MARTIAN VOROVOID

MSc 2 2025

Group C3

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1. INTRODUCTION

With the growing interest in human exploration of Mars, the question of sustainable living on the Red Planet is becoming increasingly relevant. The **Martian Vorovoid** project, part of the MSc2 2025 1:1 Interactive Architectural Prototypes Studio at TU Delft, addresses this issue by designing a self-sufficient habitat within Martian lava tubes. These natural formations provide protection from Mars' extreme radiation, temperature swings, and dust storms—critical environmental challenges for any potential habitat.

Focusing on the Arsia Mons region, known for its extensive lava tubes and stable geology, the project utilizes basalt-rich regolith for construction through in-situ resource utilization (ISRU), robotic excavation, and 3D printing. This approach reduces reliance on Earth-based materials and promotes long-term autonomy.

Architecturally, the habitat is organized vertically and shaped using Voronoi geometry, providing flexibility and structural integrity. A central void connects different zones - living, working, recreation, and life support - while allowing natural light to penetrate the underground structure. The project also integrates robotic milling and assembly with human-robot collaboration, ensuring a buildable, maintainable habitat in a low-resource environment.

This report details the development of the **Martian Vorovoid**, from site analysis and concept design to digital modeling, prototyping, and robotic fabrication. It envisions a resilient, adaptive system tailored to the Martian context, advancing the possibility of life beyond Earth.

2. RESEARCH AND METHODOLOGY

The project began with a literature review and analysis of precedent projects such as Moonshot and Rhizome 1.0 & 2.0. These provided insights into robotic construction and ISRU in extraterrestrial architectural design. A comprehensive methodology combining systems thinking, parametric modeling, and robotic simulation was applied.

Tools like Rhino and Grasshopper facilitated the design process, including structural analysis and HRI (Human-Robot Interaction) simulations. Case studies informed material selection, spatial layout, and environmental responsiveness. Finally, milling and fabrication processes were explored and documented to evaluate feasibility.

