LUNASCAPE REPORT

1:1 Interactive Architecture Prototypes

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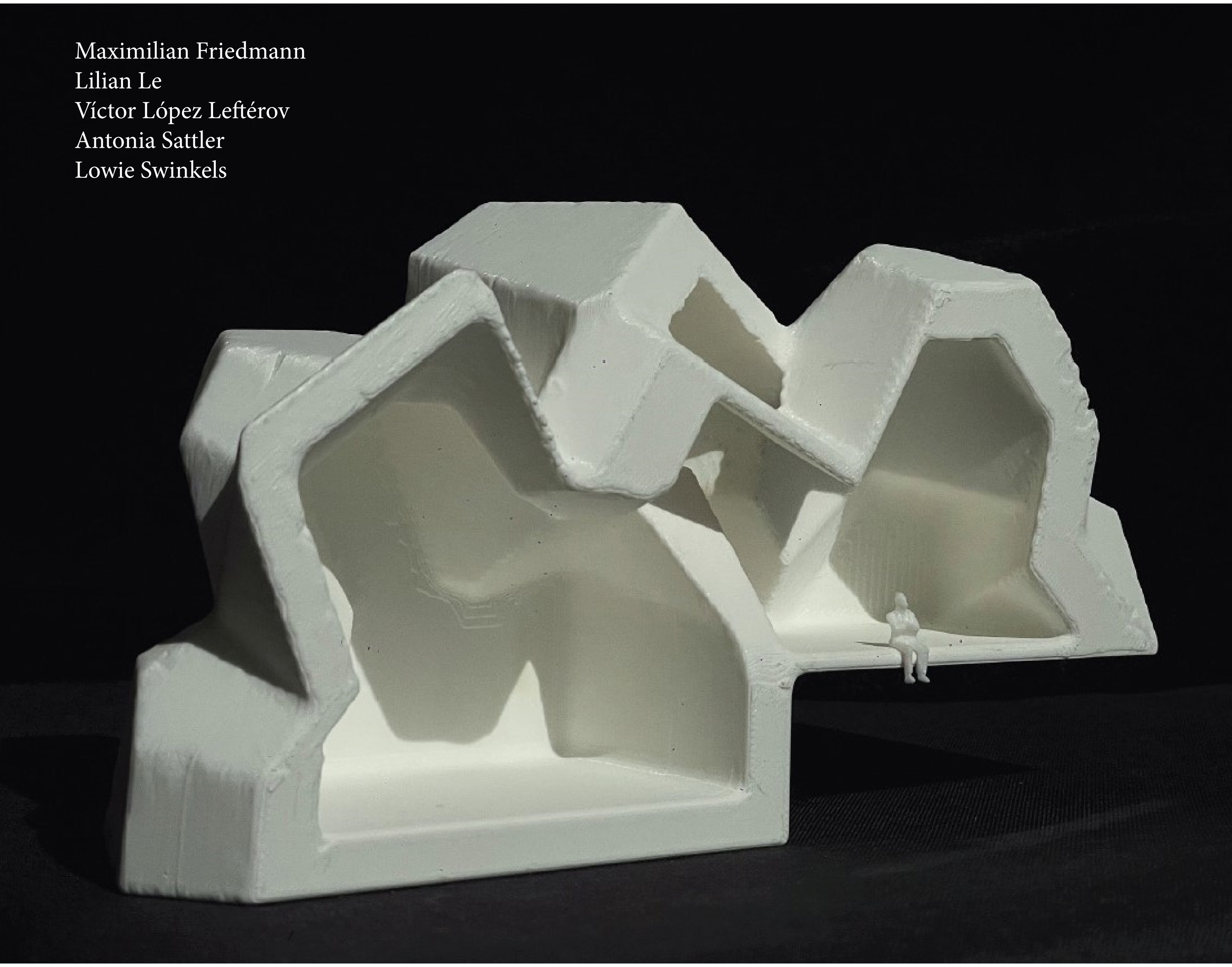

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Abstract

Moving to off-Earth environments requires architecture and infrastructure suitable to provide a safe home for its inhabitants. In order to achieve that, local resources and innovative architectural concepts must be applied to reduce the transport expenses, supply sufficient radiation protection and enable good wellbeing of the astronauts. This project aimed to do that by creating a Voronoi-based habitat structure that can grow with the size of the crew and adapt to the local environment. This work documents the development of those habitats located on the Lunar South Sverdrup-Henson crate intended for a crew size of 5 astronauts at first arrival with the option to expand to a small moon village. Consequently, the local terrain of the Lunar South Sverdrup-Henson crate was analyzed, the interior configuration of the habitats was designed and the assembly process was detailed. Further, a Grasshopper script was developed that incorporates the growing process of the habitat modules and considers different room purposes and the correlating needed radiation protection.

Keywords: Space Architecture, Lunar Architecture, Voronoi

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1. Introduction

“Lunascape” represents a pioneering endeavor at the intersection of architecture, robotics, and additive manufacturing. The project embodies the culmination of interdisciplinary collaboration and technological ingenuity, aimed at addressing the multifaceted challenges inherent in lunar habitat construction and operation.

At its core, “Lunascape” leverages advanced 3D printing techniques to fabricate intricately designed Voronoi-shaped concrete blocks. Inspired by the organic structures found in nature, the Voronoi tessellation serves as a paradigm of efficiency and resilience, optimizing material usage while enhancing structural integrity. Through the utilization of lunar regolith as a primary construction material, “Lunascape” epitomizes the principles of in-situ resource utilization (ISRU), laying the foundation for self-sustaining extraterrestrial habitats.

Central to the realization of “Lunascape” is the integration of robotic systems capable of autonomous assembly and interaction with human collaborators. These robotic agents, equipped with sophisticated sensors and AI algorithms, orchestrate the assembly process with precision and adaptability. By facilitating seamless human-robot collaboration, “Lunascape” redefines traditional notions of construction methodology, fostering a symbiotic relationship between man and machine in the extraterrestrial context.

