meters in diameter, able to extend its length using compressed liquid air stored in cylinders inside the unit [3].

Today, other inflatable solutions for Moon habitats have been explored by prominent architectural firms such as Foster & Partners and Andrea Vogler. The proposals of the two teams are similar in that they both include an inflatable structure, but differ in how they respond to loading due to micrometeoroid impact and radiation protection. The project by Foster & Partners includes a shield over the tensile pneumatic structure made from regolith, or Lunar soil [6]. Vogler's design, Moon Capital, is composed of domes, over inflatable modules, that form an intelligent skin realized by 3-metre thick layer of small-regolith sandbags, filled and mounted by swarm smart robots [13]. However, the weight of the regolith sandbags that will enable the protection from radiation will not counterbalance the entire internal pressure.

Another interesting conceptual design that explores an overnight inflatable module on the Moon has been developed by MIT's Department of Aeronautics and Astronautics and Brown University's Department of Geological Sciences [17]. The inflatable habitat will be folded and packaged into a manageable volume to fit on the Apollo Lunar Rover. To deploy the habitat, the astronauts will remove the habitat from its container and unfold it on a flat surface. The ribs will then be inflated, establishing the habitat structure. This ribbing consists of a frame of small-diameter inflatable tubes that, when inflated to high pressure, provide a rigid structure for the habitat. Thus, the astronauts can inflate the ribbing prior to entry without filling the interior of the habitat with O_2.

Recently, several inflatable structures have been deployed and tested in space applications. TransHab was a concept pursued by NASA in the 1990s to develop the technology for expandable habitats inflated by air in space [12]. Specifically, TransHab was intended as a replacement for the already existing rigid International Space Station crew Habitation Module. When deflated, inflatable modules provide an 'easier to launch' compact form. When fully inflated, TransHab would expand to 8.2 meters in diameter (compare to the 4.4 meter diameter of the Columbus ISS Module). From a technical point of view, TransHab's inflatable shell consisted of multiple layers of blanket insulation, protection from orbital and meteoroid debris, an optimized restraint layer and a redundant bladder with a protective layer.

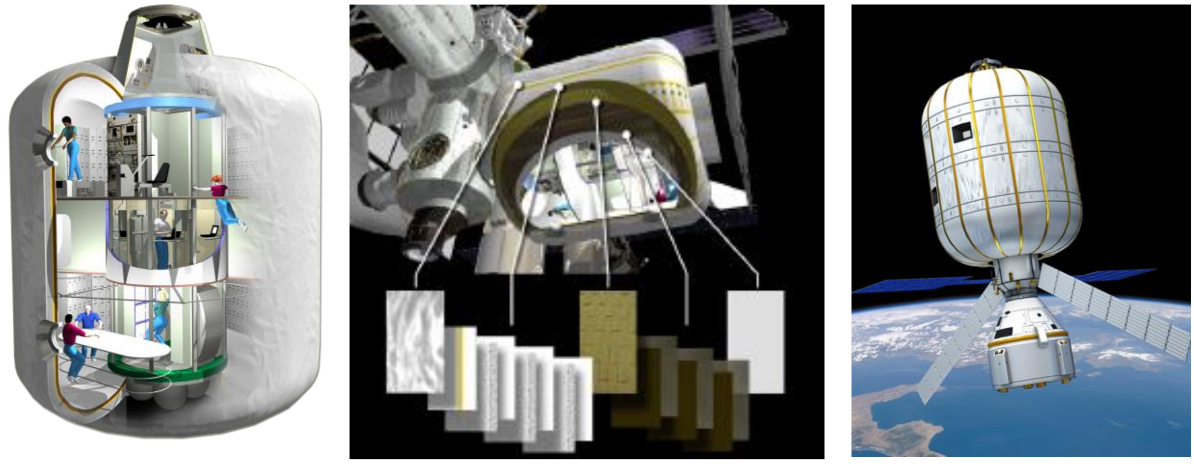

Figure 3: NASA's TransHab section and Bigelow Aerospace's module B330 [12].