3. SITE

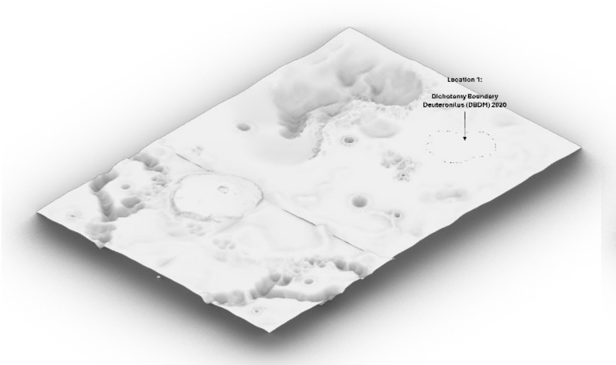


Figure 1: **Deuteronilus Mensae (DBDM)**

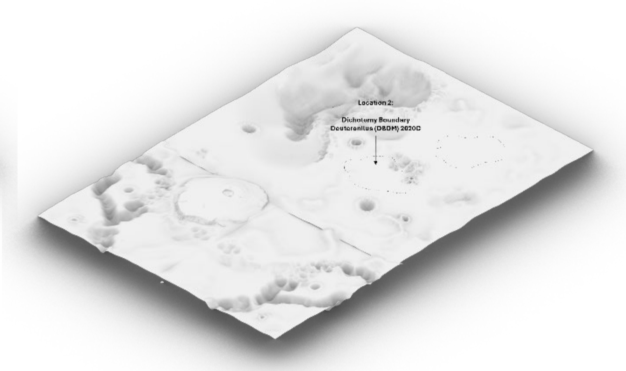


Figure 2: **Protonilus Mensae**

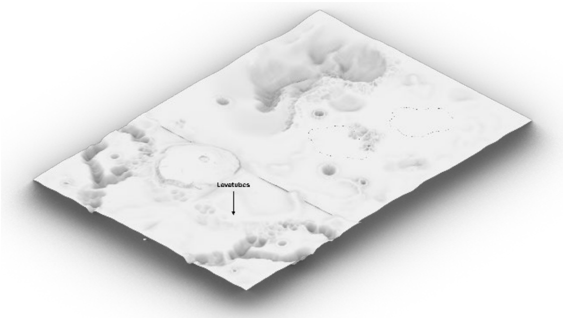


Figure 3: **Presence of Lava Tubes**

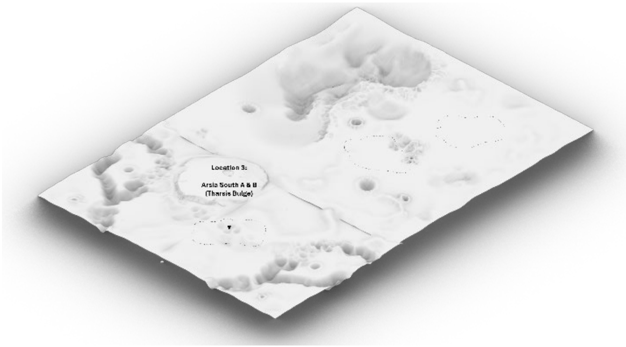


Figure 4: **Arsia South (Tharsis Bulge)**

Multiple potential sites were evaluated during the Rhizome project, based on key criteria such as elevation, presence of water, terrain, and energy generation potential. The locations considered included:

- **Deuteronilus Mensae (DBDM)** - Chosen initially for its abundant water ice and low elevation, ideal for early-stage energy modeling.
- **Protonilus Mensae** - Selected in the second iteration for its stronger wind resources to support an airborne wind energy system.
- **Arsia South (Tharsis Bulge)** - Considered for its extensive lava tube networks, but ultimately dismissed due to its high elevation (9 km) and low atmospheric density, which posed challenges for wind energy utilization.

Mars presents a hostile environment with extreme conditions that directly influence habitat design.

- Temperatures can plummet below -100°C.
- Radiation levels are significantly higher than on Earth due to the thin atmosphere and lack of a magnetic field.
- Frequent dust storms pose challenges to both human health and electronic equipment.
- Low atmospheric pressure and limited oxygen necessitate airtight structures.

