The *Submartian* – New Vernacular on Mars

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Abstract

This research explores a new habitat design for Mars, proposing a new architectural vernacular grounded in sustainability, adaptability, and cultural continuity. The SUBMARTIAN project proposes a modular underground settlement. It is located in the Tharsis region, inside a lava tube, which offers natural protection from Mars' harsh environmental conditions. The design uses local materials, such as Martian regolith, for sustainable construction. The central part of the habitat is a shared garden, supporting mental health and cultural connection to Earth. Nature becomes part of the architecture, not a separate system.

The project integrates parametric tools and generative design methods. It uses a Voronoi-based structural system to optimize space, strength, and modularity. This type of geometry supports 3D printing using local materials such as regolith. The design follows a Design-to-Robotic-Production and Operation (D2RPA&O) workflow, enabling digital-to-physical translation of complex forms. Human-Robot Interaction (HRI) allowed safe and precise collaboration between humans and machines. The design process was based on site analysis, parametric modeling in Grasshopper, and robotic prototyping. These steps helped test how the structure could be formed and built.

The result is a scalable, site-specific habitat system that addresses both logistical and human-centered needs. Further research is recommended to test the structural strength of regolith-based structures and develop interlocking components suitable for both manual and robotic assembly. This work contributes to the broader discourse on space architecture by emphasizing the intersection of vernacular form, digital fabrication, and the well-being considerations essential to off-Earth living.

Keywords:
Design-to-Robotic-Production and Operation (D2RPA&O), Human-Robot Interaction (HRI), In-Situ Resource Utilization (ISRU), Mars Habitat, Voronoi-Based Design

1 Introduction

The increasing interest in human presence on Mars has brought new urgency to developing autonomous, sustainable off-Earth habitats. Mars' extreme environmental conditions demand site-adaptive, resource-efficient, and technologically innovative solutions. Recent projects have emphasized integrating in-situ resource utilization (ISRU), robotic construction, and self-sustaining systems from the earliest design stages (Foster + Partners, 2025; Moonshot+, 2024).

The *SUBMARTIAN* project proposes a new Martian vernacular architecture: a modular underground habitat system embedded within lava tubes in Arsia Mons' northern region. Central to the design is a shared garden space - a spatial and cultural anchor that reintroduces nature into the Martian context. The aim was to create a prototype for 5 astronaut groups, scalable to accommodate a community of 50.

The design employs a Voronoi-based system to optimize the structure's adaptability and fabrication potential. This approach maximizes space efficiency and structural integrity while supporting modular expansion and on-site 3D printing using Martian regolith. Generative tools like Grasshopper enable site-specific, parametric adaptation.

This research contributes a site-sensitive architectural strategy that responds to both physical constraints and cultural needs, advancing a human-centered, materially conscious vision for life beyond Earth.

2 Research Methodology

The project explores the development of the Mars habitat using Design-to-Robotic-Production-Assembly and -Operation (D2RPA&O) methods. The building integrated Voronoi-based design for robotic 3D printing on Mars and used Human-Robot interaction (HRI) for construction, with a consideration of the Life Support System involved. The methodology began with the research process to determine the Mars habitat’s location, function, and concept, parametric modelling using grasshopper script, and physical prototyping using robotic milling and 3D printing to generate the form.

3 Analysis

3.1 Challanges on Mars

Designing for Mars means confronting an extreme environment. Challenges include extreme temperatures (ranging from –143°C to +20°C), a thin atmosphere with low pressure, and high radiation levels. Its surface, shaped by craters, canyons, and volcanic activity, requires careful adaptation of materials and construction methods. Due to its pristine nature, Mars has great scientific and cultural significance. Designing in such an environment requires careful consideration. Resource scarcity forces the use of in-situ materials such as regolith. Despite being a sustainable solution, their extraction could lead to permanent changes to the Martian landscape.

Figure 1 Landscape of Mars (ESA/DLR/FU Berlin; JPL-Caltech/University of Arizona/NASA)

Figure 2 NASA/JPL-Caltech/MSSS

3.2 Case Studies

The four projects present distinct yet interconnected strategies for extraterrestrial living, each responding to the challenges of sustainability, space, construction, and materiality with its own logic.

Energy is the thread that binds survival. Moonshot gathers the sun, weaving solar panels and waste recovery into a closed system. Rhizome 1.0, by contrast, builds in modules, expanding outward, but its energy source remains undefined—a structure without its vital stitch.

Space is both containment and connection. Communal Housing Typology on Mars links its units in a flexible grid, a fabric of shared living. Moonzome compacts itself into a dome, curving inward for protection, where circulation is internal, movement contained. One spreads, the other shelters.

Construction is a negotiation with the ground. Rhizome 1.0 and Moonshot descend into it, burying themselves for protection. Moonzome and Communal Housing Typology on Mars remain partly exposed, suspended between concealment and accessibility. To dig or to rise—a choice that shapes resilience.

Each project is a weaving of choices—expansion or containment, exposure or shelter, what is found or what is made—together forming the patterns of habitation beyond Earth.

