Outside the Box

highlighting the out-of-the-ordinary within the realm of structural engineering

Several decades after the first space age, there is renewed interest in space exploration and specifically in future human habitation far beyond the Earth's surface. NASA recently received funding with an ambitious target: to send a manned mission to Mars by the 2030s and allow for future human habitats and even cities. This is a challenging, multi-disciplinary problem that requires expertise from a wide variety of fields: aerospace engineering, environmental engineering, social science, urban planning, design, architecture – and especially structural engineering. 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 or the Moon. There is exciting potential to shape this discussion with fundamental structural engineering principles and forward-looking material and fabrication strategies.

Structural Challenges for Space Architecture

Engineering Habitats for the Moon and Mars

By Valentina Sumini, Ph.D. and Caitlin T. Mueller, Ph.D.

Valentina Sumini is a postdoctoral fellow at Massachusetts Institute of Technology in the Department of Civil and Environmental Engineering. Sumini's research aims to explore form-finding and structural optimization strategies for deep-space exploration habitats on the Moon and Mars. She can be reached at ***vsumini@mit.edu****.*

Caitlin T. Mueller is an Assistant Professor at the Massachusetts Institute of Technology in the Departments of Architecture and Civil and Environmental Engineering. She leads the Digital Structures research group, which focuses on new digital technologies for the design and fabrication of innovative structures.

Much like their Earth-based counterparts, the requirements of future space habitat structures are defined by their ability to protect their occupants and provide usable space to live and work. On Mars, the environmental loads are more extreme and the settlements more confined and isolated. Due to the high cost of transporting resources from Earth, up to $2 million for a single brick, recent efforts have focused on using in-situ materials for long-term sustainability. Throughout human history, settlers have adapted their construction methods to the locally available resources: snow huts, adobe walls, thatch roofs, and bamboo structures are just a few examples. Martian soil may be next on this list.

Loading and Structural Considerations

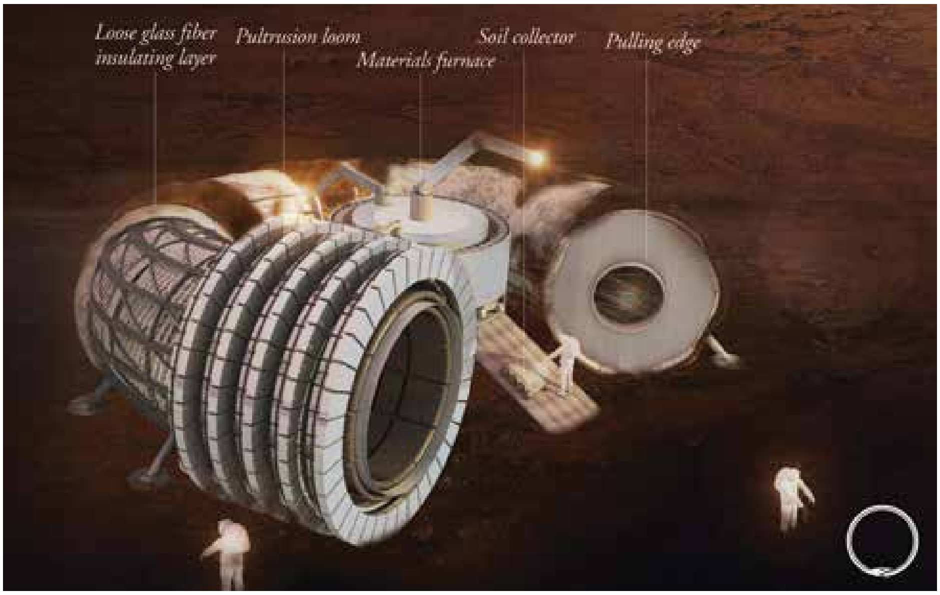
Structural systems for space habitats must be designed for four main loading types: internal pressure, reduced gravity (one-sixth on the Moon and one-third on Mars as compared to Earth), thermo-elastic loads, and micrometeoroid impact.

Because of the lack of atmosphere on the Moon and Mars, a pressure differential of up to 2090 psf across the habitat enclosure is required to sustain Earth-level pressures inside. This results in outward pressures on the structure that are 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. In comparison, a tension structure on Earth, such as an air-inflated sports dome, typically withstands a net pressure of 1 psf (Herzog, 1976) and the pressure differential on an airplane may be between 1100 and 1400 psf. Furthermore, since the loss of pressure is catastrophic to human life, the structure must be designed with redundancy and safety measures against decompression disasters caused by accidental and natural impacts.

According to NASA research, it is possible to safely reduce the internal pressure to values that are lower than those typical on Earth. Minimum pressures of 1150 psf and 1100 psf are recommended for the Moon and Mars, respectively, for normal operations. However, these lower pressures require increasing the percentage of oxygen in the air from 21% to 32%. This higher oxygen concentration corresponds to the maximum non-metallic materials flammability certification level currently used in operational human space flight programs. These recommendations must be studied further before the development of requirements for surface habitats.