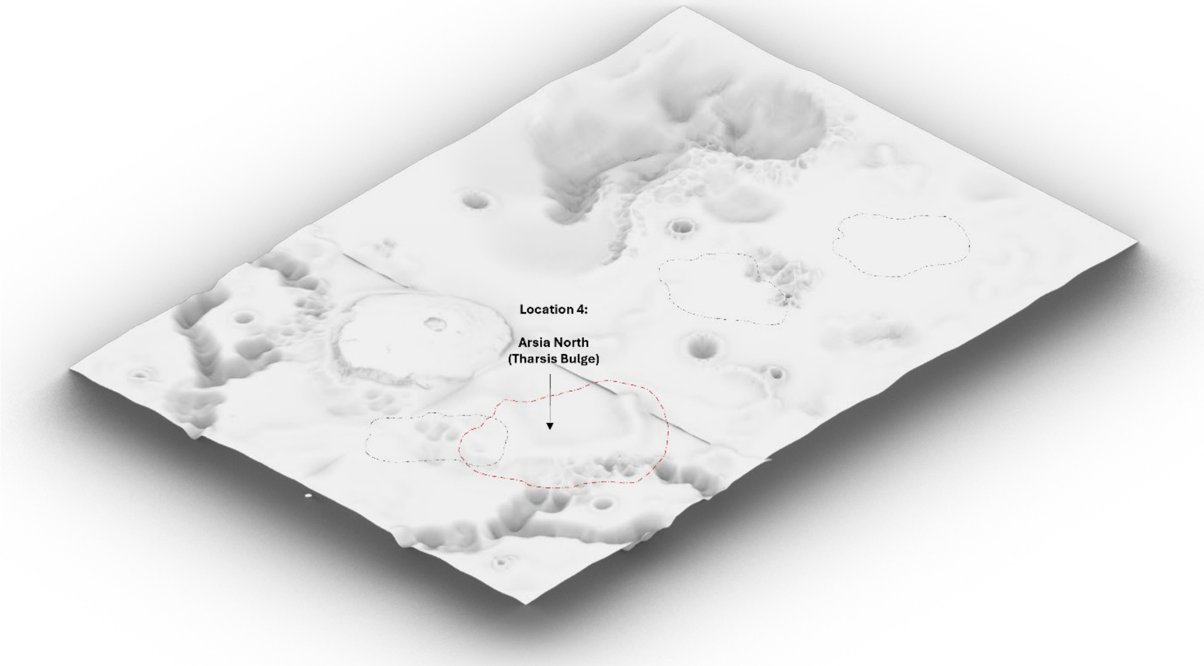


Figure 5: **Arsia North (Tharsis Bulge)**

The final location selected for the Mars habitat is **Arsia North**, a region situated on the **Tharsis Bulge**. This decision was made after extensive analysis and iterations during the Rhizome project, which considered several factors such as terrain, atmospheric conditions, subsurface geology, and energy potential. Arsia North emerged as the most viable option owing to a unique combination of geological shelter, accessibility, energy generation potential, and environmental stability.

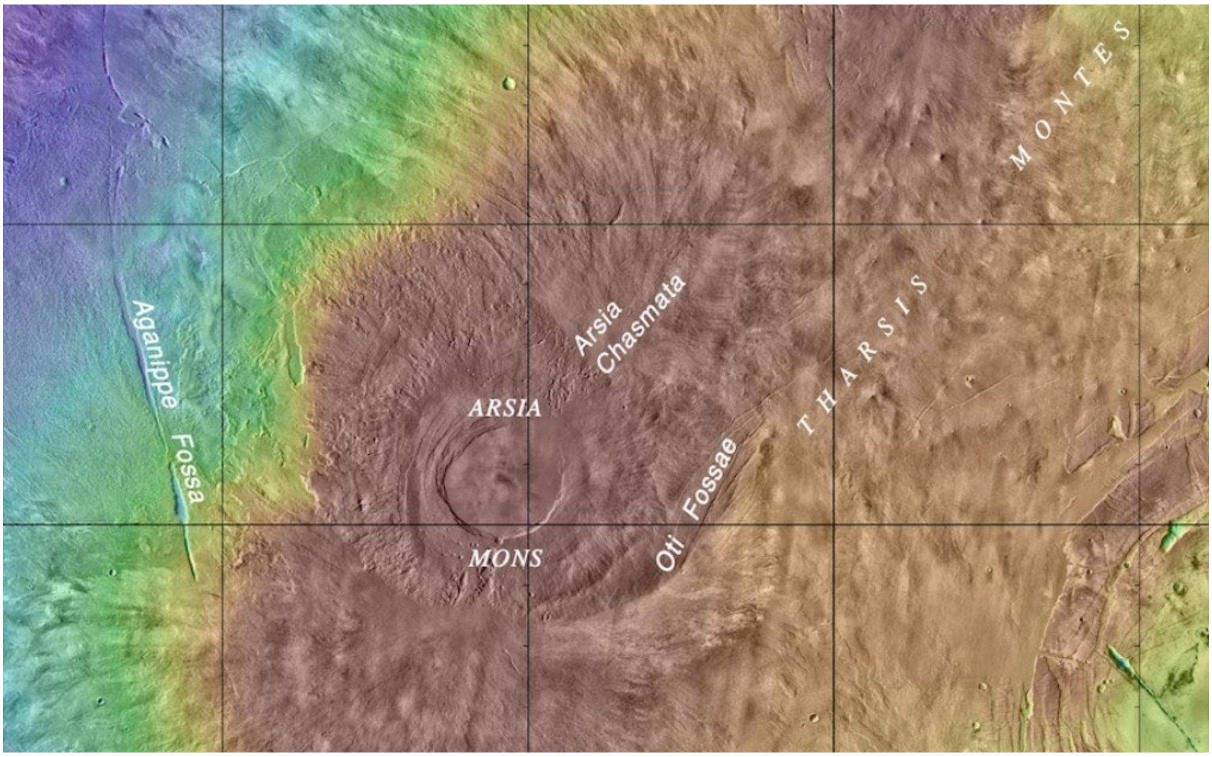
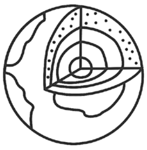


Figure 6*:* **The Arsia Mons expedition | VolcanoCafe**

3.1 CONSIDERATIONS AND OPPORTUNITIES



Geological Features

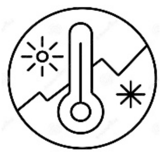
- Lava tubes offer a structurally stable environment, minimizing radiation exposure and thermal fluctuations.
- The presence of basalt-rich regolith can be leveraged for In-Situ Resource Utilization (ISRU) in construction

Energy Potential

- The combination of wind and solar power can be optimized to sustain the habitat.
- Subsurface placement within lava tubes can reduce energy needs for thermal regulation.

