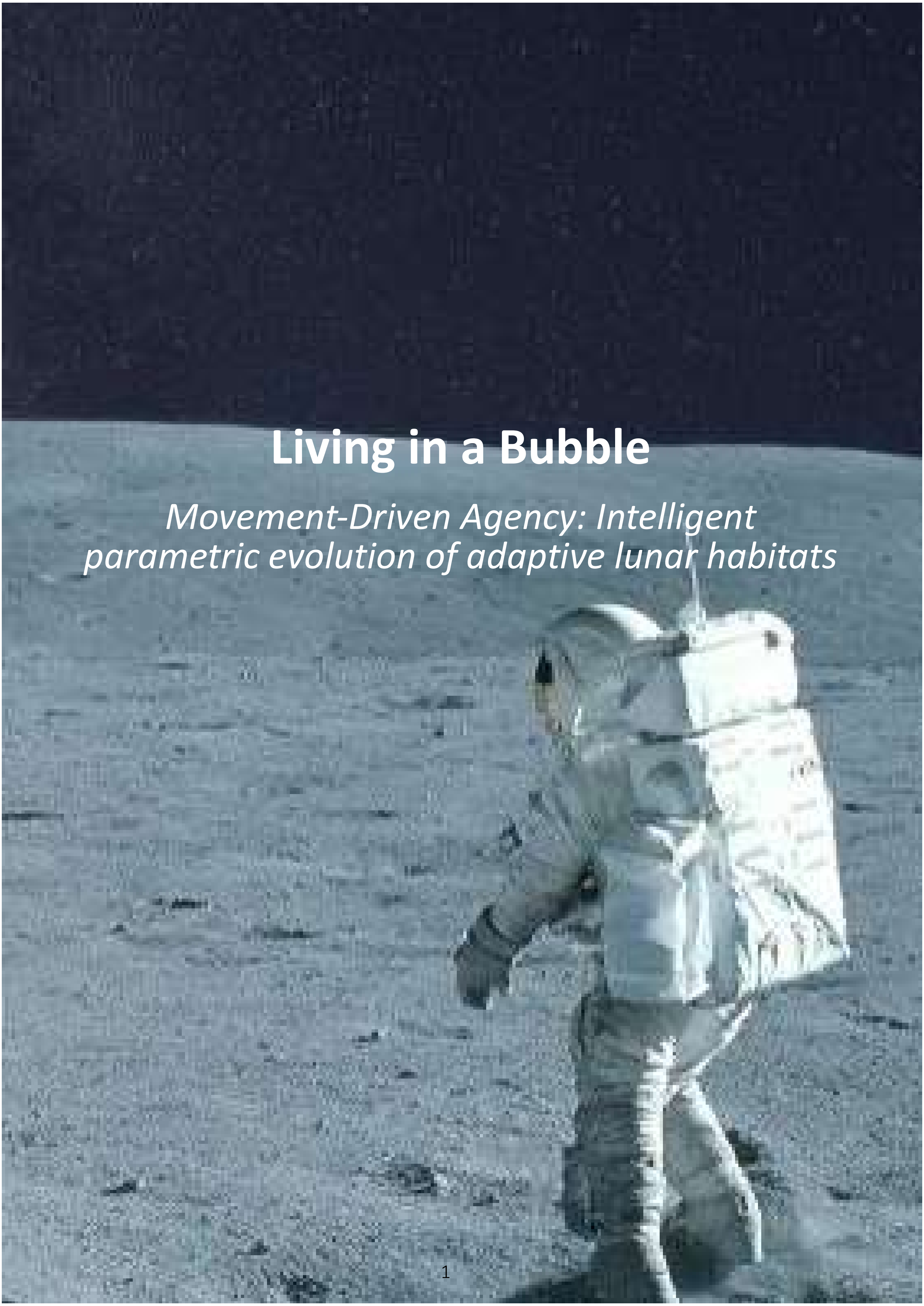
Living in a Bubble

Movement-Driven Agency: Intelligent parametric evolution of adaptive lunar habitats



Bouncing on the Moon
Movement-Driven Habitat Design

Master thesis

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Abstract

Extreme environments pose significant challenges to architectural design due to constantly changing environmental conditions, limited resources, and the demands of long-term human habitation. Conventional architectural approaches, which rely on static spatial configurations, often fail to respond effectively to these conditions. This project investigates the potential of responsive architectural systems that adapt based on human presence and movement, for a lunar habitat.