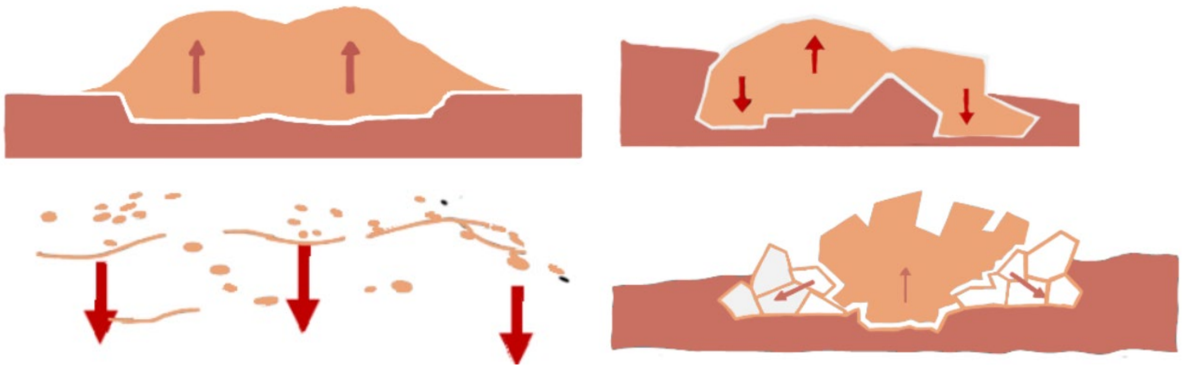

Figure 3 Site implantation; case study

3.3 Implementation

The architectural strategies we have adopted draw directly from our previous case studies.
First, the use of regolith is a core principle: inspired by Communal Housing Typology, we have employed local material to create protective shells that values in-situ resources.

Next, the underground siting echoes the approach of Rhizome 1.0 and Moonshot: fully burying the structure maximizes safety and thermal stability. We have explored light wells and ventilation shafts to maintain occupant comfort while remaining below the surface.

The dome form, inherited from Moonzome, proves particularly well-suited to resisting external loads. Its simple, efficient geometry evenly distributes stresses and reduces exposed surface area. Finally, the evolving modular system, inspired by Rhizome 1.0 and Communal Housing, allows for progressive expansion: standard modules multiply and interconnect over time, adapting the habitat to the community's growing needs.

4 Design

4.1 Concept

The SUBMARTIAN envisions a new Martian vernacular structure that merges architecture and nature in an underground habitat. The central part of the design is a communal space – a garden. More than a food source, it is a cultural anchor that supports psychological health, social interaction, and a sense of Earthly continuity Nature is not an afterthought but a vital, integrated presence, reflecting traditions of courtyards and communal green spaces across civilizations.

The underground habitat uses existing lava tube structures for natural insulation and protection. This strategy shields inhabitants from extreme conditions while reducing construction demands. By building within and with the Martian landscape, *SUBMARTIAN* minimizes environmental disruption and fosters a self-sufficient, ethically conscious model for future extraterrestrial living.

Figure 4 Growing plans for food as necessity (DLR / NASA / Bunchek - EDEN-ISS; ESA)

Figure 5 Visionary images of space designs that include plants – a well-being aspect (Silent Running, 1972; NASA/Painting by Rick Guidice - Bernal Sphere)

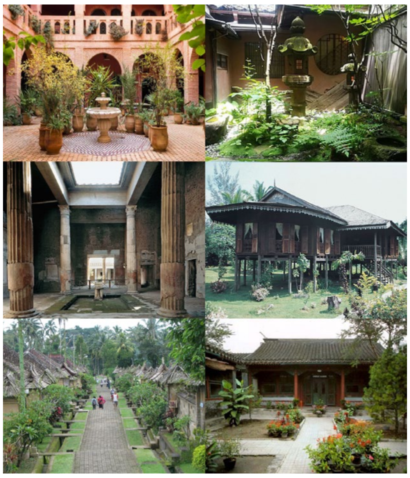

Figure 6 Green courtyards and gardens as part of our culture (Riad, Morocco; Tsuboniwa, Japan; Atrium, Ancient Rome; Malay Stilt House ; Balinese Houses; Siheyuan, China)

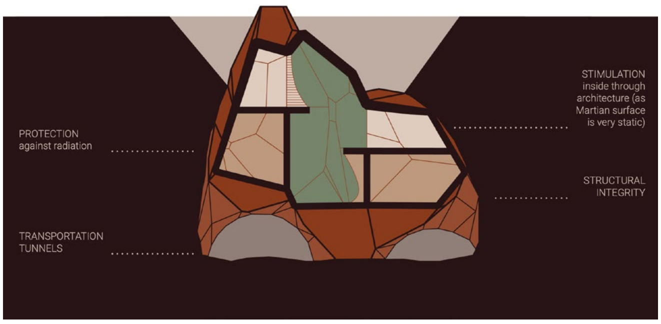

Figure 7 Cross-section showing new vernacular on Mars

4.2 Location

The *SUBMARTIAN* habitat is sited just north of Arsia Mons in the Tharsis region, selected for its network of candidate lava tubes, inferred from skylight-like depressions observed in orbital imagery (Tettamanti, 2019). The site was chosen for its smaller tube diameters, ideal for initial modular development. While their full structural integrity remains uncertain, they offer significant environmental advantages, such as protection from radiation, temperature extremes, and micrometeorite impacts. The habitat is designed to reinforce and support the lava tube structure to address potential instability. The site also shows promising indicators of wind energy and possible subsurface water ice - key factors in enabling long-term, self-sufficient habitation (Schmehl et al., 2022; JPL; Burnham, 2018; USRA, 2012; Kolb, 2007).