Protection from Radiation

- Martian surface is exposed to cosmic and solar radiation, but lava tubes provide natural shielding, reducing exposure risks for inhabitants.



Temperature Stability

- The underground environment within lava tubes helps mitigate extreme temperature fluctuations, which range from -125°C at night to 20°C in the daytime.

STRENGTHS

- Lava tubes offer a structurally stable environment, minimizing radiation exposure and thermal fluctuations.
- The presence of basalt-rich regolith can be leveraged for In-Situ Resource Utilization (ISRU) in construction.

WEAKNESSES

- Accessibility challenges related to lava tube entry and exit points.
- Limited direct solar energy due to terrain obstructions.

OPPORTUNITIES

- Development of hybrid energy solutions combining wind, solar, and nuclear options.
- Advancements in robotic excavation and 3D printing could enhance habitat scalability.

THREATS

- Unpredictable Martian dust storms could affect energy generation.
- Structural uncertainties of lava tubes requiring in-depth geotechnical analysis.

4. CASE STUDIES

4.1 Moonshot & Moonshot+

The Moonshot projects aimed to develop self-sufficient lunar habitats using interdisciplinary collaboration at TU Delft. These systems emphasized autarky, renewable energy sources like solar and kite-power, and ISRU with lunar regolith.

Design-to-Robotic-Production-Assembly & Operation (D2RPA&O) methods enabled automated construction with robotic units. Challenges included temperature fluctuations, radiation, material suitability, and autonomous robot scaling.

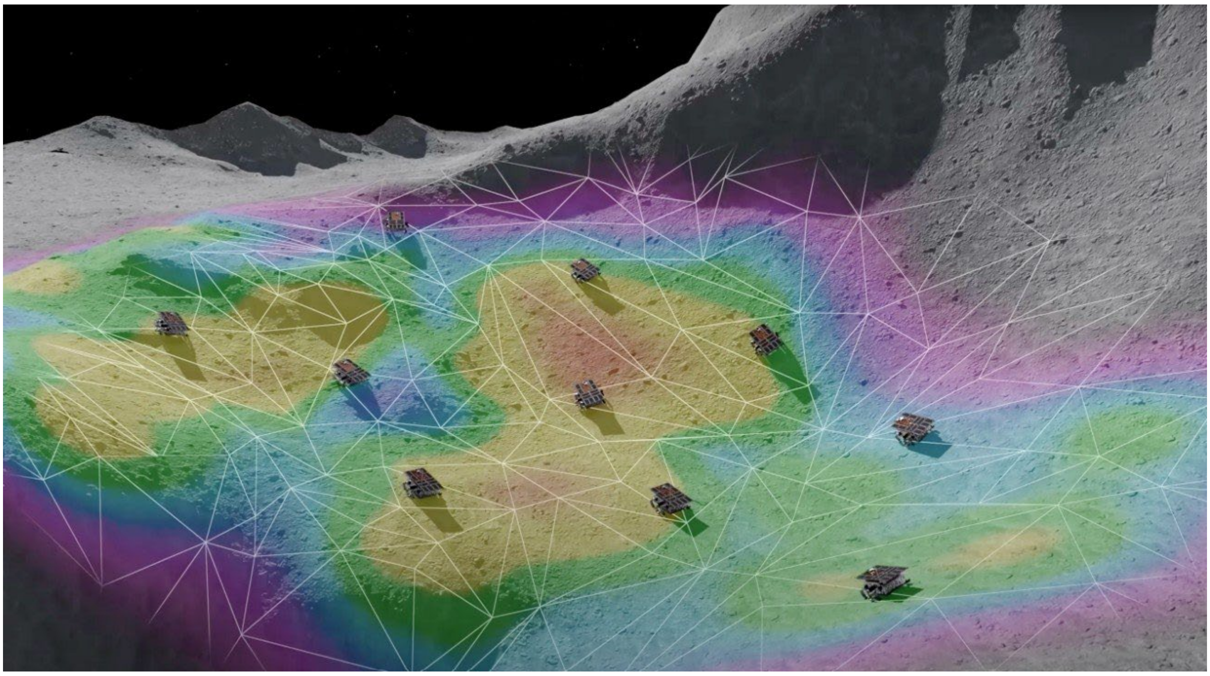


Figure 7: **Moonshot – CPA**

Key takeaways included the viability of robotic construction and material innovation using local resources—essential lessons for Martian architecture.