TransHab's inflatable shell is composed of four functional layers: the internal scuff barrier and pressure bladder, the structural restraint layer, the micrometeoroid/orbital debris shield, and the external thermal protection blanket. Particles hitting at hypervelocity expend energy and disintegrate on successive Nextel layers, spaced by open-cell foam. Backing layers of Kevlar add an additional degree of protection. An inner liner of Nomex provides fire retardant and abrasion protection. Three Combitherm bladders form redundant air seals. Four layers of felt provide evacuation between bladder layers (necessary for launch packaging). The overall thickness is about 41 cm of thickness with 60 different layers.

Another interesting deployable inflatable project is the Bigelow Aerospace's module B330 (previously known as the Nautilus space complex module and BA 330). The design was developed by the previous NASA's TransHab habitat concept for generating a volume of about 330 m^3.

4. Functional space planning

Previous and current space habitat design examples demonstrate evolution of a spacecraft interior design that mostly follows activity function allocation.

Typically the organization of the interior layout follows the functional needs of the crew, such as working, hygiene, preparing and eating food, etc. A typical kind of diagram used by architects to "explore relationship among the sizes, adjacencies, and approximate shapes of the spaces needed for various activities" [4] is the 'Bubble Diagram'. Sometimes text, lines, or arrows are used in addition to show the relationship between functions. Diagrams help to evaluate design considerations and make functional constraints visible. These kinds of diagrams can also be used to analyze existing designs.

For example, in the Apollo Lander, all functional activities overlap (which was efficient for short term missions); In Skylab crew quarters and galley were spatially separated, whereas the galley had a window to the outside. In the Mir space station, the crew quarters were spatially separated as well, but had a window. The food and exercise areas were next to each other (in the main module).

The 'Adjacency Matrix' [11,4] is a tool that helps to analyze linkages between functions and subsystems. A diagram can be used to allocate activities according to preliminary requirements. For example, crew quarters are considered private/individual domain. They should be located in a quiet area in the habitat.

Zoning and functional adjacency are guiding principles that provide constraints for positioning internal systems. Zoning is the grouping of elements that share common attributes or resources. Typically, this includes separating quiet and noisy activities, placing crew access functions such as galley/wardroom and personal hygiene in the wall location, positioning subsystems in the overhead and floor locations, and grouping microgravity science at the best location within the spacecraft. Functional adjacency refers to a proximity assessment determining which activities prefer to be next to one another, separated, or are indifferent. An adjacency matrix is often created to provide guidance on functional proximity.

The 'Adjacency Matrix' [11,4] is a tool that helps to analyze linkages between functions and subsystems. A diagram can be used to allocate activities according to preliminary requirements. For example, crew quarters are considered private/individual domain. They should be located in a quiet area in the habitat.

Zoning and functional adjacency are guiding principles that provide constraints for positioning internal systems. Zoning is the grouping of elements that share common attributes or resources. Typically, this includes separating quiet and noisy activities, placing crew access functions such as galley/wardroom and personal hygiene in the wall location, positioning subsystems in the overhead and floor locations, and grouping microgravity science at the best location within the spacecraft. Functional adjacency refers to a proximity assessment determining which activities prefer to be next to one another, separated, or are indifferent. An adjacency matrix is often created to provide guidance on functional proximity.