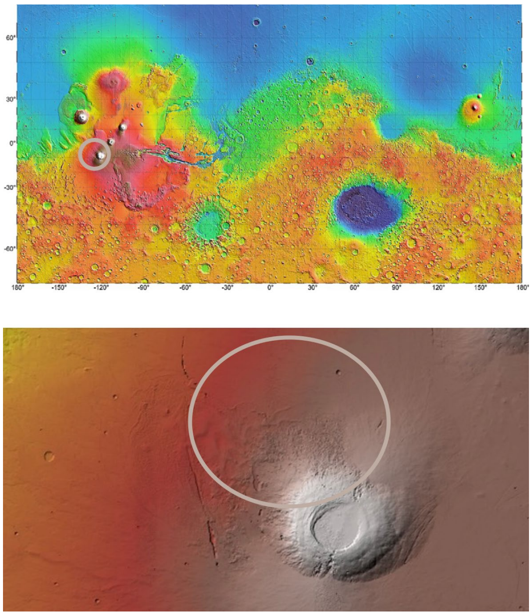

Figure 8 Northern Arsia Mons region (NASA / JPL / USGS - Topography of Mars by MOLA; MGS MOLA and Mars Express HRSC)

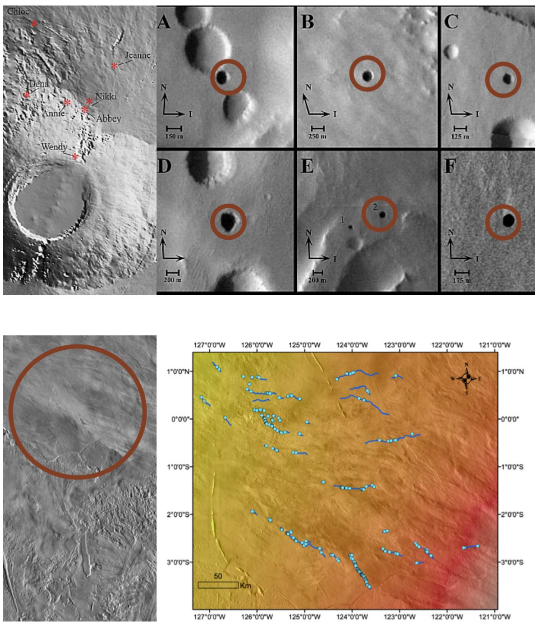

Figure 9 Lava Tubes of Arsia Mons (Cushing et al., 2007; MO THEMIS-IR Day; Tettamanti, C., 2019)

4.3 Circadian Rhythm

Meal timing, light exposure, movement, and social or mental activity are key factors influencing circadian rhythm. While meals are behavioral, the remaining elements can be supported through architecture. The *SUBMARTIAN* uses lighting strategies, vertical circulation, and spatial zoning to enhance daily activity patterns, reduce isolation, and maintain biological rhythm on Mars.

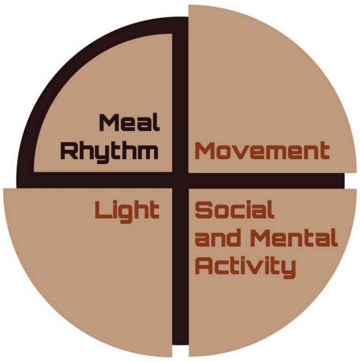

Figure 10 CIRCADIAN RHYTHM: INFLUENCING FACTORS

5 Design-to-Robotic-Production and –Operation System

5.1 Volume to cells

5.1.1 Conceptual Volume and Vector Generation

The spheres input defines a conceptual volumetric base used as a spatial reference for Voronoi cell generation. The script extracts sphere coordinates and generates a bounding box to frame the area of influence. From this, two sets of vectors are derived: one from the sphere centers and another from the bounding box center. These vectors guide the direction and strength of geometric deformation.

5.1.2 Proximity Filtering and Transformation

The script identifies Voronoi seed points (spaces) located near the conceptual volume using a Closest Point function. Points within a defined distance threshold are selected and transformed according to the influence vectors. A slider allows adjustment of the deformation intensity, making the system responsive.

5.1.3 Geometry Application and Output

The modified seed points are applied to the input geometry, a pre-generated mesh structure. The resulting form adapts to the influence field. Finally, the geometry is grouped and prepared for visualization or export from Rhino.

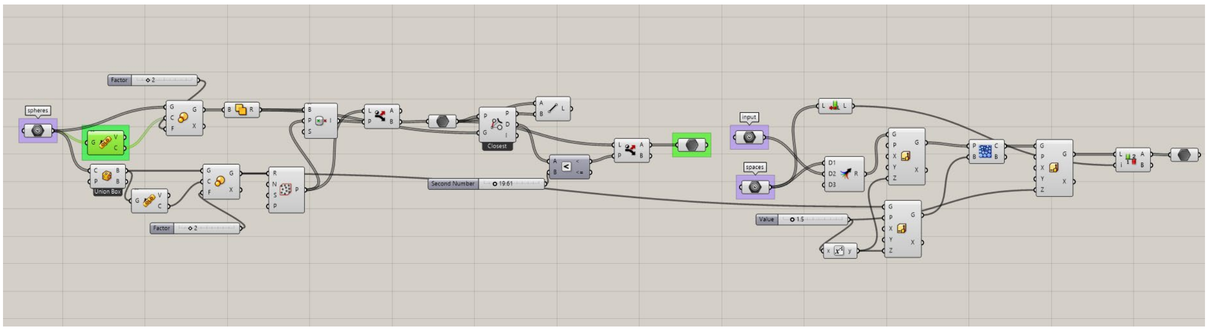

Figure 11 Input; voronoi generation script

5.1.4 Fragment Geometry Processing – Interlocking Structural Blocks

This section prepares two intersecting fragments of a volume for transformation into interlocking Voronoi blocks. The inputs include:

- Brep segment 1 and Brep segment 2: Two geometries that meet at a corner of the overall form.
- Double surface: The shared interface surface between the two segments, acting as the joint.