Despite their promising frameworks, the Moonshot projects encountered several notable challenges. These included:

- The need to design habitats that could withstand extreme temperature fluctuations, radiation exposure, and micrometeorite impacts.
- Material constraints related to the mechanical properties of lunar regolith and its suitability for 3D printing.
- Ensuring autonomous robots could operate at scale with minimal human intervention.

LEARNINGS:

- **Autonomous Construction Technologies**: Proving the viability of **robot-based construction** and its potential to reduce reliance on human labor in dangerous environments.
- **Material Innovation**: Overcoming the challenges of working with lunar materials (e.g., regolith) for practical construction.

These lessons provided a valuable foundation and reference point for future Martian habitat designs, particularly in the areas of robotic workflows, autarkic systems, and modular construction principles.

4.2 Rhizome 1.0 & 2.0

Develop a **3D-printed Martian habitat** in lava tubes using **In-Situ Resource Utilization (ISRU)** and autonomous robotic construction.

Figure 8: Rhizome 2.0: Scaling-up of Rhizome 1.0 – Robotic Building (RB)

Rhizome 1.0 (2020–2022)

Rhizome 1.0 introduced the concept of an autarkic Design-to-Robotic-Production and -Operation (D2RPA&O) system for Mars. The project introduced autonomous systems for habitat construction in Martian lava tubes using in-situ materials and solar and wind energy. It featured robotic 3D printing and swarm strategies for excavation and assembly.

Rhizome 2.0 (2023–2026)

Building on the innovations of its predecessor, Rhizome 2.0 scaled up these ideas, optimizing material use and structural performance, and refining human-robot collaboration. It tackled challenges in scalability, material durability, and autonomous construction.

Together, **Rhizome 1.0 and 2.0** form a progressive roadmap toward the realization of resilient, sustainable, and autonomously constructed habitats on Mars, where architecture, robotics, and space science intersect to envision the future of extraterrestrial living.

CHALLENGES:

- Scalability: Can the method work at real-life construction scales?
- Autonomous construction: Coordinating swarm robots for mining, 3D printing, and assembly.
- Material properties: Ensuring cementless regolith concrete is durable in Mars' extreme conditions.

LEARNINGS:

- **R/HRI-supported robotic workflows** are crucial for off-Earth construction.
- **Lava tubes offer natural protection**, but adaptability in habitat design is essential.
- **Energy self-sufficiency & closed-loop life support** are key to long-term survival.

5. DESIGN

Designing for Mars is not merely a question of architecture; it is a multidisciplinary challenge that must reconcile environmental constraints, technological feasibility, and human needs. The Martian Vorovoid project approaches this challenge by developing a habitat that is modular, self-sufficient, and deeply integrated with both the Martian context and robotic construction methods. The design narrative unfolds in two key phases: the **conceptual stage**, where foundational spatial and structural ideas are formulated, and the **development phase**, where these ideas are translated into an implementable system.

5.1 CONCEPT

Initial studies explored how to support both physical and mental health in a resource-limited, enclosed setting. The design features a vertical layout centred around a light-filled void. This void acts as a circulation spine, a light source, and a psychological anchor.

Two design variants were explored. Both emphasized modularity and resilience but differed in spatial organization and integration of access routes. Variant 02, ultimately selected, featured a centralized vertical core that supports better light distribution and connectivity across all levels. This layout enables flexible zoning and is better suited for robotic construction due to its repetitive and vertically stacked configuration.

