SPACE ARCHITECTURE FOR EXTRAPLANETARY EXPLORATION

PRINCIPAL ACADEMIC TUTOR

Dr. Laura Mainini, Adjunct professor, Department of Mechanical and Aerospace Engineering, Politecnico di Torino; Research affiliate, Department of Aeronautics and Astronautics, MIT;

ACADEMIC TUTOR

Prof. Paolo Maggiore, Associate professor confirmed, Department of Mechanical and Aerospace Engineering, Politecnico di Torino;

Prof. Franco Bernelli Zazzera, Full professor, Department of Aerospace Sciences and Technologies, Politecnico di Milano;

EXTERNAL INSTITUTIONS

Massachusetts Institute of Technology;

EXTERNAL TUTOR

Dr. Valentina Sumini, Postdoctoral Associate, MIT Media Lab, Responsive Environments, MIT;

Prof. Jeffrey Hoffman, Professor of the practice, Department of Aeronautics and Astronautics, MIT.

TEAM MEMBERS

Aldo Moccia, Architettura delle Costruzioni, Politecnico di Milano

Jana Lukic, Interior and Spatial Design, Politecnico di Milano

Fabio Maffia, Architettura, Costruzione, Città, Politecnico di Torino

Samuele Sciarretta, Architettura per il Progetto Sostenibile, Politecnico di Torino

Executive summary

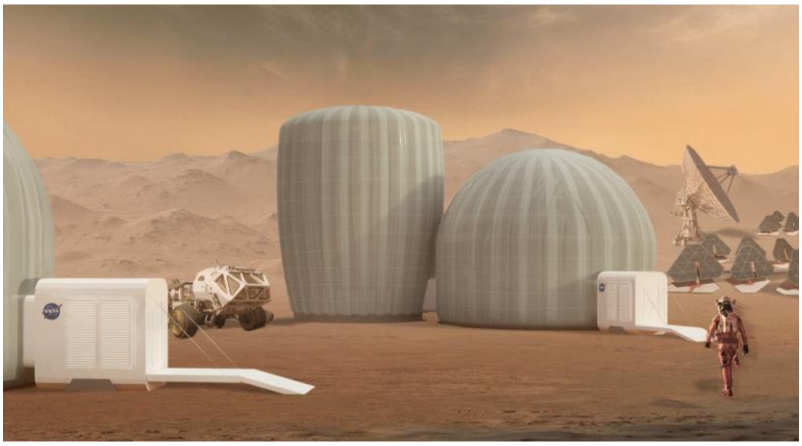
In an era of renewed interest in deep space exploration, the Space Architecture for Extraplanetary Exploration (SAEXE) project set the objective to provide an innovative yet feasible solution to allow manned exploration of Mars in the next years. The project addressed the design of a greenhouse for on-site food production on Mars, conceived to grant self-sufficiency to human-tended space missions, through the implementation of an optimized spiral design of the crops cultivation system. Moreover, the internal space of the module exploits innovative, human-oriented solutions to enhance mental and physical well-being of the crewmembers.

The project is the result of a joint research and design effort between our group of Alta Scuola Politecnica (ASP) and a team of students from the Massachusetts Institute of Technology (MIT). The collaboration of the two teams led to a project awarded second place at 2019 NASA BIG Idea Challenge, to the peer reviewed conference paper “Mars Garden: an Engineered Greenhouse for a Sustainable Residence on Mars” [1], included in the proceedings of the 2019 AIAA Propulsion and Energy forum, and to a poster awarded among the top 5 best works at the 2019 International Conference on Environmental Systems (ICES).