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2. Research and Methodology

The 10-week project followed the workflow as seen in Figure 1. On the architecture site, it started with a Research phase about human needs and environmental conditions, continued with a Concept Generation phase about the habitat concept, which was followed by the concept detailing defining the specific design decision. On the technical site, in parallel to the concept generation, the phase dedicated to the Grasshopper script started and was followed by the project phases about the robotic milling and 3d printing.

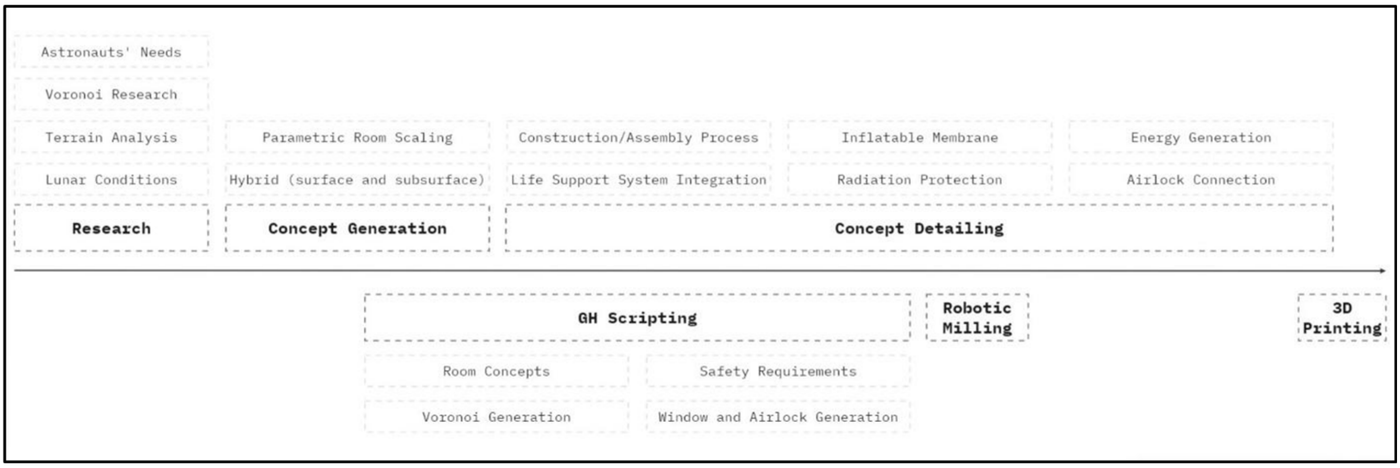

Figure 1: Project Workflow

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The following chapters detail the analysis process of this project by looking at the location, local climate, astronauts' needs and programmatic needs.

2.1 Site and Climate Analysis

The Lunar South Sverdrup-Henson crater, offers ideal conditions for a prospective lunar settlement. Its flat topography, abundant ice water supply in permanently shaded regions (PSRs), and continuous sunlight during the day make it suitable for various operations, including solar power generation and ground antenna construction for Earth communication. Terrain slopes (which are normally between 5-10°, or lower) are conducive to safe spacecraft landings and surface operations, while the area's rich mineral resources, including iron, titanium oxides, and rare earth elements, further support future exploration and utilization efforts (Leone, G. et al., 2023). Figure 2 showcases the proposed site area and its context in both slope and topography maps.

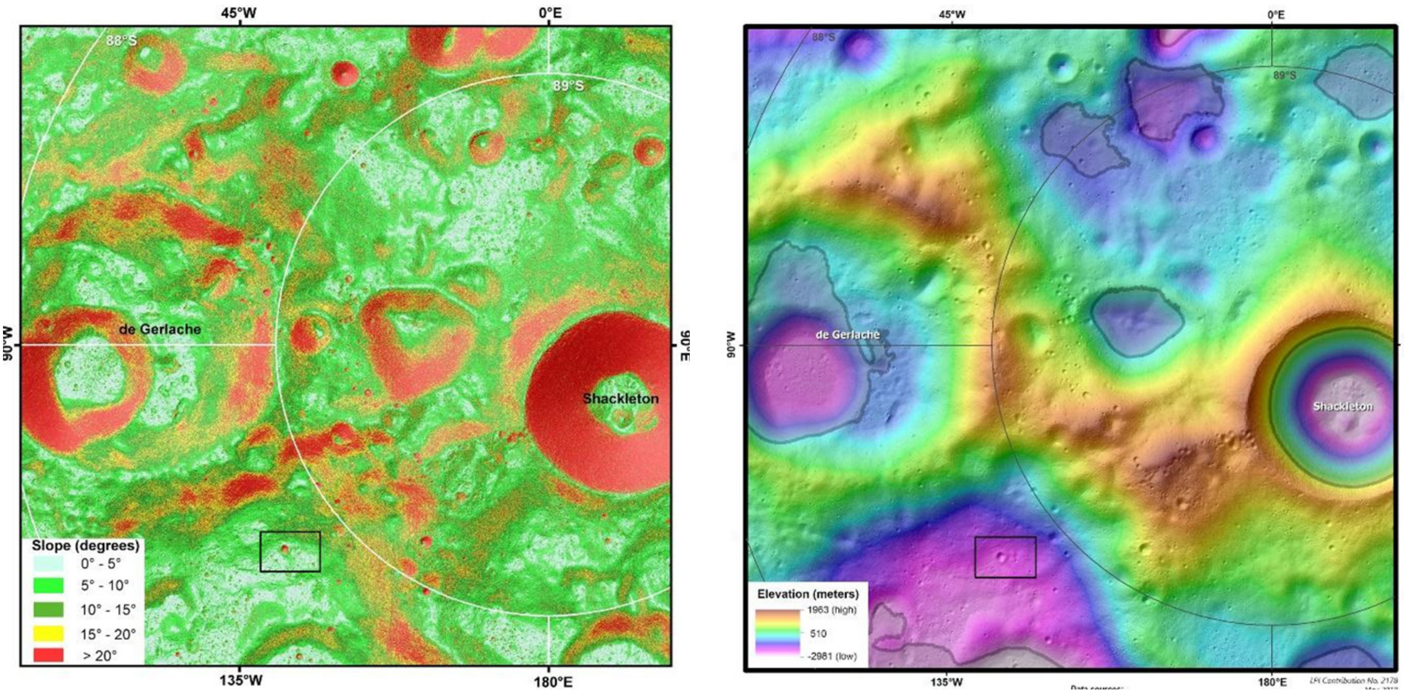

Figure 2: The Lunar South Sverdrup-Henson crater (https://www.lpi.usra.edu/lunar/lunar-south-pole-atlas/)