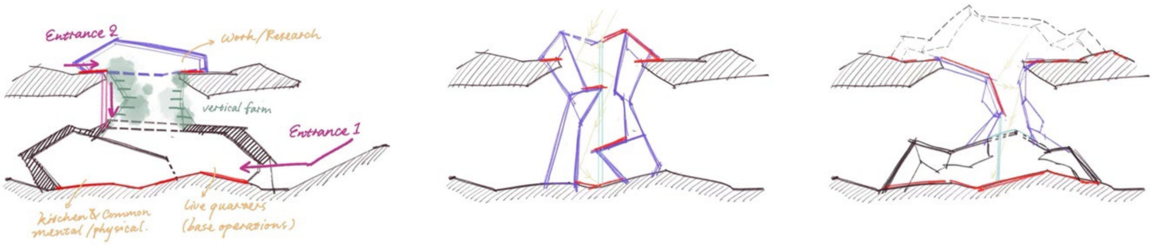


Figure 9: The three variants of design concept, Variant 02 in the middle

5.2 DESIGN DEVELOPMENT

In development, the design was refined through spatial analysis and digital prototyping. Functional zones included living spaces, work areas, medical facilities, food production zones, and recreational areas. Vertical movement solutions such as ramps, ziplines, and climbing holds were tested. Voronoi geometry was used to adapt to Martian topography and create structurally sound, adaptable forms. Each level featured essential elements like hygiene modules and EVA stations, organized to support comfort and safety.

Building upon the chosen concept, the design development phase translated abstract ideas into detailed architectural and structural systems. Here, Voronoi geometry played a key role. Inspired by naturally efficient patterns, the Voronoi logic was used to generate structurally stable forms that could house different programmatic elements while minimizing material use and maximizing spatial flexibility.

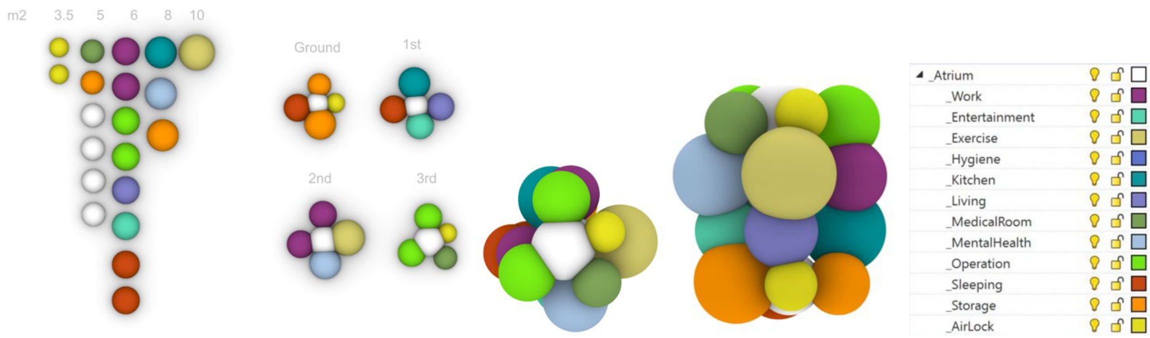


Figure 10: Voronoi structure development

A variety of mobility solutions were tested to facilitate vertical movement. Ramps allowed for robotic and human access, while ziplines and wall-climb features introduced novel strategies for both utility and recreation. These systems reinforced the goal of creating an adaptable, responsive habitat that balances efficiency with livability.

Throughout the development process, the design remained tightly linked to fabrication strategies, particularly the use of robotic milling and additive manufacturing. This allowed for continuous iteration between digital modeling and physical constraints, ensuring that every aspect of the design could be feasibly produced and assembled in a Martian context.