Thermo-elastic loading is related to the presence of the Sun that produces a thermal gradient of about 630 °F on the Moon (in 29 days) and 148 °F on Mars (in 24.6 hours). These gradients occur between the sunlit and the shadow-exposed parts of the structure, as well as between the internal and external face of the envelope. Regolith is loose, fractured soil or rock and is commonly available on the moon, Mars, and Earth. An external thick regolith layer on structures could be used to provide thermal mass to dampen temperature swings. This layer can also

Loading on the Earth, the Moon, and Mars.



NASA 3D printed Habitat Challenge. Project: Ouroboros. Team Digital Structures Research Group. Faculty Advisor Caitlin Mueller.

serve as shielding from solar and cosmic radiation fields. The thickness of the layer would be variable, with thicker construction in the directions with greater sun exposure.

Micrometeoroids are small space projectiles (up to 0.1 inches in diameter) that do not survive entry through Earth's atmosphere but do reach the surface of the Moon and Mars at velocities up to 45 mps. Habitat structures must protect their interiors from penetration by these cosmic bullets. While it is impossible to predict this phenomenon deterministically, researchers have proposed that a habitat should resist projectile penetration with a probability of 99% over a mission time of 10 years. A commonly proposed strategy also involves utilizing the external regolith layer with a thickness of 3 to 6 feet to achieve this.

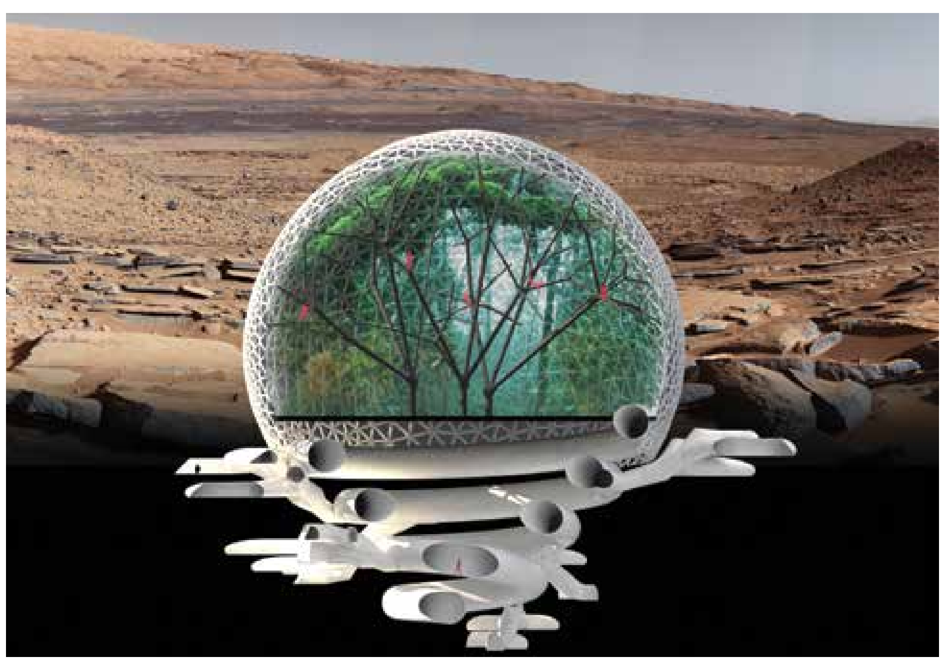
Design Concepts and Fabrication Strategies

Since 1986, several types of structures have been proposed as concept settlements for both the Moon and Mars. As internal pressurization is the controlling load on the structural system, several inflatable architectural concepts have been explored over time. The first one from Archigram in 1966, with the Living Pod project, was 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 design proposals in collaboration with Harrison Schmitt, the twelfth astronaut to set foot on the Moon in 1971 during the Apollo 17 mission. These projects are interesting because they are self-shaping, pressurized units. One of the proposals, Lunit, was essentially a kind of mechanical worm three meters (10 feet) in diameter. It would be transported and installed in a compact position and then its length would be extended telescopically using compressed liquid air stored in cylinders inside the unit.