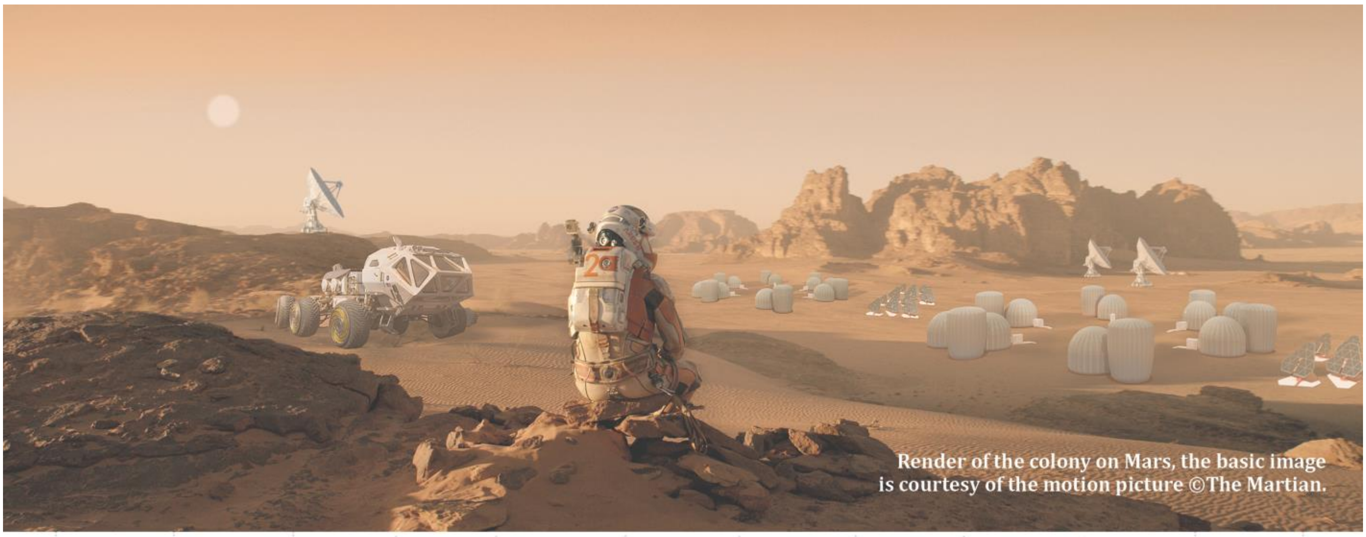
The proposed space habitat concept complements and integrates the Ice Home residential module designed by NASA [2], with an original greenhouse module creating a near closed-loop ecosystem. The proposed greenhouse combines three key elements: a hydroponic system for the cultivation of eight archetypes of plants; an internal helical layout that optimizes the usage of space; the exploitation of the same technological solutions chosen and adopted by NASA for the Mars Ice Home program, in order to guarantee full compatibility and efficient coupling with the existing module. The greenhouse is equipped with two spiral elements: an inner track for crops cultivation and an outer pathway for circulation and running. A functional and ergonomic workspace is located below the spiral at the bottom floor, while a relaxation space is arranged on top level.

Key Words

Space architecture; Mars; Hydroponic; Greenhouse; Self-sustainability.