The study focuses on, human-scale environments for small crews, examining how bodily posture, movement patterns, and daily routines can inform spatial organization. By integrating inflatable structures, soft robotic actuation, and sensing technologies, the research explores an architectural system capable of transforming its shape in response to human behavior. Rather than treating architecture as a static enclosure, the project positions space as an adaptive interface that mediates between human needs and extreme environmental constraints.

Operating within the domain of architectural design research, this study a conceptual framework and a system logic over technical optimization or construction feasibility. The findings contribute to discussions on human-centered habitat design, architectural robotization, in situ resource utilization, and sustainable design, offering insights into how adaptive spatial systems can support long-term habitation in extreme environments.

Keywords:

Responsive architecture; Human-centered design; Extreme environments; Inflatable systems; Lunar habitat

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1.0 BACKGROUND

1.1 lunar Environmental Condition

The lunar environment differs fundamentally from Earth, characterized by reduced gravity, near-vacuum conditions, extreme temperature fluctuations, and prolonged day–night cycles. The absence of atmospheric protection exposes the surface to radiation and micrometeoroid impacts, creating a hostile context for long-term human habitation and architectural intervention.

These environmental constraints shift architectural priorities away from conventional comfort-oriented design toward protection, stability, and system performance. Habitat design must therefore address radiation shielding, thermal control, airtight enclosures, and resilience to external hazards. In this sense, lunar environmental conditions directly shape architectural requirements and spatial organization.

Condition	Earth	Moon	Design Implications
Gravity	1 g	1/6 g	Human Movement
Atmosphere	1 bar (O_2,N_2,CO_2)	Almost vacuum	Site Envelope design
Length of day	24 hours	28 Earth days (14 days light/14 days dark)	Lighting design Function design
Temperature	Mean 15°C Range:-89°C - 60°C	Mean -20°C Range:-233°C - 123°C	Envelope design Material choice
Radiation	Protection by Earth's atmosphere	Exposure to space radiation secondary radiation from surface	Site choice Envelope design Material choice
Water	70.8% surface	In deep permanently shadowed craters&binded in regolith	Cycular design
Dust	Generally harmful	Lunar dust is a pervasive, toxic, and electrostatically charged abrasive	Envelope design Material choice
Others		Micrometeoroids, bright light&glare	Others

Figure 1.1: Earth–Moon Environmental Comparison for Architectural Design (Author, 2026)