5.1.5 Step-by-step Description

A bounding box and centroid are computed for the two breps to guide uniform scaling toward the center. Seed points are then distributed on the shared surface (double surface) using a population component. A condition filters fragments to sides 1 and 2, preparing the joint area for Voronoi-based structural splitting.

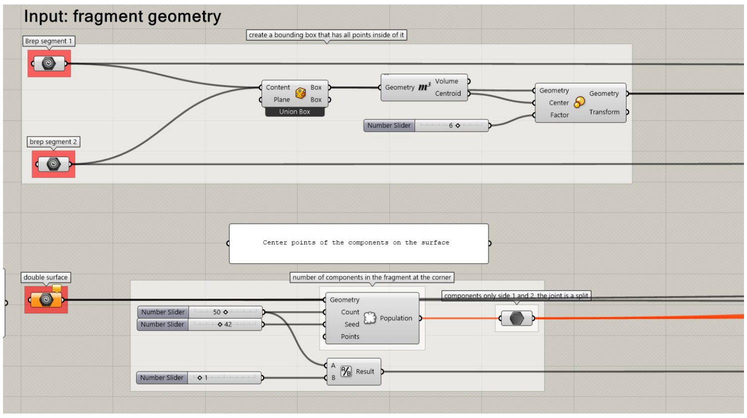

Figure 12 Input; components generation script

5.1.6 Corner Line Initialization & Interlocking Design

Initial curves are generated from the corners of the fragments, aligned with the geometry's direction. These kinked lines define the joint zones and prepare the base for interlocking. Random trimming is applied to introduce variation and ensure better fitting between adjacent top and bottom components. Line length is controlled to avoid disproportionate parts.

5.1.7 Pipe Generation & Voronoi Formation

The curves become centerlines for pipe geometries. Points placed along the pipes' surfaces are connected with kinked lines, enhancing interlocking. These points generate Voronoi cells, which are then stretched back to their original position, creating elongated, adaptive structural forms.

5.1.8 Plane Alignment

A rotational angle is applied to ensure smooth transitions between fragments, avoiding any undesired twisting.

5.1.9 Controlled Stretching

Sliders control the elongation ratio of the input points, allowing precise adjustment of the longitudinal deformation of the cells.

5.1.10 Transformation and Cutting

Each Voronoi cell is stretched according to its specific factor, resized, and then cut based on a reference geometry to finalize the modular structure.

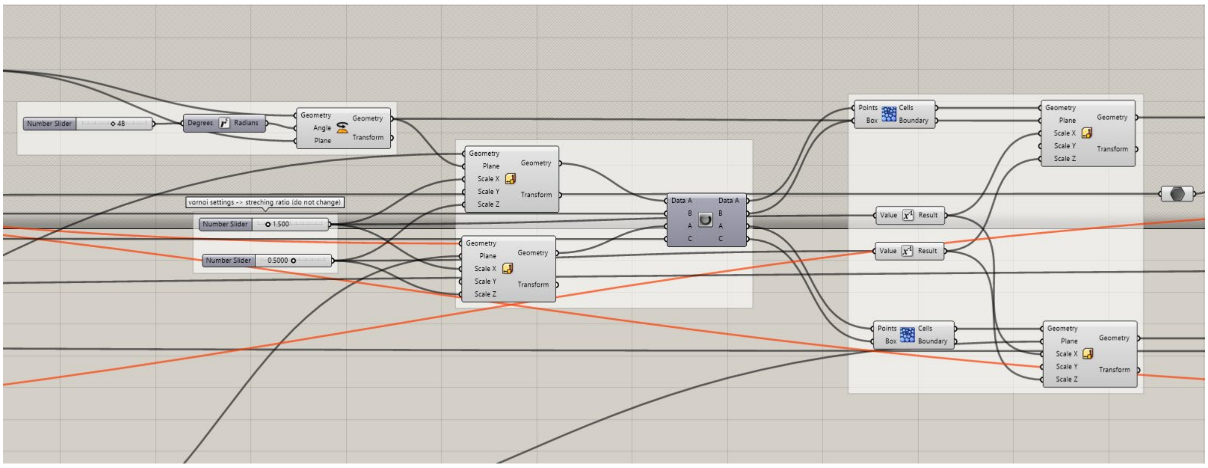

Figure 13 components generation script

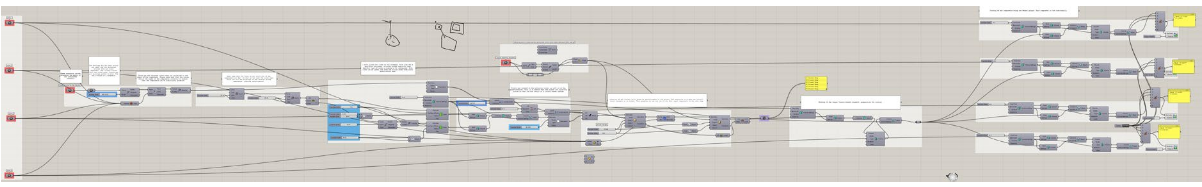

Figure 14 Pipe Generation script

5.2 D2RP & D2RO System

5.2.1 Inputs: Mesh Preparation

The main mesh to be milled is defined, along with side flaps used as support or fixtures during the milling process.