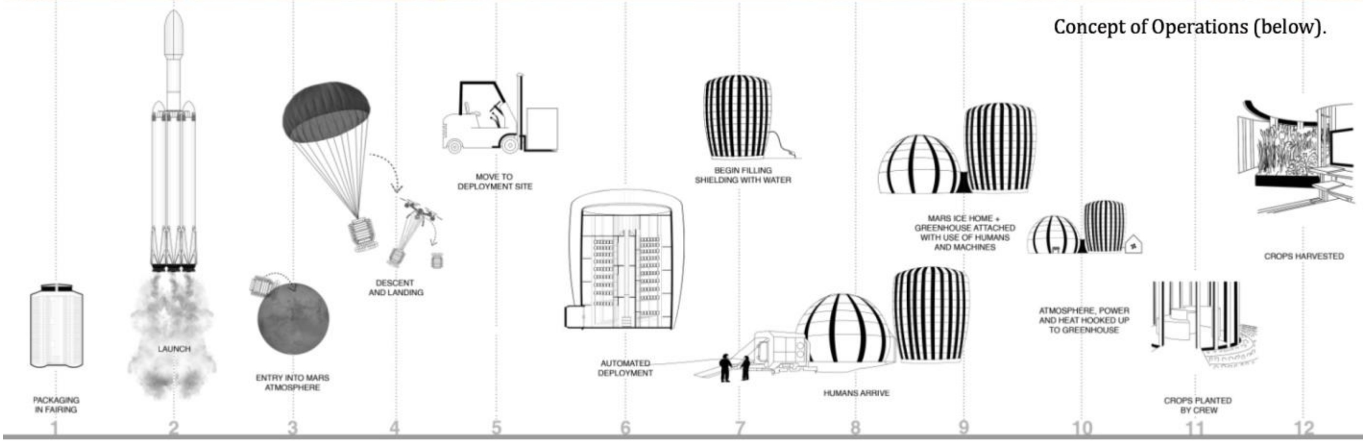


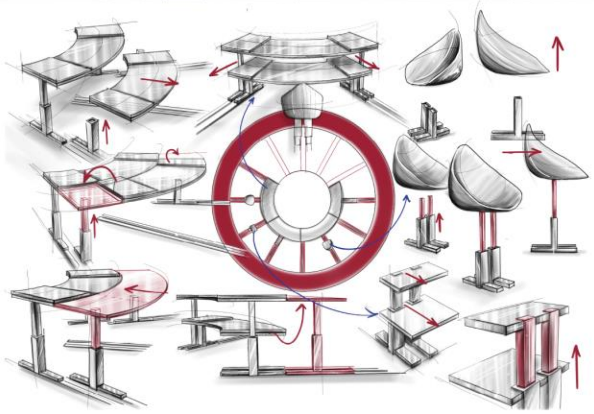
Rendered view of the proposed greenhouse module integrated with the NASA Ice Home.

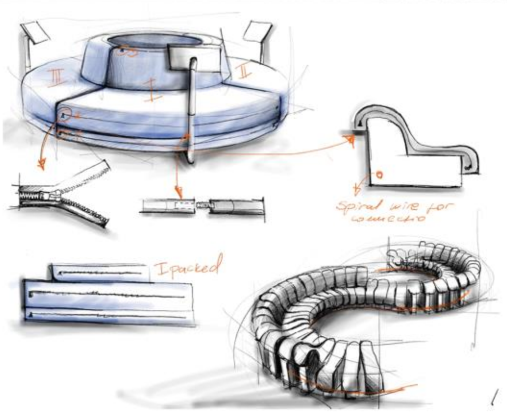


Render of the colony on Mars, the basic image is courtesy of the motion picture ©The Martian.

Concept of Operations (below).







Rendered views of bottom floor (top left) and top floor (top right), furniture study drawings (bottom).

Project description written by the Principal Academic Tutor

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 challenging, multi-disciplinary problem requires expertise from a wide variety of fields including aerospace engineering, environmental engineering, social science, nuclear engineering, 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. Project objectives include: (1) In Situ Resources Utilization for assessment and exploitation of construction materials and water; (2) energy sources and consumption: assessment of technologies; (3) system architecture and computational design methods for optimized architectural solutions; (4) construction autonomy of structures for unmanned missions that will survey current sites and start construction before human arrival; (5) integrated design solutions to solve psychological impact.

When considering a permanent settlement on another planets, one of the crucial aspects involves the 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.

Team description by skill

The team then joined a group of students from the Massachusetts Institute of Technology (MIT) for the 2019 NASA BIG Idea Challenge. The project was developed by a strict collaboration: the SAEXE team mostly handled the architectural design and the layout of the greenhouse module, while the MIT students focused on the systems engineering and ecology.

Aldo Moccia | As the team controller, Aldo supervised the collaboration with the MIT and handled the development and the presentation of the technical paper. He also exploited his architectural expertise in the design of the deployment and the structure of the module.

Jana Lukic | As interior designer, Jana focused on the design of the tailored flexible furniture for the workplace and the relaxation area of the greenhouse. She also managed the visualization of the project with renders and videos.