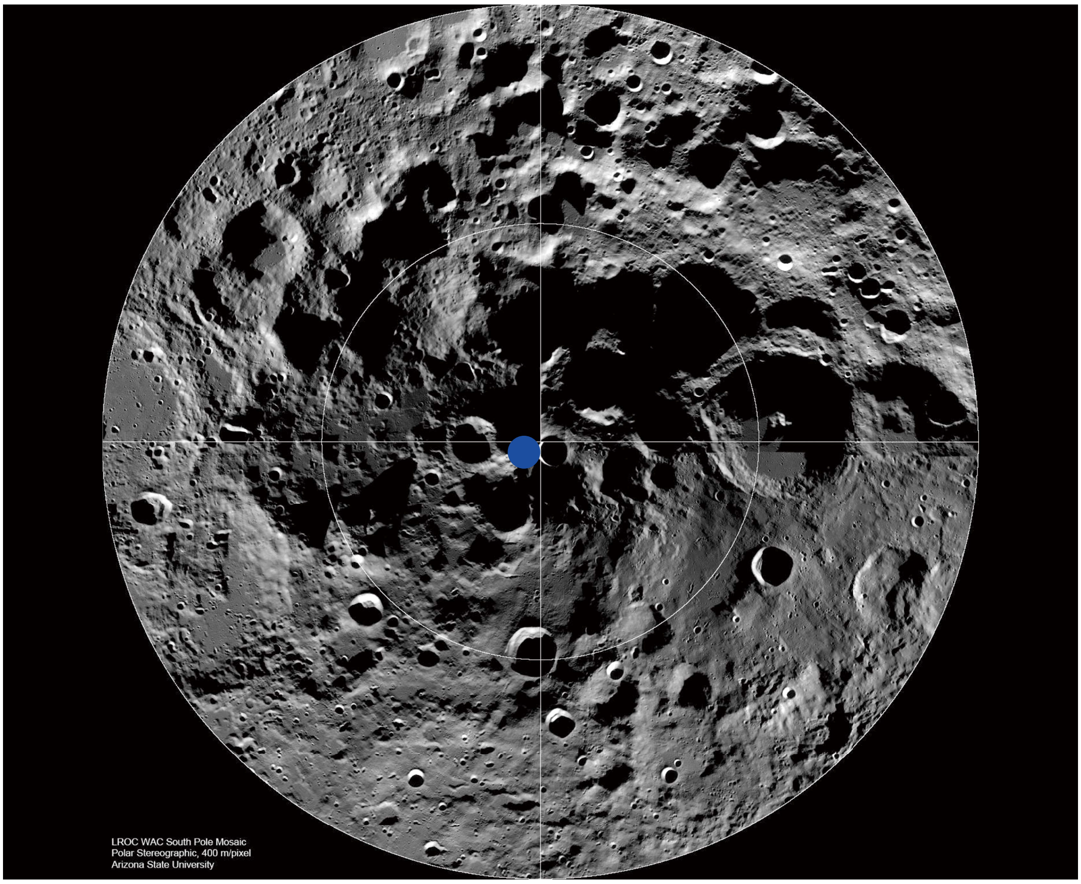

Figure 1.2: Lunar south polar region near Shackleton Crater. LROC WAC South Pole Mosaic (NASA/GSFC/ Arizona State University). Modified by author.

The selected site is located on the ridge of Shackleton Crater near the lunar south pole, a region of strategic significance due to its unique environmental conditions. Permanently shadowed areas within the crater are believed to contain water ice and other volatiles, making the site critical for long-term human presence and resource security. At the same time, the elevated ridge offers relatively stable terrain suitable for surface construction.

In contrast to the shadowed interior, the crater rim remains persistently sunlit, providing reliable access to solar energy and a more stable thermal environment. The site also maintains near-continuous visibility of Earth, supporting communication infrastructure and offering psychological benefits for crew members. Together, these conditions position the Shackleton ridge as a balanced interface between extreme lunar environments and habitable surface architecture.