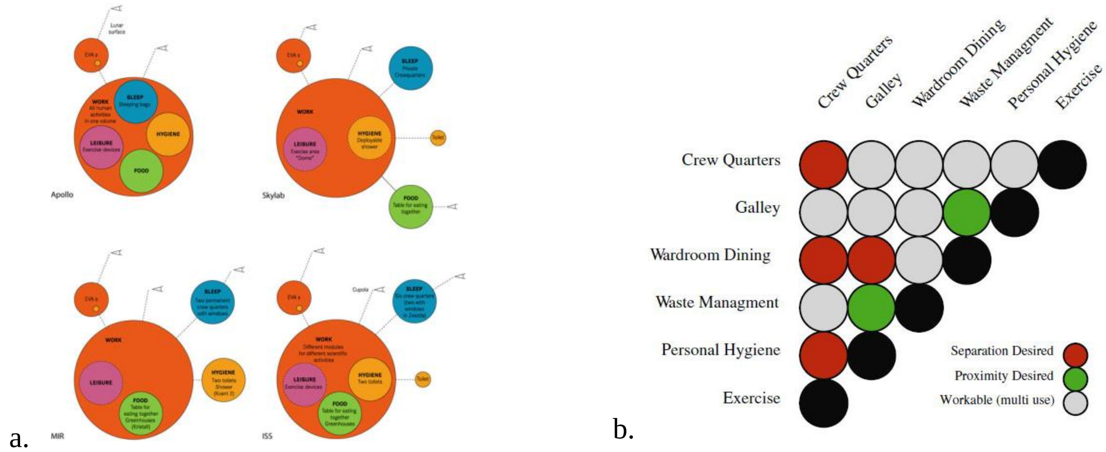

Figure 4: a. Bubble diagram [11], showing the preliminary zoning of the Lunar Lander, Skylab Station, Mir Station, and the International Space Station; b. Adjacency matrix for the collocation of functional zones.

These guiding principles provide a point of departure for the internal layout; ultimately the final arrangement is the result of an iterative process that integrates other factors including mass, volume, cost, schedule, technology level, and maintainability.

The aim of this research is defining a new computational method, that combining both Adjacent Matrix and Bubble Diagrams, automatically finds the optimal allocation of the required functions inside the habitat in the 3-dimensional space, without using a manual iterative process [14].

5. Form finding strategy

The proposed method uses a dynamic relaxation algorithm, via Kangaroo2 in Rhinoceros and Grasshopper, that allows the designer to automatically generate the space distribution of the functional requirements, and therefore the shape of the space habitat.

The main input parameter is the number of astronauts that will be living in the shelter. This data determines essentially the volume of each function. In this paper, the functions that are considered are: Sleep, Leisure, Food, Work/Laboratory, Greenhouse and Sport. In case of 10 astronauts, based on the pressurized volume per crewmember for a mission duration of 1000 days [Hauplik-Meusburger, 2016], the Sleep facilities will have a volume of 700 m^3, the Leisure 500 m^3, the Food 350 m^3, the Work/Laboratory 350 m^3, the Greenhouse 250 m^3 and the Sport 400 m^3.

The connections, shown in Figure 5, that were set among the functions are related to the proximity or separation desired among them also considering the relation between individual versus social and quiet versus noisy. For example the sleeping area has not been connected to the working activities and laboratories to avoid noise as well as to the greenhouse because of the CO_2 emission during night time.

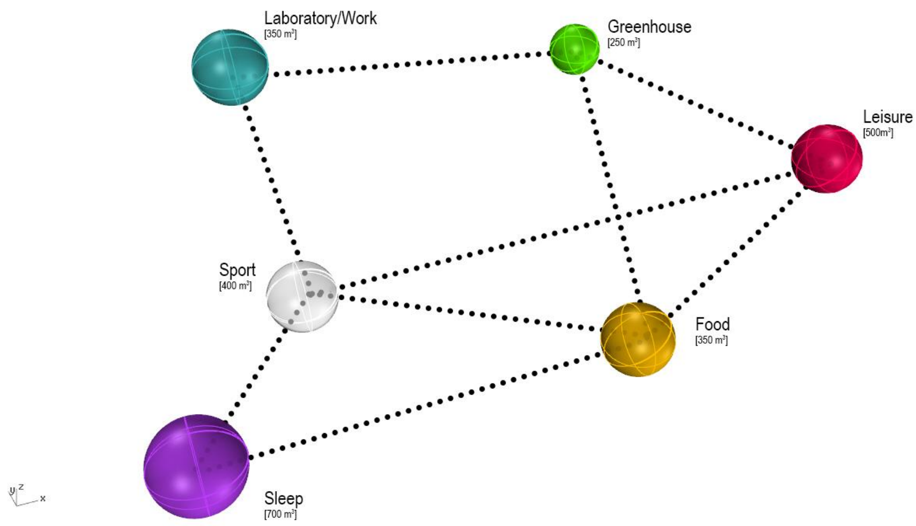

Figure 5: Sphere diagram connectivity diagram.

The connections are represented by lines that become springs during the simulation. The stiffness of each spring reflects the proximity that is desired between different functions. The functions are here represented as spheres with an equivalent volume of the functional diagram.