Fabio Maffia | Fabio supported the managing activity of Aldo through a careful work breakdown analysis, while handling the design of the general layout of the module and the deployment system. He also supported Jana with the visualization of the project.

Samuele Sciarretta | As an architect, Samuele managed the complex detailing of the spiral hydroponic system, also providing a crisp visualization of the deployment phases and the technical drawings of the greenhouse. He also handled the advanced research phase and the project budget.

Goal

The module is conceived to grant a higher level of self-sufficiency to human missions to Mars through on-site food production, to increase mission feasibility and safety, as well as to safeguard the psychological and physical well-being of the astronauts during a long-term stay in space. Structures and systems are designed to survive each phase of deep space travel, from launch to landing and deployment, while also providing maximum functionality for mission operations. Mass, loads, energy and resources consumption are minimized to reduce reliance from Earth and fully support a long-term mission. The design is developed through the application of principles of Ecology, Architecture and Systems Engineering.

Ecology

Sustaining human life on Mars means providing reliable and complete nutrition to the crew of astronauts. Therefore, the plants to be harvested in the greenhouse must fulfil nutritional requirements, provide steady yield rates, and stay healthy. The crops must provide a balanced diet with an average of 2,700 calories per person per day [3]. Plant health is also of vital importance and, while it cannot be guaranteed, must be maximized with respect to both Mars micro-gravity [4,5] and the spread of disease. Moreover, the growing system itself needs to assure crops grow efficiently and reliably and must be space efficient, in order to maximize productivity and minimize material delivery from Earth. Finally, a balance between human labour and automation to complete tasks must be sought; a more automated system reduces the labour requirements of the astronauts but increases system complexity.

Architecture

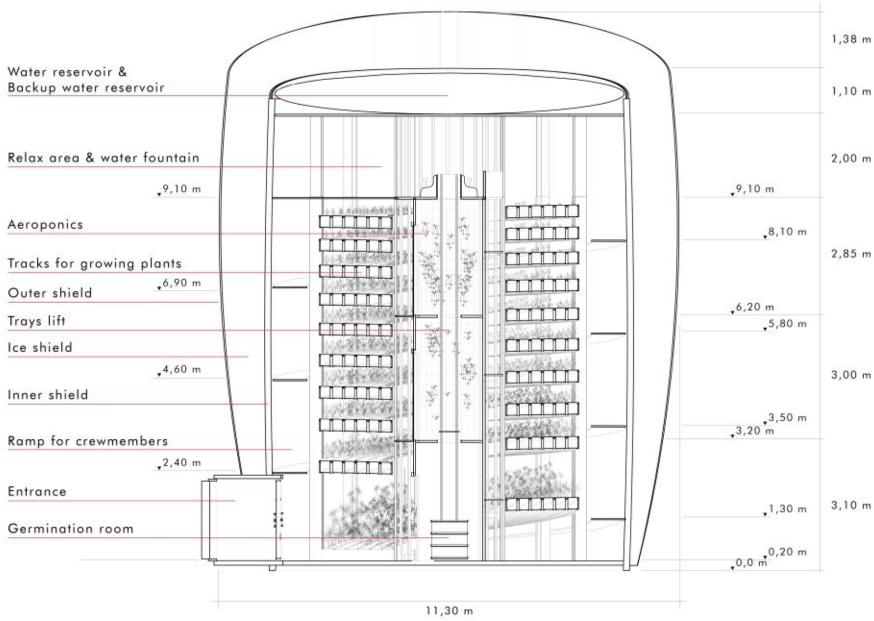
The key drivers of the design of space architecture are structural needs, functional needs and human needs. In a low-pressure environment, vertical loads become minor constraints compared to internal pressure loads, especially when an inflatable structure is used. Therefore, the shape of space modules needs to be optimized to best carry perpendicular loads. Additionally, the internal layout of the greenhouse must be arranged to host as many crops as possible, while also allowing room for a recreational area to provide mental health benefits for the crew. The entire structure must also be designed for compression and expansion in order to match a limited rocket fairing space. Finally, the selection of materials for the interior must consider each material's versatility, durability, strength to weight ratio, cost, and precedent in space use.