The lunar environment is characterized by extreme temperature fluctuations (+127 °C to -173 °C), intense solar radiation (60 µSv/hr), low gravity (1.62 m/s²), and long, alternating periods of sunlight and darkness due to the Moon's 29.5-day lunar day. Micrometeoroid impacts regularly disturb the surface, exposing fresh material, while the thin exosphere contains non-breathable gases such as helium, argon, and methane (Barry, C., NASA).

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2.2 Astronauts' Needs

Not only astronauts' physical health but also their mental wellbeing must be ensured during long term space missions. In order to facilitate an architectural concept that is considering those needs and providing a safe, comfortable work environment and home we analyzed the daily routines of astronauts and came up with a exemplary schedule to determine programmatic needs of the habitat concept:

- Wake-Up: 06:00
- Personal Hygiene and Breakfast: 06:00 - 07:00 (1 hour)
- Pre-Mission Briefing: 07:00 - 07:30 (30 minutes)
- Suit-Up and Pre-EVA Checks: 07:30 - 08:30 (1 hour)
- Lunar Surface Activities: 08:30 - 13:30 (5 hours)
- Return to Habitat/Spacecraft: 13:30 - 14:00 (30 minutes)
- Lunch and Rest Period: 14:00 - 15:00 (1 hour)
- Science and Research: 15:00 - 17:00 (2 hours)
- Exercise: 17:00 - 17:30 (30 minutes)
- Dinner and Leisure Time: 17:30 - 18:30 (1 hour)
- Evening Briefing and Planning: 18:30 - 19:00 (30 minutes)
- Sleep Period: 19:00 onwards (varies, depending on individual sleep needs)

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2.3 Programmatic Needs and Safety Requirements for each Zone

The programs onboard the space station include Berthing, Recreation, Workspace, Exercise Spaces, Hygiene, Multi-purpose Storage, and an Underground Safety Bunker. Each program occupies a specific volume, has designated time allocations, and is either above or below ground. Additionally, each program has a varying number of exit points based on internal risks, with corresponding internal risk ratings and safety precaution needs.

- Berthing: Involves docking procedures for vehicles with controlled access and secure docking mechanisms. It requires multiple exit points for emergency evacuation and has a moderate internal risk rating.
- Recreation: Includes private sleeping quarters, shared dining, and lounging spaces. These areas are below ground for heightened security. They have multiple exit points and are rated high in terms of internal risk, requiring stringent safety measures.
- Workspace: Comprising multifunctioning labs and hydroponics, this program involves controlled space usage with high-security protocols. It has multiple exit points and is rated high in internal risk.
- Exercise Spaces: Above ground areas for exercise, with interaction with lunar light. These spaces have two exits and are rated at a low internal risk.
- Hygiene: Consists of communally shared bathing and bathroom spaces below ground. They have controlled access and one exit each, with a low internal risk rating.
- Multi-purpose Storage: Provides secure storage with restricted access and inventory management systems. It has two exits and a moderate internal risk rating.
- Underground Safety Bunker: Reserved for emergencies, it has controlled access, life-support systems, and multiple exits. It is below ground and rated high in internal risk.

Overall, these programs are designed with safety and functionality in mind, considering the unique challenges of space environments and the potential risks involved.

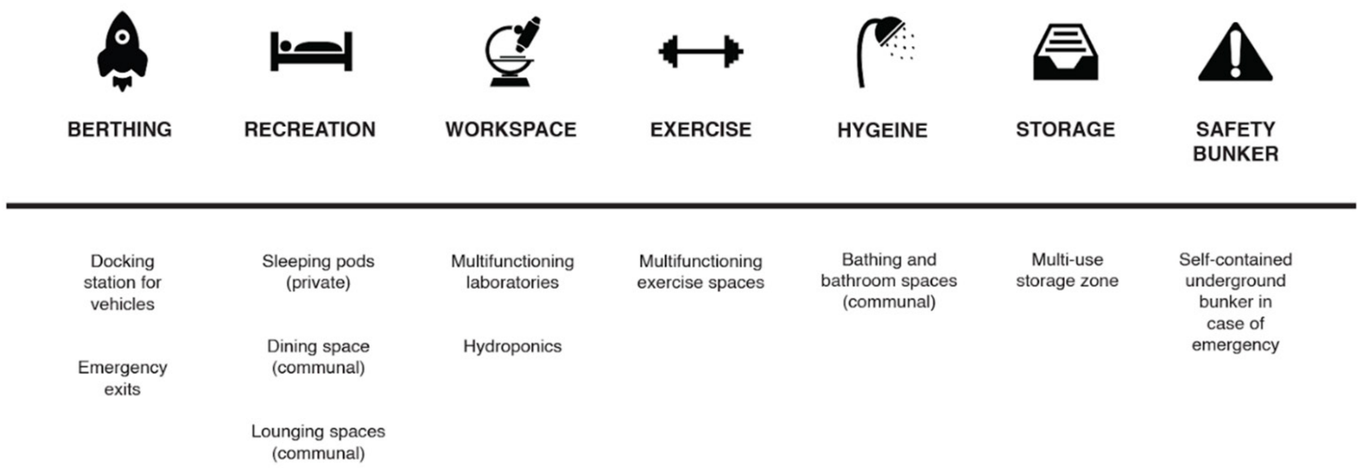

Figure 3: Overview of Room Purposes

3. Project Execution and Results

The following chapter is dedicated to the design outcome, the Grasshopper script that is generating it and the technical implementations detailing the assembly and construction process.