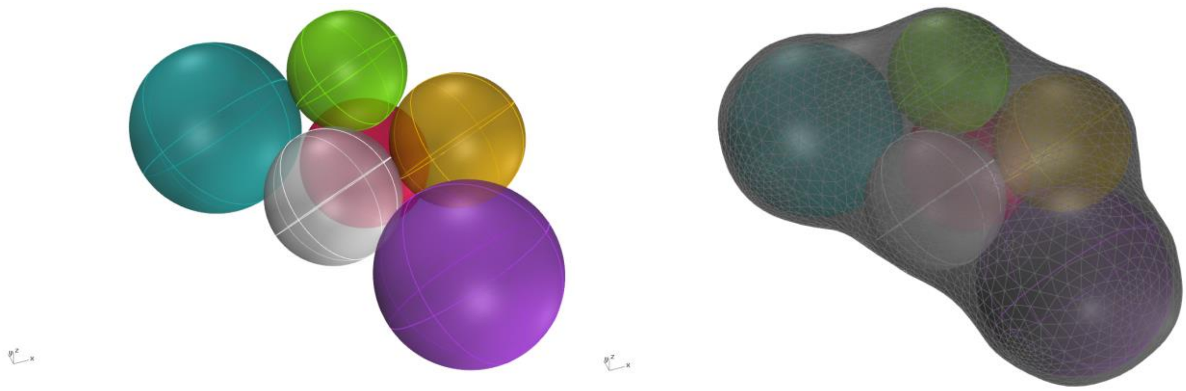

Figure 6: Sphere packing and metaball design.

The spring model is then subjected to dynamic relaxation in Kangaroo2, and the spheres reach an optimal configuration that represents the three dimensional allocation of all the areas. Because this simulation does not account for gravity loading, the orientation of the sphere packing configuration is arbitrary, and can be oriented to best fit on an extraplanetary surface by the designer or through an automated heuristic routine.

Next, the obtained sphere packing [9] is wrapped together through a metaball algorithm that encloses all the functions inside a unique smoothed mesh. The inspiring projects for the meatball design date back to Frei Otto's experiments on inflatable structures (before 1962) as well as to Manfred Schiedhelm's Civic Centre in Sprendlingen (1967), where, in both cases, anticlastic areas occur on the surface. More recently (2016), a pneumatic living structure, designed by the architects Ignacio Peydro Duclos and Isabel Collado Baíllo, has been inflated in East London to host free community events for local families and children.

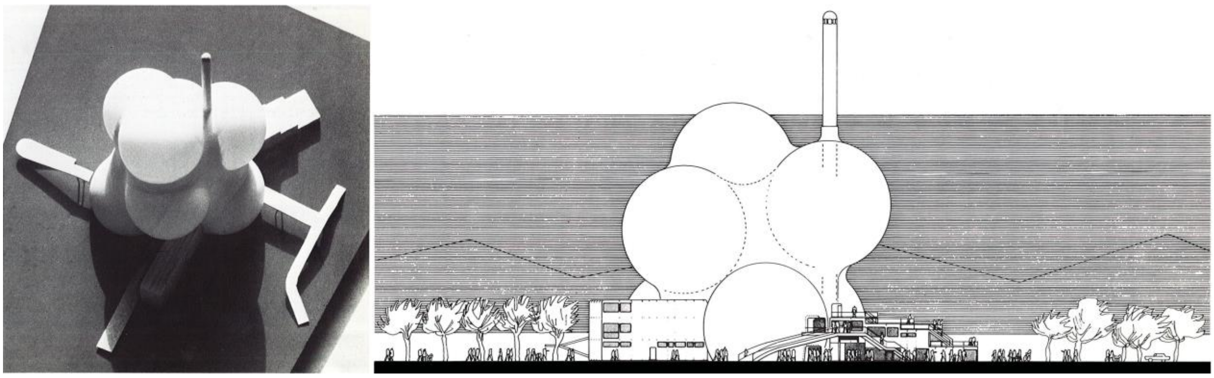

Figure 7: Manfred Schiedhelm'sproject for the Civic centre in Sprendlingen (1967) [10].

While the meatball surface effectively encloses the functional regions of the habitat, its geometry is not responsive to the forces caused internal pressurization. From a structural point of view the presence of anticlastic areas on the metaball configuration generate both tension and compression stress that don't represent a proper structural performance.

As a consequence, another form finding simulation has to be performed, applying an equal internal pressure inside the metaball configuration while maintaining the volume constant.