Systems Engineering

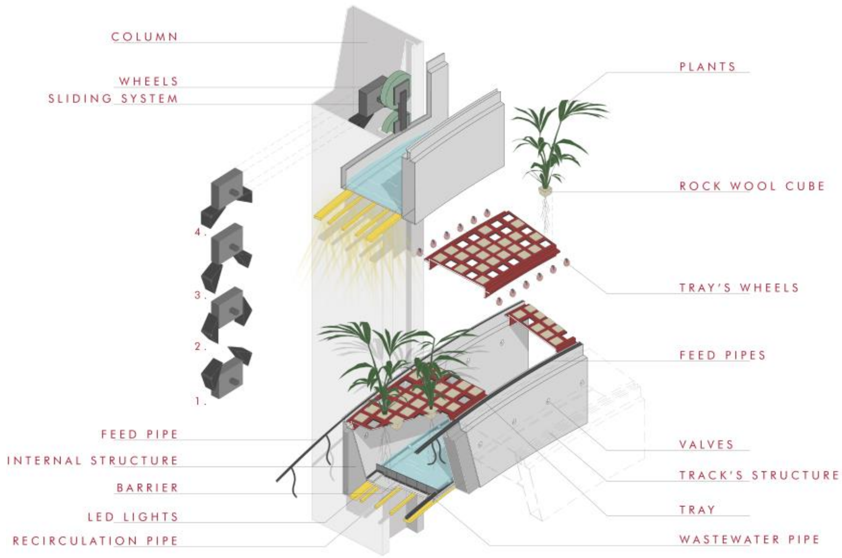
Three primary drivers lead the proposed design of systems: environmental control system, efficient resource utilization and risk mitigation. The environmental control and life support system, the tailored and original architecture designed for human well-being, and the adoption of automation technologies to enhance cultivation productivity make the greenhouse a physical and psychological healthy environment, realize a functional and ergonomic workplace, ease the intervention of the crewmembers, and foster human-machine integration. Sizing, supply, power demand, recycling and multipurpose systems are optimized to ensure an efficient use of the available resources. To mitigate the risk associated with malfunctioning and disruption, systems are designed to be multi-functional and integrated to achieve redundancy for all the critical functions.

Understanding the problem

In recent years, a renewed interest in Mars colonization, channelled into a variety of programs developed and supported by worldwide private and public space agencies, is boosting the effort for the exploration of the Red Planet through both unmanned and manned missions [6]. NASA's Mars Exploration program and Journey to Mars vision [7], ESA's Aurora program [8], the Starship / Superheavy System by SpaceX [9] stand out as the largest and most ambitious of ongoing plans, including and forecasting multiple steps of technological and scientific development. The lack of sustainability in proposed extra-planetary dwellings is one of the key aspects preventing the feasibility of space exploration: reliance on Earth supply for sustenance and maintenance needs implies too high risks and too low sustainability for the purpose of deep space exploration missions. When focusing on the human exploration of Mars, In Situ Resource Utilization (ISRU) can grant the needed self-sustainability and self-sufficiency of a mission system, with astronauts relying on the use of local resources such as water, air, nutrients and light as the basis for on-site energy and food production. The colonization of Mars opens up a broad spectrum of opportunities for the development of novel technological solutions to support human life in unconventional environments: solutions that might also be adopted for a more sustainable and safe life on Earth.



Cross section of the greenhouse module.



Axonometric detail of the hydroponic system and the trays.

Exploring the opportunities

The key criteria that drove the choice among different design alternatives relate to the overall module efficiency and the crew well-being. At the matter of fact, these objectives translate into design search directions towards higher crop productivity to guarantee food supply to the crew, lower ratios of occupied space over available volumes to allow for a better comfort of the crew, and system redundancy to guarantee a reliable implementation of all the critical functions. In response to Ecology driven requirements, the hydroponic technology is identified as the most appropriate among the alternatives because it is a well-established and reliable technology used on Earth.