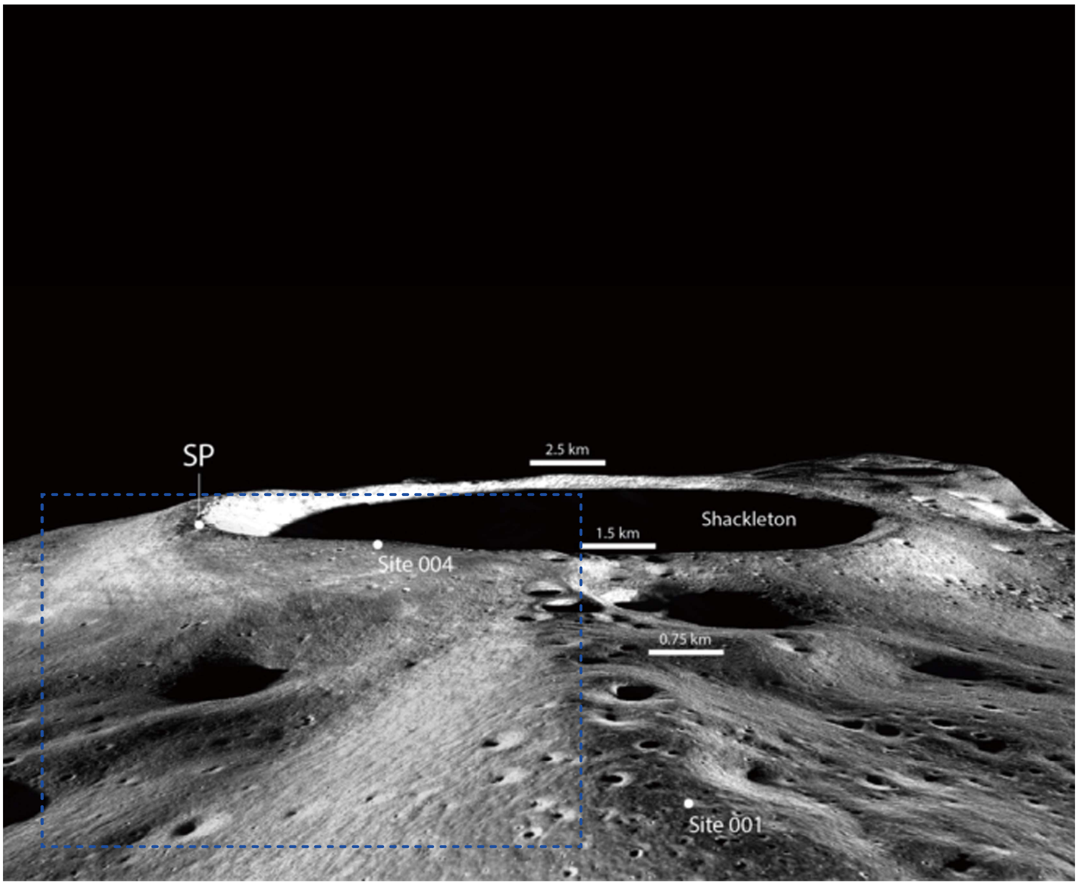

Figure 1.3: Lunar south polar region near Shackleton Crater. LROC WAC South Pole Mosaic (NASA/GSFC/Arizona State University). Modified by author.

1.2 lunar Environmental Condition

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1.3 Site Introduction

The selected site is located in the lunar south polar region near Shackleton Crater, an area of high scientific and strategic significance due to its unique topographic and geological conditions. The terrain is characterized by relatively gentle slopes ranging from 0° to 15°, offering favorable conditions for surface deployment and structural stability. Elevation and slope analyses indicate localized areas suitable for construction while maintaining proximity to permanently shadowed regions.

Subsurface studies suggest a stratigraphy composed of an approximately 10 m thick regolith layer overlying a large-scale ejecta blanket extending to depths of up to 2 km. This layered structure reflects a history of impact-driven geological processes, resulting in fractured and mechanically disturbed crustal materials. These conditions provide both challenges and opportunities for excavation, anchoring, and in-situ resource utilization, forming a critical basis for the subsequent conceptual design strategies.