5.2.2 Union & Scaling

Geometries are merged within a bounding box and scaled (e.g., 0.99 in Z, 1.1 in Y) to simulate tolerance adjustments or material subtraction.

5.2.3 Spatial Analysis & Alignment

The bounding box dimensions are used to reposition and align the mesh to a reference plane, ensuring correct orientation for robotic milling.

5.2.4 Low-Resolution Cleanup

UV analysis detects low-quality mesh areas, which are then removed to ensure a clean, high-resolution geometry, ready for precise robotic fabrication.

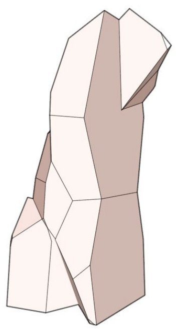

Figure 15 Extracted component for milling

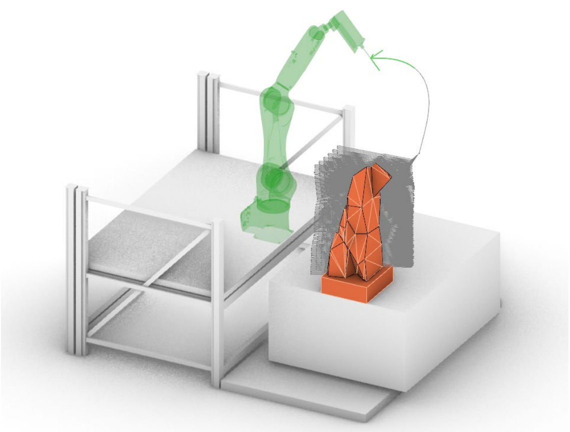

Figure 16 Milling Path

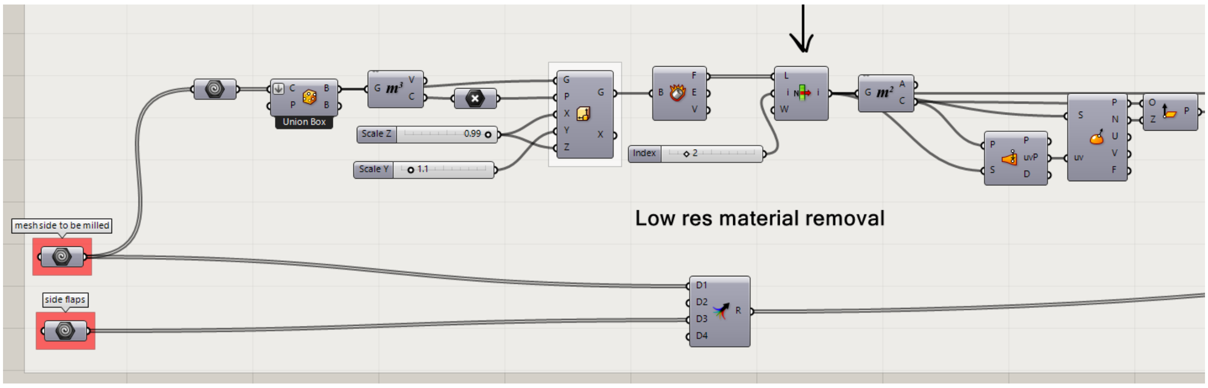

Figure 17Input; milling path script

5.2.5 Toolpath Definition and Robotic Simulation

The toolpath is defined by calculating positions and orientations derived from directional vectors and rotational values. These parameters establish the robot's movement frames, ensuring accurate path tracking.

To preview the process in real time, a simulation slider is used, allowing step-by-step control and visual verification of the robot's motion along the defined trajectory.

The robot's movement is controlled using C_DIS commands, which create smooth, continuous paths based on specified positions and speeds. Before execution, a verification step checks the entire toolpath to ensure that all movements are valid and free of potential errors.

For simulation accuracy, the robotic tool's geometry is loaded and assigned. A KUKA KR6 R1100 robot is selected as the operational model, ensuring compatibility and precision.

The KUKA|prc Core component executes the full simulation, handling collision detection, tool positioning, and alignment to the base. This process produces a detailed, functional visualization of the robotic operation.