3.1 Grasshopper Voronoi implementation

The developed algorithm consists of several components that interact sequentially. These steps are logically derived and structured as follows:

1. Input based on a ‘program of requirements’ is provided to the script.
2. The ‘program of requirements’ is transformed into a (2D) point grid, which connects the routing and spatial relationships between areas.
3. These points are associated with “attraction points,” enhancing the flexibility of the floor plan. During later stages of the design process, individual spaces linked to these points can still be relocated, with the entire floor plan being automatically adjusted accordingly.
4. Based on ‘risk levels,’ the points are moved along the Z-axis (with higher risks resulting in lower Z-axis coordinates).
5. The points (linked to the spaces) can also be manually adjusted, providing the Grasshopper script with increased flexibility.
6. Once all points are placed at their correct coordinates, they are converted into Voronoi cells/spaces.
7. The final step involves creating window openings. These openings consist of small triangular shapes, based on the required amount of light in a space and the angle of radiation. This process is linked to another “attraction point” indicating the location of the most radiation. At this point, window openings will be minimal, while the distance from this point determines the size and frequency of the openings.

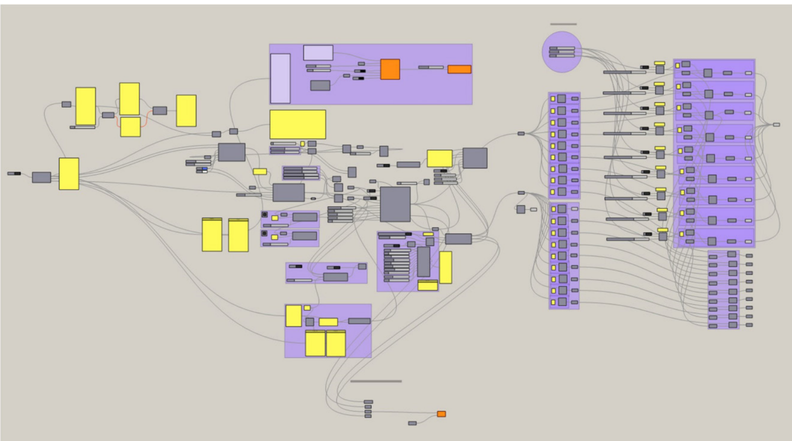

Figure 4: Floorplan, Risk Level script

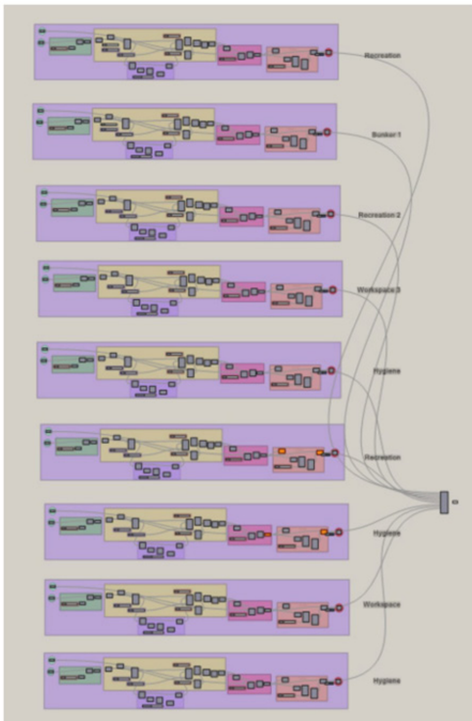

Figure 5: Manuel adjustment per room based on risk level script.