The output of the analysis shows a new geometrical configuration that reflects the need of having a uniform tensile stress inside the structure. In this case the stress will be tension as the main load is the internal pressurization.

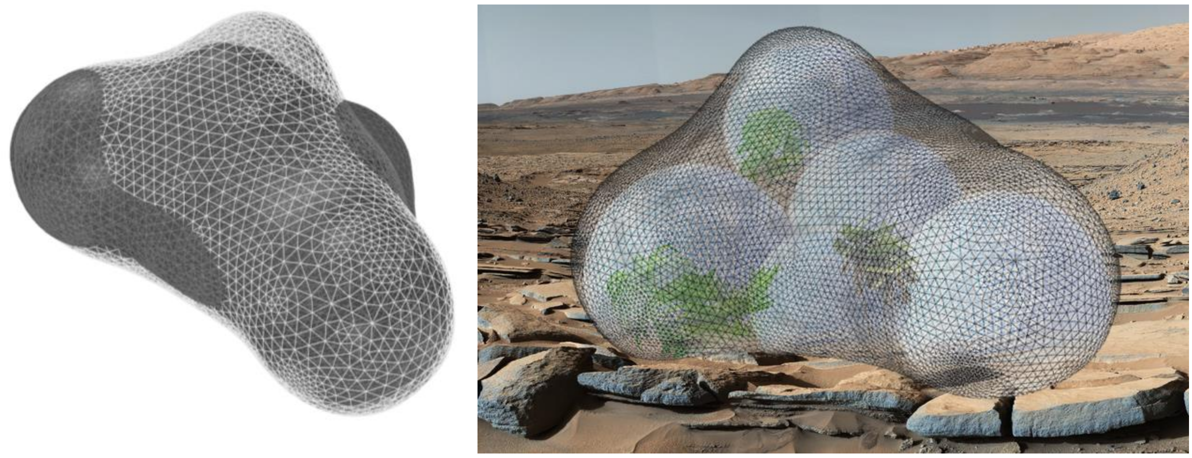

Figure 8: Inflation of the metaball design with constant volume.

6. Results of the structural analysis

The structural performance of the membrane has been tested through a finite element model, implemented in Karamba, in which the load is represented by the internal pressurization (100 kPa). The material used for the inflatable structure is Kevlar (DuPont), as all the other structures designed for space by NASA and Bigelow Aerospace. The Kevlar Elastic module and density are respectively equal to 8460 kN/cm^2 and 1440 kg/m^3 [18]. The support system has been defined considering that the inflatable structures will be located and partially dig into the ground, to improve the anchoring system.

In Figure 9, the tensile stress distribution of the final membrane. The areas that have higher stress are the ones in which we have a change in the curvature of the surface.

The structural model has been evaluated with three different loading conditions: internal pressure, internal pressure with lunar gravity (1/6 g) and internal pressure with Mars gravity (1/3 g). The results are exactly the same in terms of stress distribution and displacements, highlighting that the reduced gravity is negligible when designing for space habitats that have a differential pressure of about 1 atm.

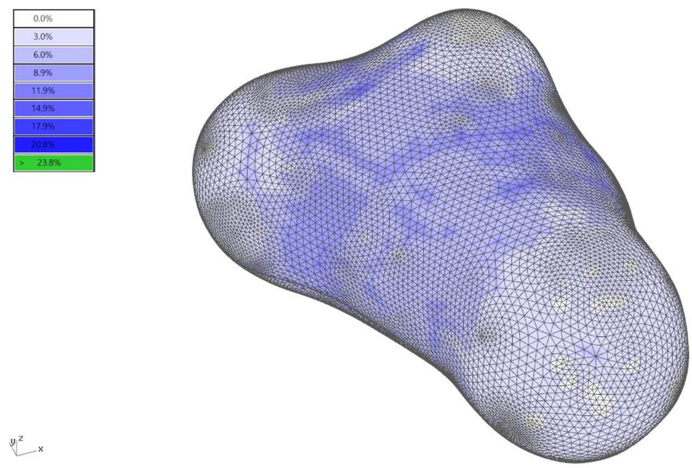

Figure 9: Tensile stress distribution inside the inflatable structure.