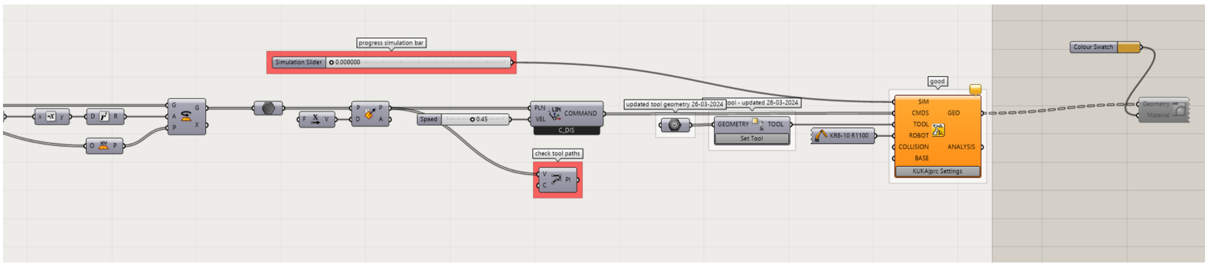

Figure 18 Output; milling path script

5.3 HRI-supported D2RA

5.3.1 Human-Robot Collaboration Setup

This phase involves integrating computer vision with Human-Robot Collaboration (HRC) to enable precise component assembly. A camera system detects the position of each part on the worktable using visual markers, such as a grey chart whose endpoints define reference coordinates. These guide the robotic arm's movements, including grip location, component size, and spatial clearance to avoid collisions.

The robotic arm navigates from an origin to an endpoint using a predefined path based on the camera's data. The component's dimensions and its distance from the table are factored into the motion planning to ensure safe handling.

5.3.2 Human-Robot Assembly Process

The assembly begins with the robot identifying the exact location of the table and frame vertices through visual recognition and coordinate mapping. Safety is ensured by integrating mid-air nodes to guide the robot's path and reducing speed near critical zones.

During placement, the robot adjusts its grasp to avoid collisions and slows down as it approaches other components. Due to potential discrepancies in vision-to-motion translation, human input is used to calibrate height and guide force-sensitive handling. The final assembly involves joint movement between the robot and human operator, ensuring stable placement through controlled speed and reduced stiffness.

6 Conclusions

Designing for Mars is not just an engineering challenge but a cultural one. The SUBMARTIAN habitat proposal imagines a way of living beyond Earth that is rooted not only in survival but also in meaning. At its core is a habitat shaped by the site: embedded within a lava tube for protection and built with Martian regolith using forms inspired by the underground landscape. The SUBMARTIAN optimizes space efficiency and structural resilience using a Voronoi-based system. The design process is enhanced by parametric tools such as Grasshopper, enabling data-driven results tailored to site-specific environmental data. Integration of HRI during construction supports safe and precise assembly.

The significance of this work goes beyond conceptual design. It proposes a framework for scalable, flexible Mars settlements that could evolve with mission duration and crew size. The modular approach and integration of a shared garden space contribute to both logistical efficiency and crew well-being. Further studies are needed to validate structural, thermal, and behavioural assumptions through physical prototyping and simulation. Additionally, future research may explore the development and testing of bouldering-inspired structural components designed for dual compatibility with human and robotic assembly. These geometries offer intuitive grip logic and structural interlock potential and may simplify collaborative construction workflows in extraterrestrial environments.

Study Limitation

Limitations include the untested structural behavior of lava tubes under human use and the unknown long-term performance of regolith-based construction in Martian conditions.

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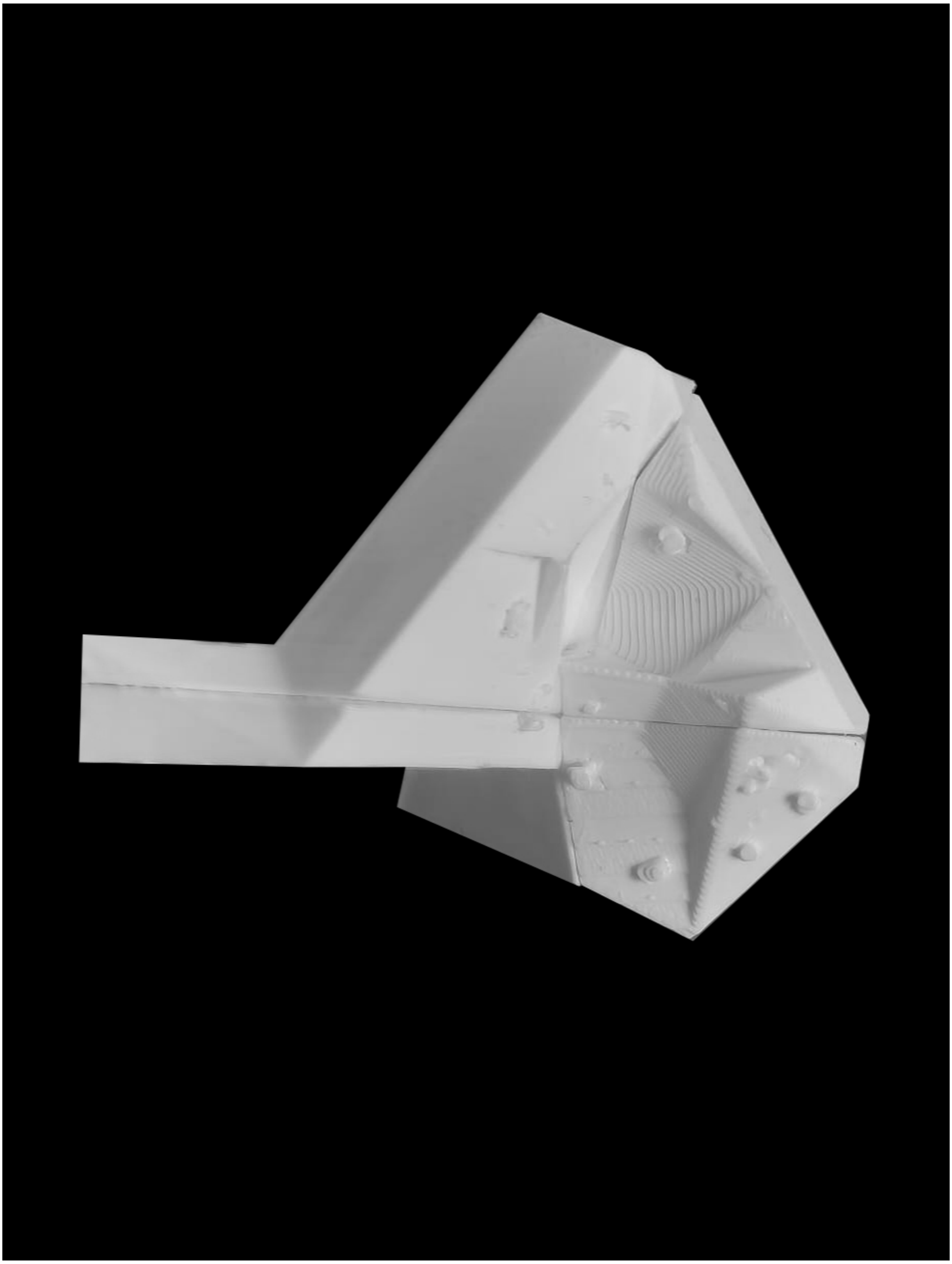