Figure 11: Visualisation of the central void

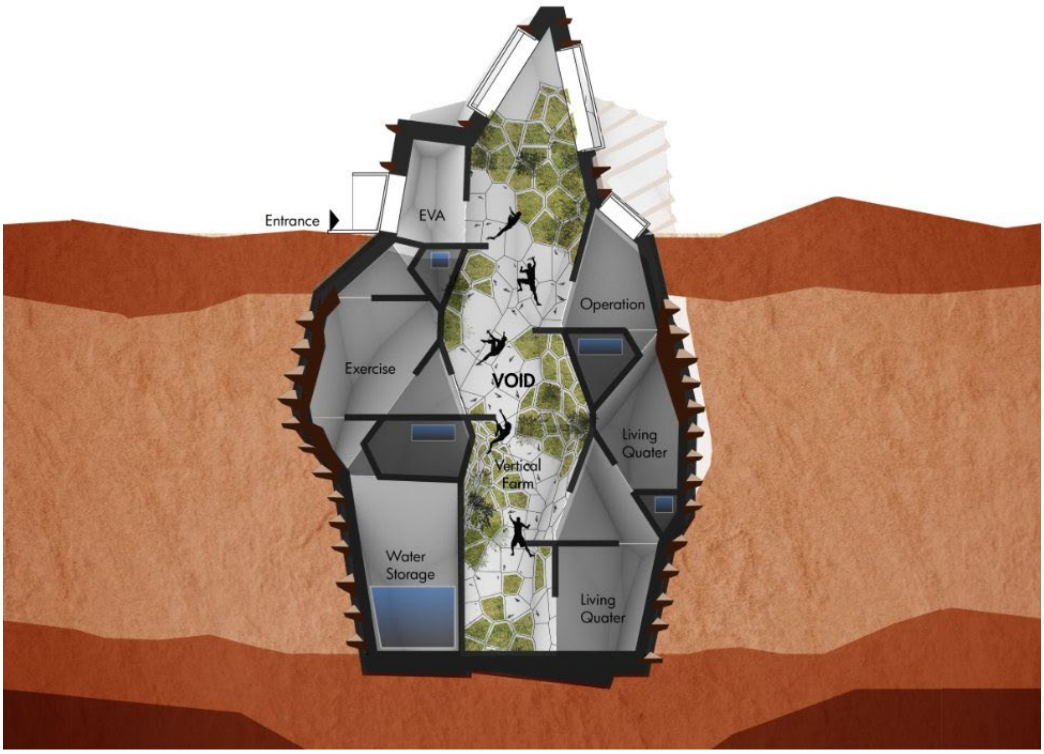


Figure 12: habitat section

6. PROJECT EXCUTION AND RESULTS

6.1 GRASSHOPPER VORONOI IMPLEMENTATION

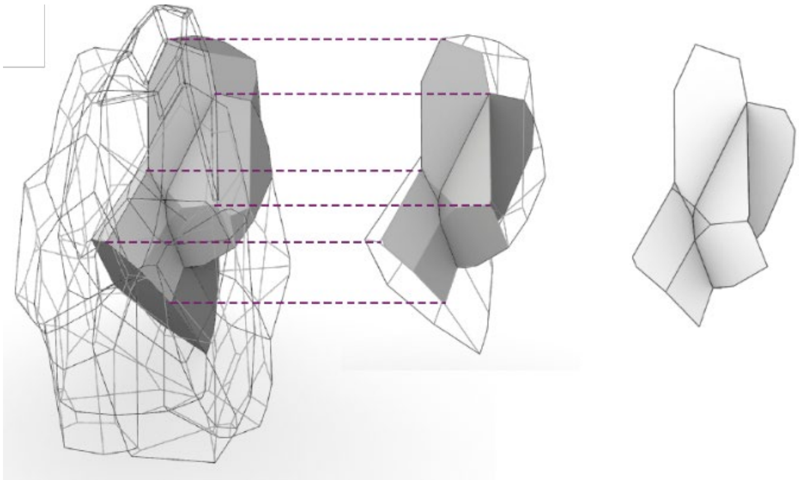
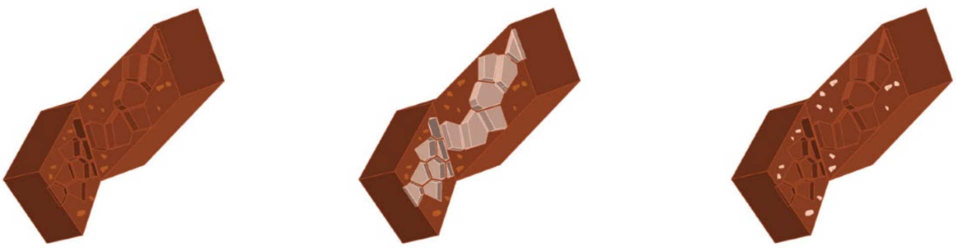


Figure 13: Selection of the fragment from the habitat

The process began by selecting a representative fragment of the habitat for testing. This fragment was digitally transformed using Grasshopper, dividing it into two polysurfaces that defined the outer and inner layers. Directional lines and meshes were used to shape kinked Voronoi cells. Randomized polylines introduced organic variability, while attractor curves guided the integration of Life Support System piping and cabling. Boolean operations adapted components for hydroponic planting and climbing, combining utility and engagement.