7. Conclusions

This research aims to explore form finding strategies for deep space exploration habitats considering the Moon and Mars as target planets. A new methodology for space shelter form finding has been analyzed, in order to optimize the location of different functions as well as to respond to the high pressure differentials required in these environment. Today, the internal layout is designed through an iterative process that integrates several factors (mass, volume, cost, schedule, technology level, and maintainability) and relies on Adjacent Matrix and Bubble Diagrams. Instead, the proposed algorithm automatically finds the optimal allocation of the required functions inside the habitat in the 3-dimensional space, without using a manual iterative process

The potential impact of this study relates to the possibility of designing in real-time the final layout of the habitat by simply defining the linkages between functions and subsystems. This method could be applied to different scales of the habitat, from the urban level down to the architectural one, and to even more complex systems. However, increasing the complexity could slow down the simulation process.

Moreover, being the obtained functional diagram readily translated in a structural Finite Element model, it was possible to prove that the reduced gravity is a negligible load when designing for space habitats that, have a differential pressure of about 100 kPa. Therefore the internal pressurization is the main load to consider. Future research could expand this study analyzing also other types of loads, such as the micrometeoroid impact, and the airlock systems.

In conclusion, this paper presents a new computational design method for space surface habitats that responds to both functional and physical requirements, offering new ways to support future space exploration.

Acknowledgements
This research was supported by Progetto Rocca Postdoctoral Fellowship.

References

[1] Benaroya, H. et al., Structural design of a lunar habitat, *Journal of Aerospace Engineering 19.3*, 2006, 133-157.

[2] Benvenuti, S., et al. Living on the moon: topological optimization of a 3D-printed lunar shelter. *Nexus Network Journal* 15.2 (2013): 285-302.

[3] Bini, D., *Building with Air*, McLean, 2014.

[4] Blackwell, Alan F. *Thinking with diagrams*, Springer Science & Business Media, 2001.

[5] Bodiford, Melanie P., et al., Lunar in situ materials-based habitat technology development efforts at NASA/MSFC., *Earth & Space*, 2006, 1-8.

[6] Cesaretti G., Dini, E. et a., Building components for an outpost on the Lunar soil by means of a novel 3D printing technology, *Acta Astronautica*, Volume 93, January 2014, 430–450

[7] Drake, B., *Human Exploration of Mars Design Reference Architecture 5.0*, NASA Johnson Space Center, Houston, TX, 2009 (NASA/SP2009- 566).

[8] Freeland, R. E., et al., Inflatable deployable space structures. Technology summary, in *48th International Astronautical Congress, Seot. 28-Oct. 2, 1998, Melbourn,e Australia.*

[9] Hales, T., *Dense Sphere Packings. A blueprint for formal proofs*, Cambridge University Press, 2012.

[10] Herzog, T., *Pneumatic Structures. A handbook of Inflatable Architecture*, Oxford University Press,1976.

[11] Hauplik-Meusburger, Sandra, and Olga Bannova. *Space architecture education for engineers and architects: designing and planning beyond earth*., Springer, 2016.

[12] Kennedy, K.J. , ISS TransHab architecture description., in *Proceedings of the 29th International Conference on Environmental Systems (ICES1999). Society of Automotive Engineers, Warrendale PA.1999.*

[13] Leach, N., ed. , Space Architecture: the New Frontier for Design Research, *Architectural Design* Nov. 2014.

[14] Preisinger, C., Linking Structure and Parametric Geometry. *Architectural Design*, 2013, 83: 110-113.

[15] Ramachandran, N., Gale, A., Space colonization, *Aerosp. Am*. 46(12) (2008)77.

[16] Sadler, S., *Archigram. Architecture without architecture*, MIT Press, 2005.

[17] Schreiner, S. S., et al., An overnight habitat for expanding lunar surface exploration, *Acta Astronautica*, Volume 112, July–August 2015, pp. 158–170

[18] Strife, J., Prewo, K., The Thermal Expansion Behavior of Unidirectional and Bidirectional Kevlar/Epoxy Composites, *Journal of Composite Material*, October 1979.

[19] Stroud, K., Pickett, L., Tillman, B., *NASA Human Integration Design Handbook (HIDH): Revitalization of Space-Related Human Factors, Environmental, and Habitability Data and Design Guidance*, NASA, 2008.