Figure 19 Physical model : Fragment with seat and bouldering area

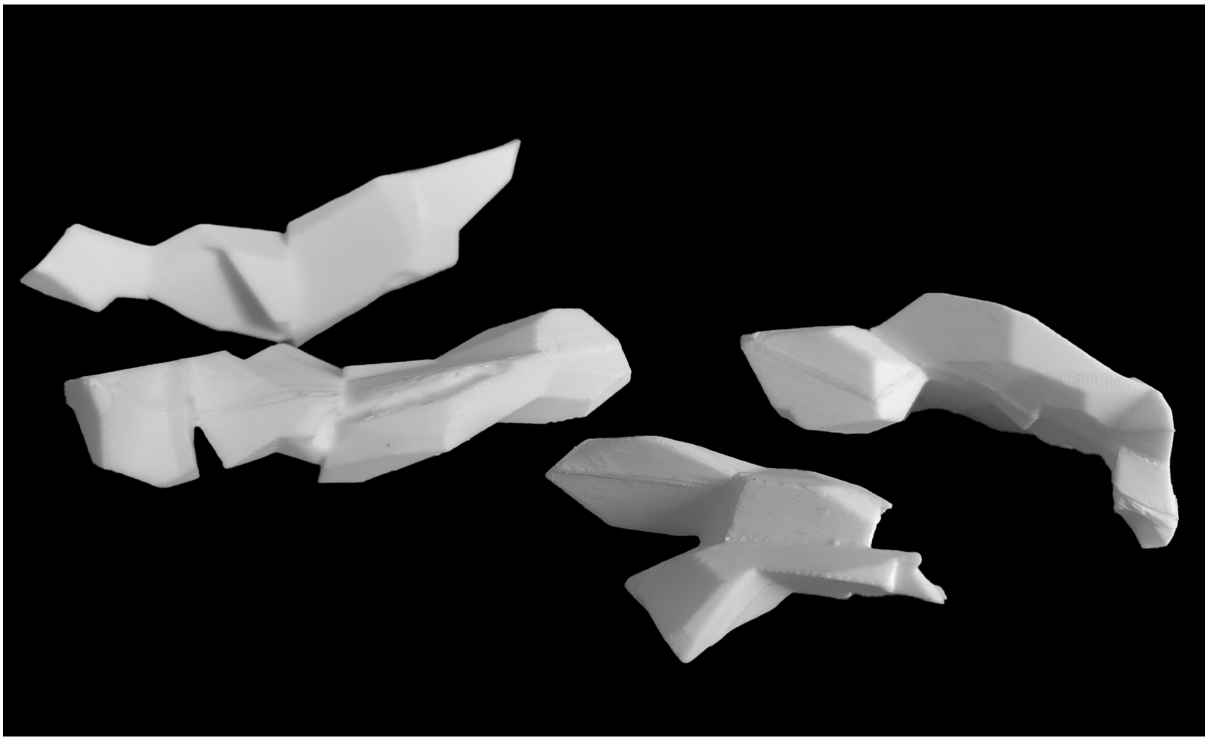

Figure 20 Physical model : 4 interlocking fragments

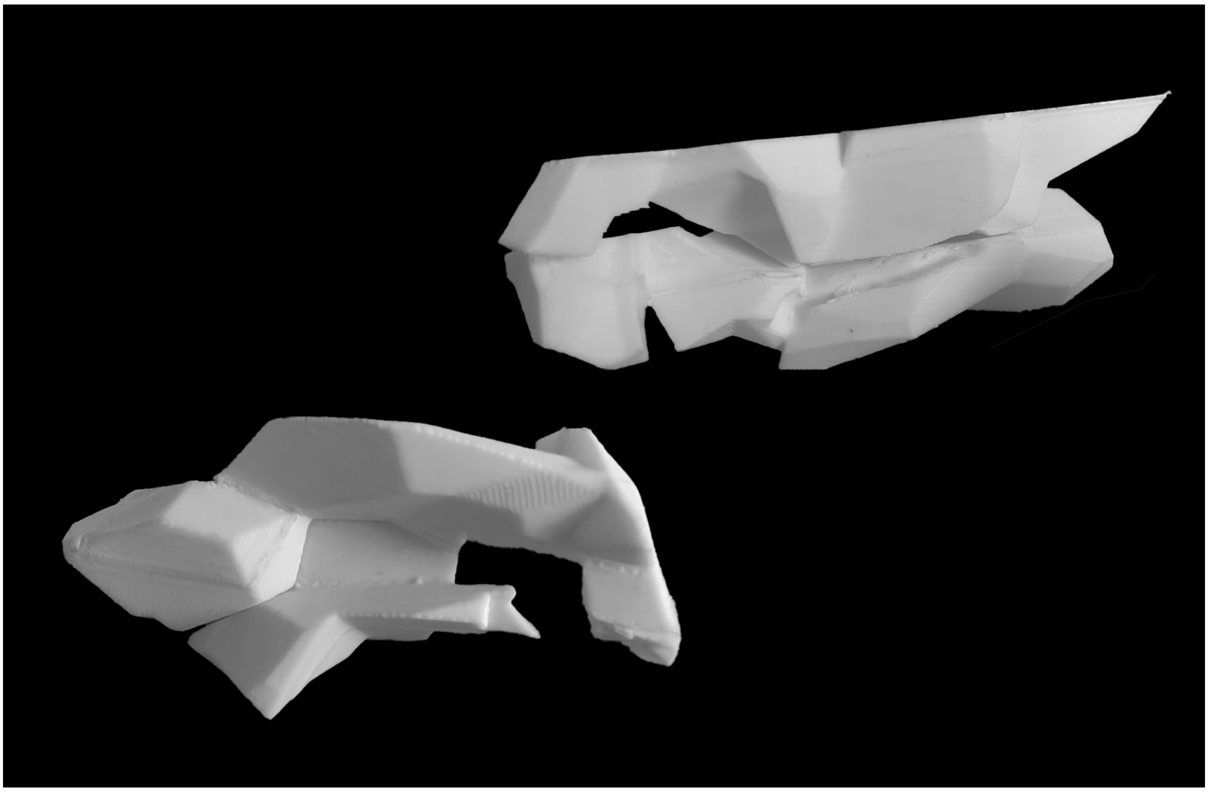