In response to the architecture-related requirements, our design permits to optimize surfaces and volume distribution in the deployed configuration, while minimizing the weight and the space occupied in the packed configuration. In response to the requirements related to the functioning and integration of systems and equipment, energy production, supply and distribution constitute a critical aspect. For our greenhouse concept, nuclear power is preferred over solar power for its better performance in guaranteeing production continuity, independently on day-night cycles and external environmental conditions; in addition, nuclear discourses require less maintenance interventions.

Generating a solution

The greenhouse is designed to integrate the NASA Ice Home prototype with a complementary food production module. The habitat implements a novel closed-loop hydroponic system to provide food support for a long-term extraplanetary mission. Its architecture is centred around an elegant and purposeful spiral. The harvesting process starts at the bottom floor of the module, where plants are seeded and germinate. Seedlings are then lifted to the top floor of the module through an elevator, they are transplanted into trays and placed on a helical track, that spirals back to the bottom floor. During their life-cycle, crops slowly slide down the spiral, reaching the ground floor of the module once they reach their maturity. At this stage they are ready to be harvested. The heights between levels of the spiral increase as one moves down from top to bottom, in order to match the growth of plants and thus maximize vertical space.

The greenhouse is stowable in a standard rocket fairing and can autonomously deploy to a larger configuration able to produce enough food to meet 100% of the astronauts' nutritional needs. The module is designed to minimize the risks of structural and energetic failure, as well as plants disease spreading with redundant systems and simplicity. The greenhouse is also conceived to minimize labour and maximize production.

Main bibliographic references

[1] S. Babakhanova, S. Baber, F. B. Zazzera, E. Hinterman, J. Hoffman, J. Kusters, G. Lordos, J. Lukic, F. Maffia, P. Maggiore, L. Mainini, A. Moccia, H. Nowak, T. Schneiderman, S. Sciarretta, S. Seager, S. Seaman, T. Smith, N. Stamler, V. Sumini, Z. Zhan, "Mars Garden: An Engineered Greenhouse for a Sustainable Residence on Mars", AIAA 2019-4059, August 2019.
https://arc.aiaa.org/doi/abs/10.2514/6.2019-4059

[2] NASA, "Ice Home Concept of Operations", *Ice HomeMars Habitat*, MIH.ConOps.001, 2017.
http://bigidea.nianet.org/wp-content/uploads/2018/07/IceDome-ConOps-2017-12-21vreduced.pdf

[3] NASA, "Space Flight Human-System Standard", NASA-STD-3001, Volume 2, Revision A, 2015.

[4] Maggia, F. and Pallud, C., "Martian base agriculture: The effect of low gravity on water flow, nutrient cycles, and microbial biomass dynamics", *Advances in Space Research*, Vol. 46, No. 10, 2010, pp. 1257-1265.
https://doi.org/10.1016/j.asr.2010.07.012

[5] Manzano, A., et al., "Novel, Moon and Mars, partial gravity simulation paradigms and their effects on the balance between cell growth and cell proliferation during early plant development", *Npj Microgravity*, Vol. 44, No. 9, 2018.
https://doi.org/10.1038/s41526-018-0041-4

[6] The Planetary Society, "Missions to Mars", n.d. Accessed January 28, 2019.
http://www.planetary.org/explore/space-topics/space-missions/missions-to-mars.html#grunt

[7] NASA Science, "Mars Exploration Program", n.d. Accessed January 28, 2019.
https://mars.nasa.gov/#mars_exploration_program/0

[8] ESA, "The European space exploration programme Aurora", n.d. Accessed January 28, 2019.
http://www.esa.int/Our_Activities/Human_and_Robotic_Exploration/Exploration/The_European_Space_Exploration_Programme_Aurora

[9] Space X, "Making life multiplanetary", n.d. Accessed January 28, 2019.
https://www.spacex.com/mars