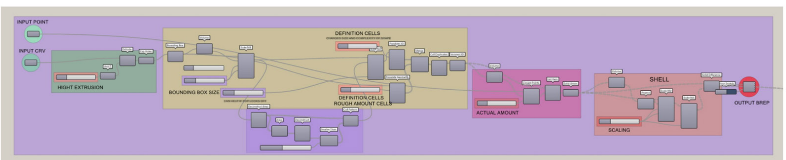

Figure 6: Voronoi script

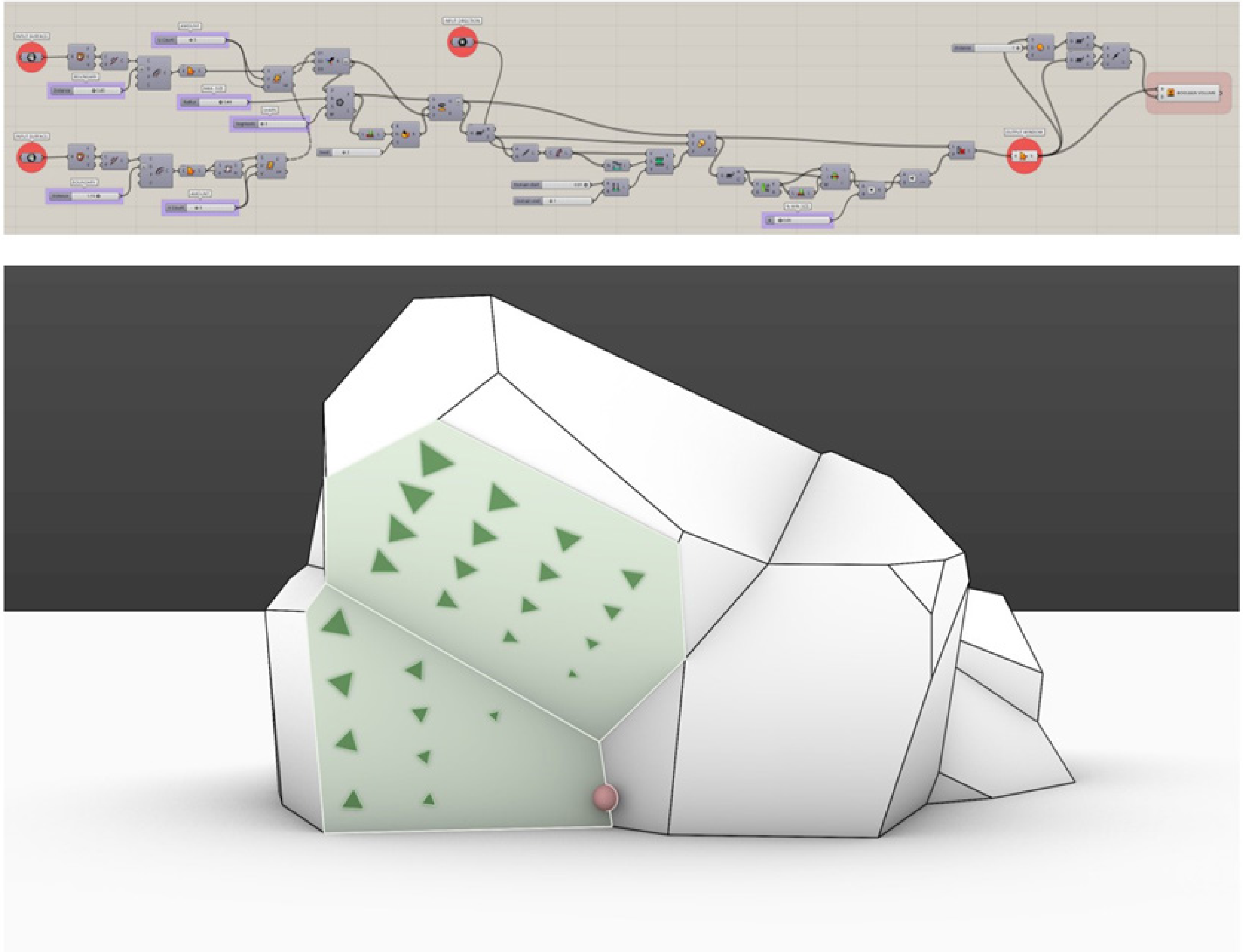

Figure7: Generation of Windows script

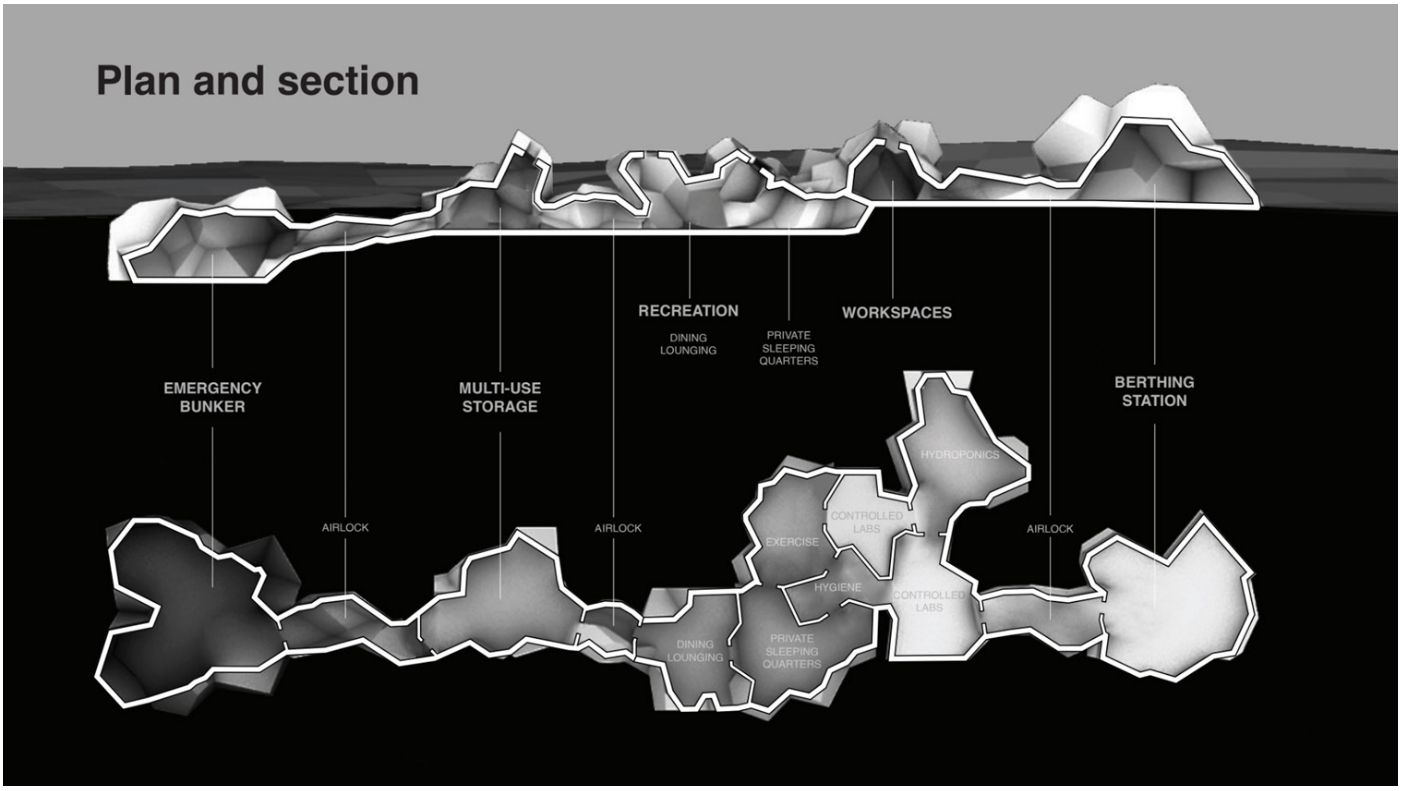

Figure 8: Plan and Section

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3.2 Assembly and Construction

The habitat grid follows a hexagonal pattern. The 3d printed Voronoi components will be connected though airlocks and contain an inflatable membrane on the inside. Two sizes of inflatable membranes exist. The “base” membrane is large and attached to an airlock on one side and to a connector on the other side. The small membrane, the “add-on”, has two connectors on each side of the membrane.The airlock modules have three entrances to connect modules and provide access from the lunar surface. They also contain the bio-regenerative life support system MELISSA.