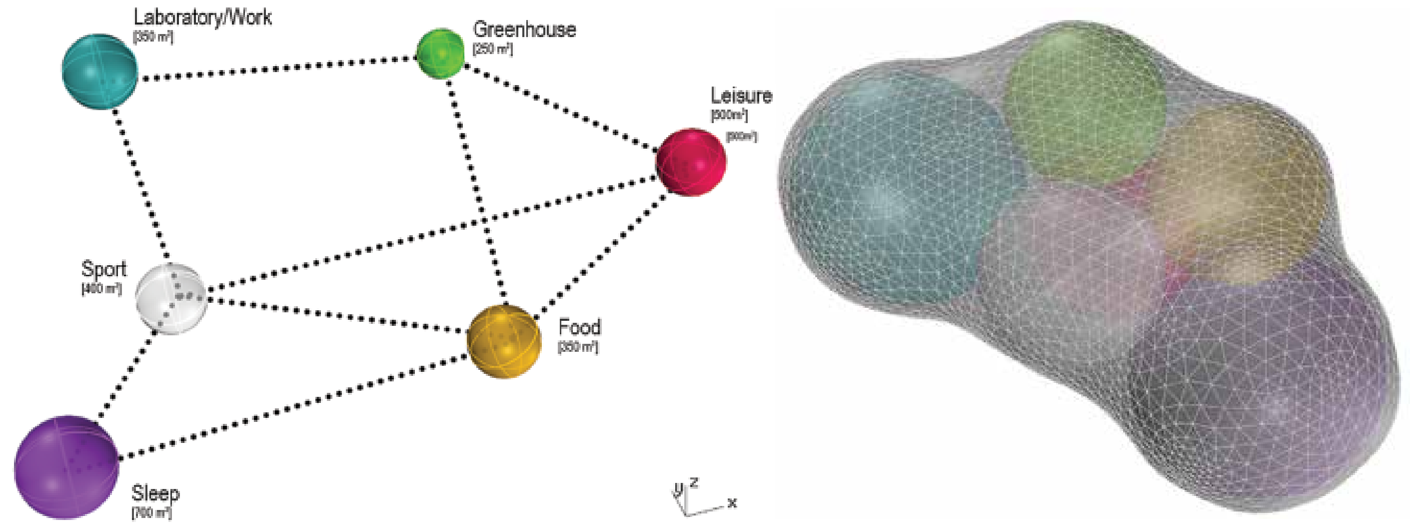
To date, other inflatable solutions for Moon habitats have been explored by prominent architectural firms such as Foster & Partners and Andreas Vogler. The project conceptualized by Foster & Partners has an internal inflatable membrane covered by a shelter made of regolith which could be constructed using robotic fabrication processes (such as 3D printers).

The state-of-the-art about rapid prototyping of building blocks is seen in research by the engineer Enrico Dini (Monolite Ltd.) who designed a 3D-printer, called D-shape technology. The technology has allowed for the construction of several prototype projects on Earth including housing, sculpture, military structures, and furniture. For the moon outpost (Foster & Partners in collaboration with Alta-Space), the 3D printer built a section through a regolith simulant.

The NASA Innovative Advanced Concepts Fellow, Neil Leach, is involved in a research project that aims to develop a robotic fabrication technology capable of printing structures on the Moon and Mars using lunar dust. The mechanical properties of the lunar regolith simulant (available at Orbitec of Madison, WI, USA, called JSC-1A) appear promising from a structural point of view, as the compression resistance is about 2900 psi and the Elastic modulus is equal to 341,000 psi. Density data for the regolith can be estimated from samples collected in space missions: the density of Moon regolith from the Apollo 15 mission data ranges from 84 pcf for the top foot, to 115 pcf at a depth of 2 feet. The powdered regolith with naturally occurring metallic oxides is mixed with chemical admixtures that react to form a type of concrete. One of the analyzed regolith mix design techniques is known as Contour Crafting, which is a digitally controlled construction process developed by Behrokh Khoshnevis that fabricates components directly from computer models. The material used is a form of rapid-hardening cement that gains sufficient strength



Redwood Forest City – Mars City Design™ Competition 2017. Team: Valentina Sumini, Alpha Arsano, George Lordos, Meghan Maupin, Zoe N. Lallas, Sam Wald, Matthew Moraguez, John Stillman, Mark Tam, Alejandro Trujillo and Luis Fernando Herrera Arias. Faculty advisor: Caitlin Mueller.



Application of sphere packing as a form-finding strategy for inflatable Moon exploration habitats.

to be self-supporting almost immediately after extrusion. At the moment, other 3D printing technologies are also being developed by private companies such as Made In Space and Redworks.

For the Mars regolith, indirect evaluations suggest densities from 75 to 100 pcf. In these respects, regolith is not very different from typical concrete aggregate used on Earth. Recent studies at Northwestern's McCormick School of Engineering highlighted that a concrete mix design that includes Martian regolith exhibits characteristics similar to terrestrial concrete, as well as easy handling, fast curing, high strength, recyclability, and adaptability in a dry and cold environment. The mix uses molten sulfur which is abundant on Mars. The regolith can be properly proportioned to allow the optimization of both the coefficient of thermal expansion and the mechanical strength.