Figure 21 Physical model : Fragments with integrated LSS channel

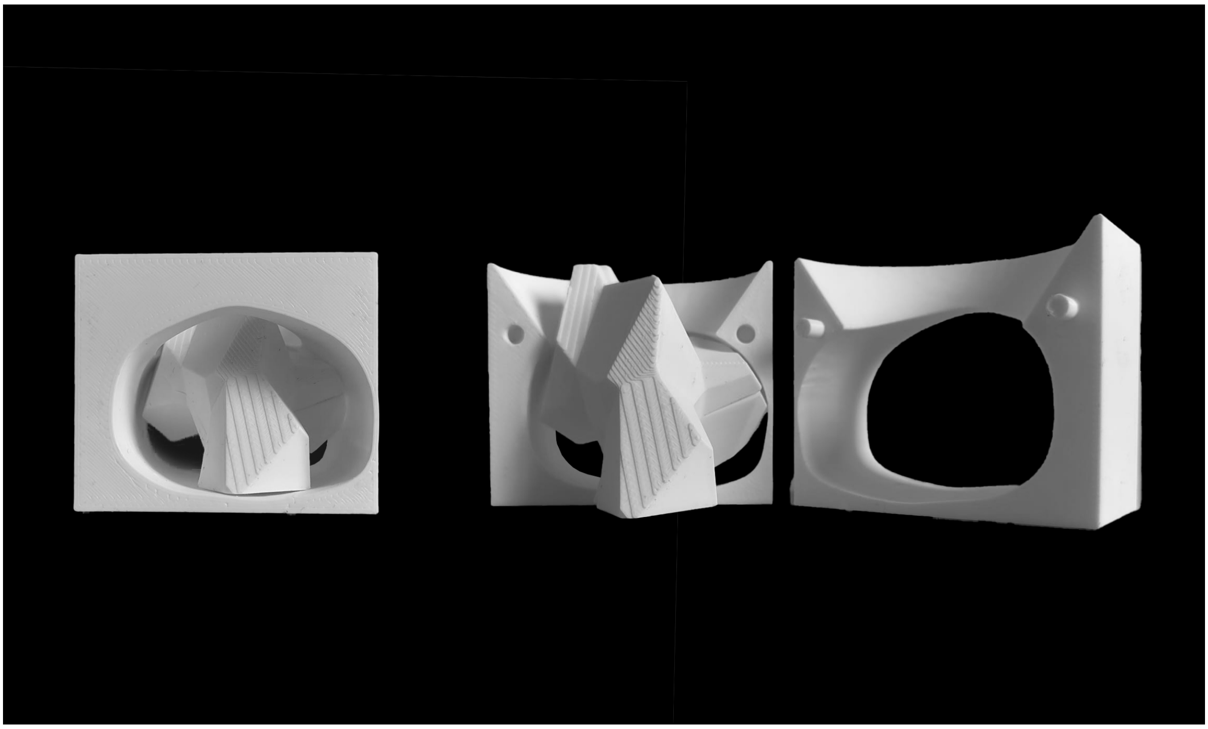

Figure 22 Physical model : Submartian inside of the lava tube