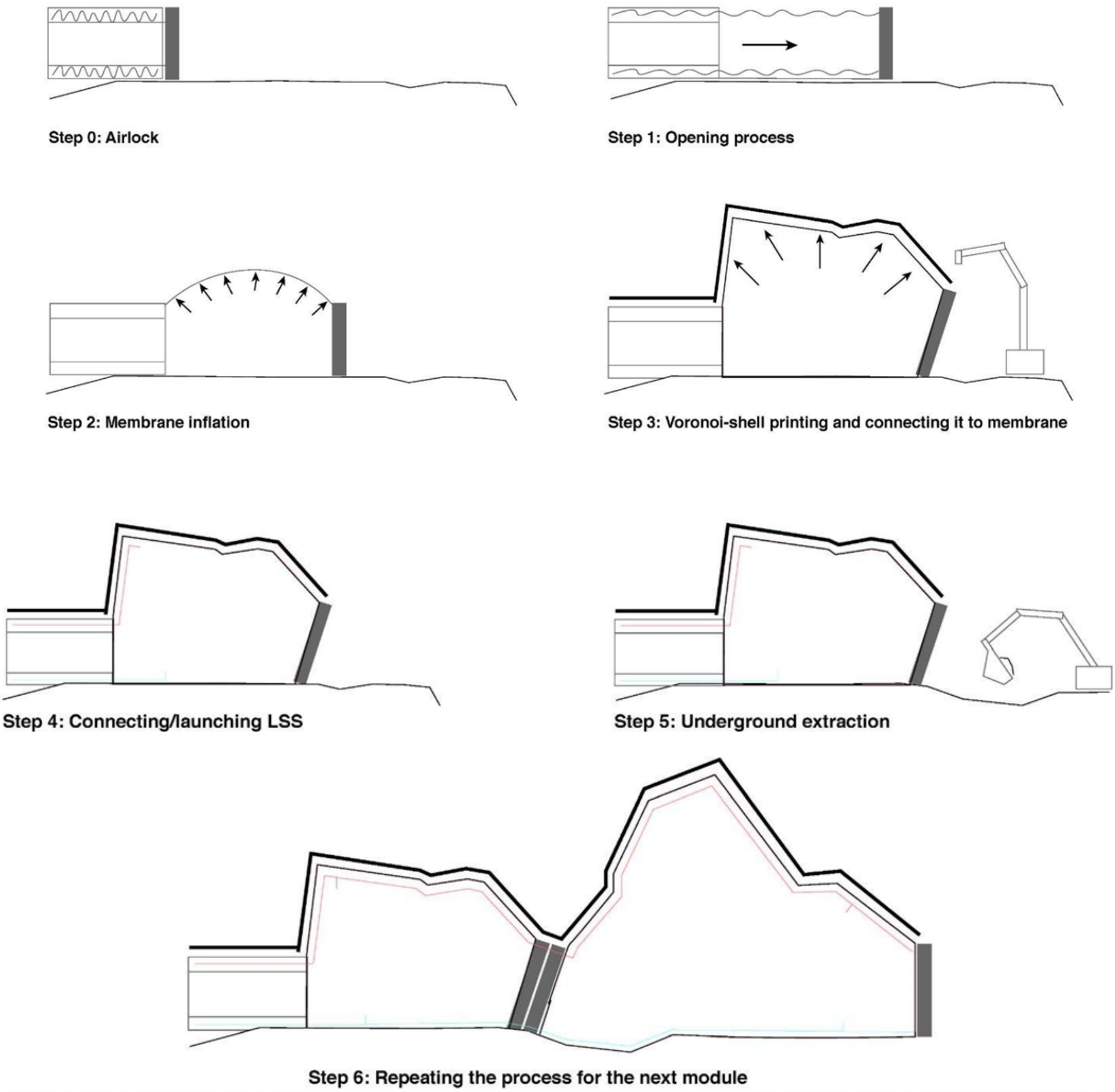

Figure 9: Assembly Process

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The membrane consists of four layers. The first one, is an array of sensors monitoring the oxygen level, carbon dioxide and temperature as well as smoke levels. The sensors are connected to the second layer that is made from Vectron and acts as an air barrier. The third layer is a thermal shield made from Mylar. The outer layer is the radiation shield (Polyethylene) with solid spikes to interlock with the Voronoi structure and provide a solid connection between membrane and 3D print.