Andrea Vogler's design, Moon Capital, is composed of domes, positioned over inflatable modules, which form a unique intelligent skin using a 3-meter (10-foot) thick layer of small-regolith sandbags. The weight of the regolith sandbags will provide protection from radiation and impact; however, it will not counterbalance the internal pressure of the entire structure. An innovative aspect of this project relies on the use of small swarm robots that will fill and mount the regolith sandbags on the smart skin. The potential application of swarm robotic systems is becoming very attractive because of their miniaturization and reduced costs, especially for areas with difficult or dangerous access. On Earth, drones have been used by University researchers at the Swiss Federal Institute of Technology (ETH), Zurich, to build a prototype rope bridge between two sets of scaffolding. While drones come to mind when picturing swarm robots, drones could only fly in indoor pressurized environments. Swarm robots operating on Mars or the Moon, exterior to the habitat, would be surface robots with collecting and hauling capabilities, similar to a robotic ant colony.

Another interesting conceptual design that explores a temporary inflatable module on the Moon has been developed by MIT's Department of Aeronautics and Astronautics and Brown University's Department of Geological Sciences. 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. The structure can be used for protection on overnight missions while the astronauts remain in their space suits.

Habitat Organization and Current Projects

Previous and current space habitat design examples mirror the evolution of a spacecraft interior design that mostly follows activity functions. Typically, the organization of the interior layout follows the functional needs of the crew, such as working, hygiene, personal spaces, and preparing and eating food. Typical architectural tools for the interior organization of terrestrial buildings, such as bubble diagrams and adjacency matrices, could also be used to explore the relationships among the sizes, adjacencies, and approximate shapes of the spaces needed for various activities in space habitats.

A project underway by MIT's Digital Structures research group is investigating this potential, developing a new sphere packing form-finding approach for conceptual space habitat design. The method aims to optimize the location of different functional systems and subsystems inside a space habitat. Spherical bubbles representing different functional programs can combine in 3D space by prioritizing the preferred connections and maintaining the requested volume. The sphere packing achieved through a dynamic relaxation algorithm allows for the combination of both bubble diagrams and adjacency matrices, allocating all activities and respecting all required linkages between functions and subsystems. The obtained functional diagram is also considered as a pressurized architectural space, made of spherical components, and evaluated, in terms of its structural performance, through finite element analysis tools. The individual spheres may be pressurized, and the encapsulating envelope can be pressurized, creating a layer of redundancy if one membrane is breached.

Designers and researchers are also working on proposals for human habitation at the urban scale, including the recent Mars City Design™ competition that aims to develop concepts for future Martian cities. One winning proposal from MIT, called Redwood Forest, is located in an unusual circular depression where a network of bright, green, and water-rich pressurized habitats are proposed to nurture 10,000 people. The city will exist both above and below ground, mimicking the structure of trees. Within the root network, residents will have their private spaces protected from harsh radiation, meteoroid impact, and thermal environment. The root network will house most of the machines that process, store, and distribute resources vital to everyday life. The public spaces will exist above ground, in enclosed structures which filter daylight down to the root network. The main transportation network will be an underground thoroughfare modeled after rhizomes present in various plant species. The radiation protection will be enhanced by the inclusion of a layer in the shield consisting of a water reservoir. The regolith that was dug out for the initial root system will be used as a catalyst to start water production and extract other mineral resources for construction.

Going Forward

Designing a structure on an extraterrestrial surface includes numerous challenges, including the internal pressure, the dead loads/live loads under reduced gravity, the consideration of new failure modes such as those due to high-velocity micrometeoroid impacts, and the relationships between severe Lunar/Martian temperature cycles and structural and material fatigue. Also of concern is the structural sensitivity to temperature differentials between different sections of the same component, the very extreme thermal variations and possibility of embrittlement of metals, the out-gassing for exposed steels and other effects of high vacuum on steel, alloys, and advanced materials. In addition, the factors of safety and the reliability (and risk) must be major components for lunar structures, as they are for significant Earth structures.

When considering a permanent settlement on another planet, one of the crucial aspects involves an evaluation of the total life cycle of the structure. That is, taking a system from conception through retirement and disposition or the recycling of the system and its components. Many factors affecting system life cannot be predicted due to the nature of the Lunar/Martian environment and inability to realistically assess the system before it is built and utilized. Therefore, even if the challenges in space exploration are very peculiar, the colonization of satellites and planets could teach us to be wiser in our consumption of natural resources, pushing us to pursue efficiency and sustainability here on Earth. The multidisciplinary methodology connected to space exploration research will be a wise starting point for optimizing the terrestrial consumption of natural resources for designing more sustainable architectures and improving ground logistics research.▪

For more on Mars regolith densities, see K. Seiferlin et al., Simulating Martian regolith in the laboratory, *Planetary and Space Science,* vol. 56, 2009-2025 (2008).