Figure 14: Fragment design schemes showing pots for plants and climbing holders



6.2 MILLING PROCESS

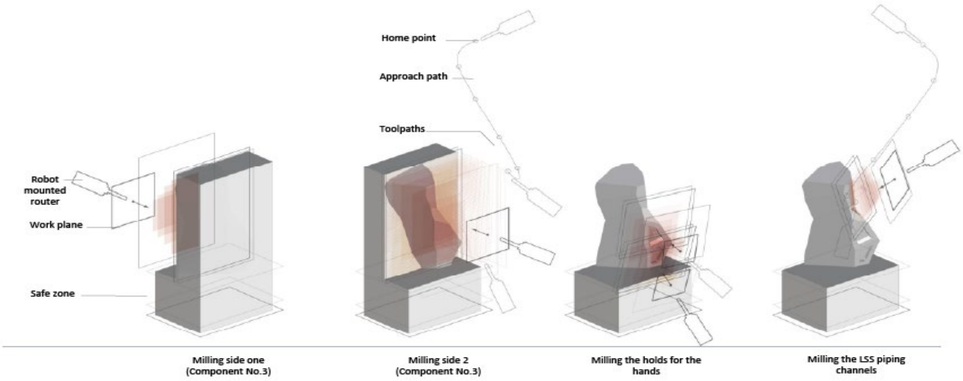


Figure 15: Milling process simulation

Robotic CNC milling was used to fabricate the fragment, divided into two sides to better prevent collision between the robot and the component. Toolpath planning, safety zones, and milling simulations ensured that the milling would go smoothly. Besides the milling of the actual component, the process also included the integration of structural and functional features - such as cable channels and plant pots - into sides and edges of the component accordingly.

6.3 HUMAN ROBOTIC INTERACTION (HRI)

Following fabrication, the habitat was assembled through coordinated human-robot collaboration. The components were designed for modular, vertical stacking to streamline construction. External ramps integrated into the outer shell allowed robots, such as the Lunar Zebro equipped with robotic arms, to ascend the structure and perform tasks.

Martian regolith was first processed into a printable material, used to fabricate the Voronoi-based components through robotic milling or 3D printing. During assembly, the robot, guided by computer vision, handled lifting and positioning while the human operator ensured precision in placement. This hybrid approach leveraged both robotic accuracy and human adaptability, resulting in a safe and efficient construction process.

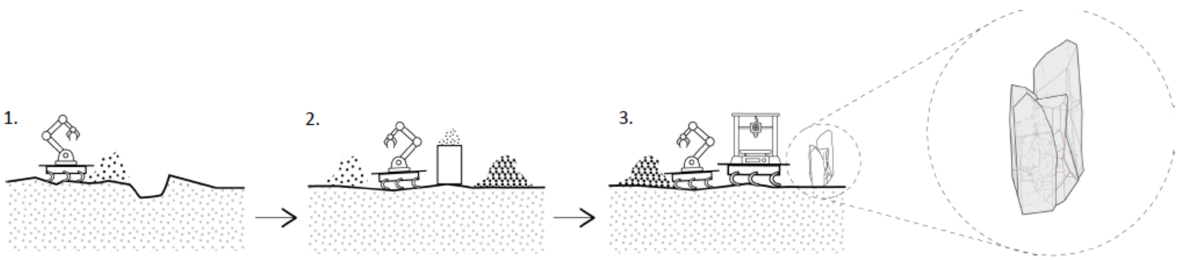


Figure 16: Construction process from the extraction of regolith to 3D printing of fragments

7. CONCLUSION

The Martian Vorovoid project represents a comprehensive exploration into how we might live sustainably on Mars. By leveraging Martian lava tubes, in-situ materials, robotic construction, and adaptive architectural design, the project offers a viable prototype for future habitation. Through detailed site analysis, precedent research, parametric modeling, and physical prototyping, the team addressed challenges of autonomy, structural integrity, and environmental adaptation. The integration of human-robot collaboration and multifunctional design elements furthers the goal of constructing livable habitats in harsh extraterrestrial environments.

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