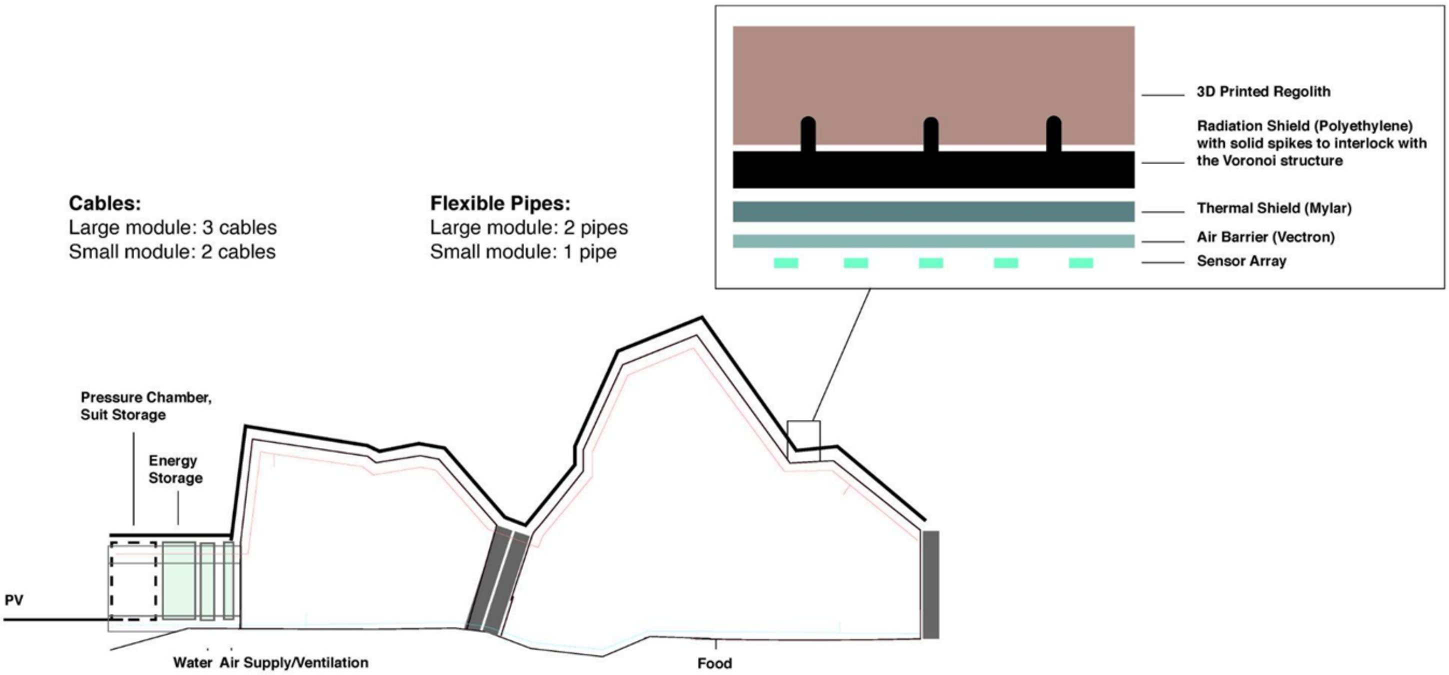

Figure 10: Membrane Layers and Airlock Overview

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3.3 Robotic Milling

To investigate the geometrical properties of the Voronoi components, five segments were selected, see Figure 11, and prepared for robotic milling in Grasshopper 3D, see Figure 12. The process commences with a Grasshopper simulation to preemptively identify potential clashes, facilitating preemptive action. Subsequently, the milling process is executed on an EPS foam block using a KUKA robot, this robot can be manually adjusted giving it input on the speed and movement for the milling-proces. The robot that was used for this process is a 6 axis production robot from KUKA.

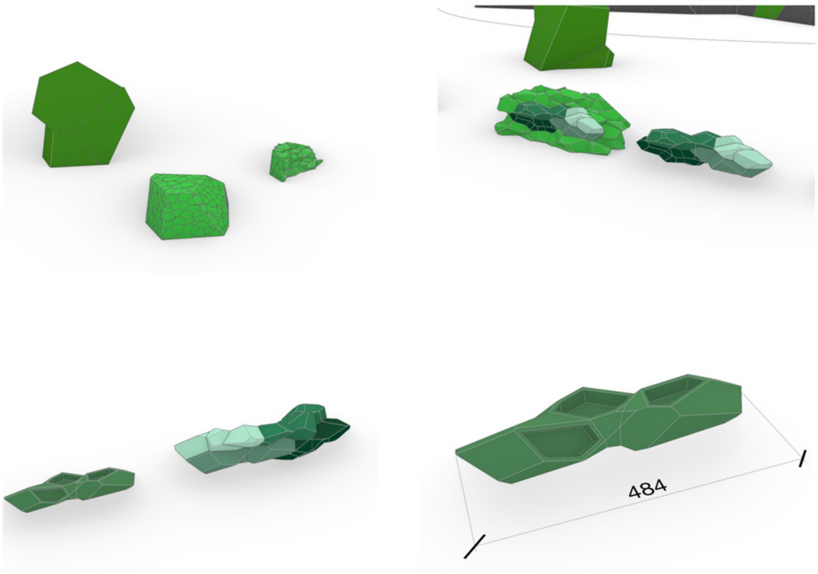

Figure 11: Selected Voronoi fragments

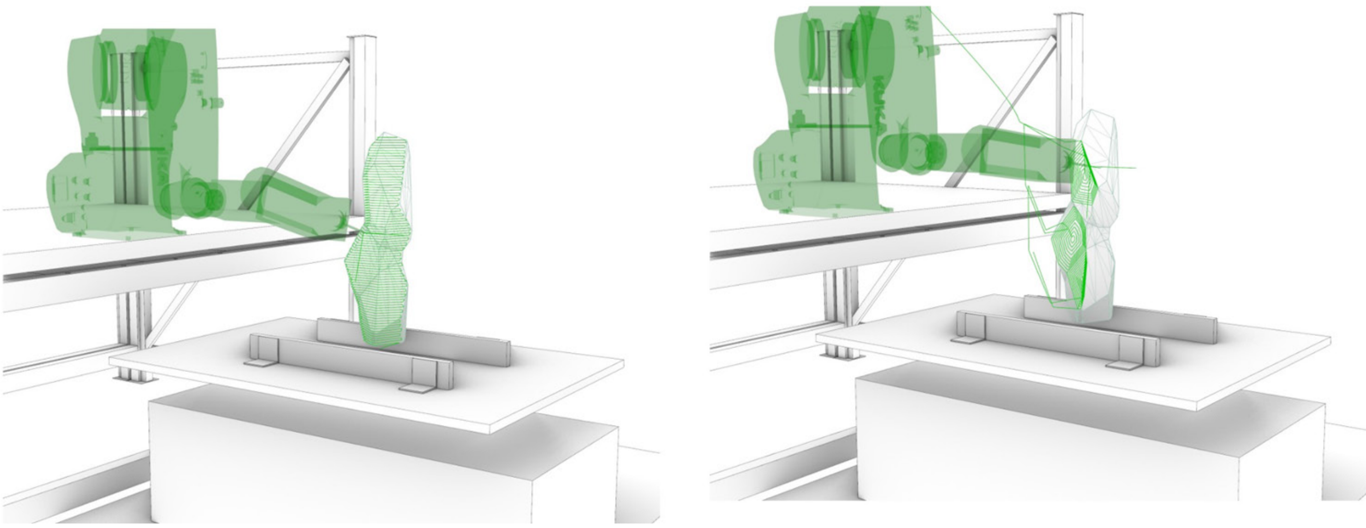

Figure 12: Robotic milling simulation in Grasshopper

Figure 13: Robotic Milling of Voronoi fragments

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The milled Voronoi fragments were used as part of a human robot interaction workshop to further explore the possibilities and limitations of that construction method.

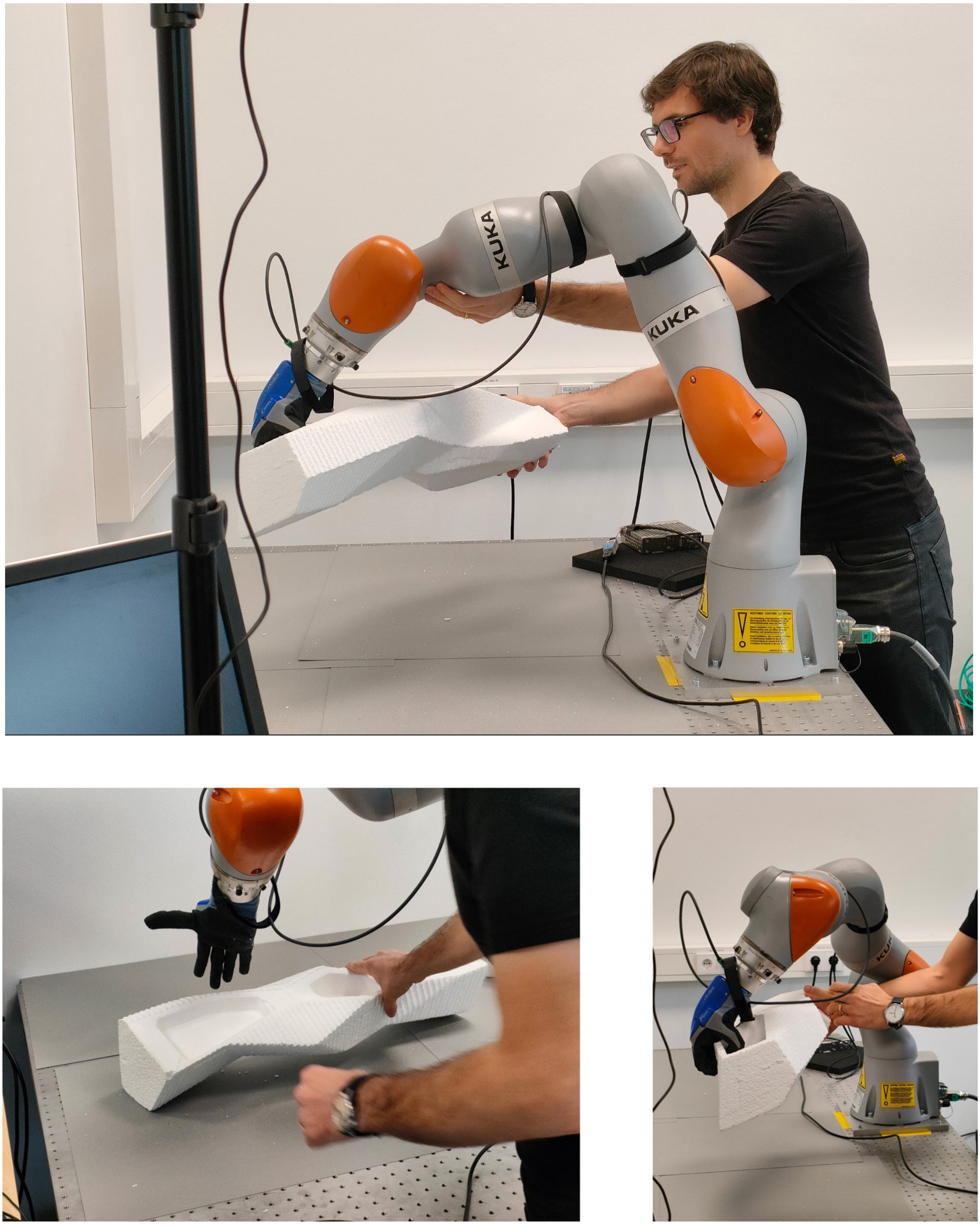

Figure 14: Assembly Process of the robotically milled Voronoi fragments

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4. Conclusions

This document describes the research, methodology and outcomes of a student project developed as part of the 1:1 Interactive Architecture Prototype Workshop at TU Delft in 2024. It detailed the analysis of the astronauts' needs and lunar environment, explained the methodology including the parametric design concept with Grasshopper, technical implementation regarding assembly and construction and robotic milling of Voronoi fragments. The project shows a scalable habitat concept made from 3D printed Voronoi components and its potential implementation. While certain aspects concerning the complex requirements for a lunar base are covered as part of this project, due to the limited time scope, critical aspects must be further and in more depth explored in the future. Due to the complex nature of a lunar base, the specifics of a robotic construction and assembly process on the Moon as well as many other technical details must be researched and tested during extensive development periods. Next steps as part of the "LunaScape" project would entail feasibility tests concerning the 3D Printing of the Voronoi cells around the inflated membrane and detailing the connection between the two.

Figure 15: Artistic Impression of the Voronoi Environment

5. Acknowledgements

We would like to thank Henriette Bier and Arwin Hidding for providing us with the resources and tools to create new insights for architectural and robotic innovation in an extraterrestrial setting and for the great support throughout the course of the project. Special thanks as well to Luka Peternel for giving a very interesting Human-Robot Interaction workshop.

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