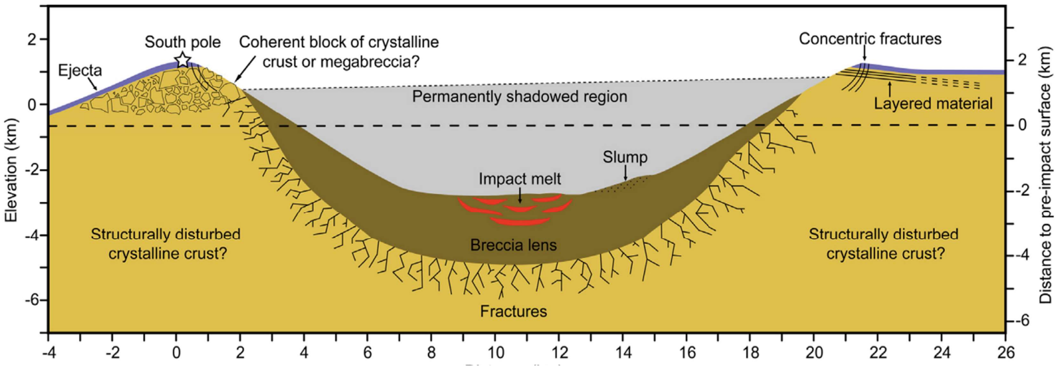


Figure 1.4: Lunar south polar region near Shackleton Crater. LROC WAC South Pole Mosaic (NASA/GSFC/Arizona State University). Modified by author.

The lunar subsurface is characterized by a layered structure consisting of a thin regolith layer, a thick ejecta blanket, and a fractured crystalline crust beneath. This stratification reflects long-term impact processes and results in decreasing material stability with depth. For architectural intervention, the shallow regolith and upper ejecta layers offer the most feasible zone for excavation and anchoring, while deeper fractured crusts present increasing structural uncertainty. The conceptual design therefore responds to these environmental constraints by prioritizing shallow, adaptable, and minimally invasive construction strategies.

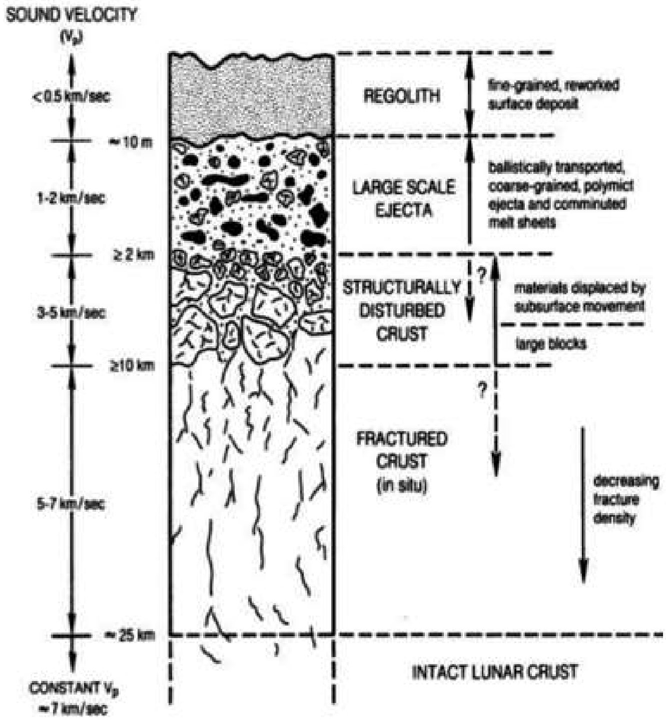


Figure 1.5. Conceptual subsurface section of lunar crust structure for architectural and environmental analysis. Author’s interpretation based on lunar seismic and geological studies. Author, 2026.

2.0 PROBLEM STATEMENT

2.1 Main problem

Static spatial configurations fail to support long-term habitation in extreme environments.

In extreme environments such as the lunar surface, environmental conditions are highly variable and unpredictable, including extreme temperature cycles, radiation exposure, and geological instability. Conventional architectural approaches often rely on static spatial configurations that are fixed in form and function, limiting their capacity to respond to long-term environmental change. As a result, these rigid systems struggle to accommodate evolving operational needs, maintenance demands, and human adaptability over extended habitation periods. This mismatch between static spatial design and dynamic environmental conditions presents a fundamental challenge for sustainable long-term habitation.

2.2 Sub Problem

Lunar Environmental Condition

Current lunar habitat designs largely inherit spatial dimensions, floor heights, and circulation systems developed under Earth-gravity assumptions. Interior layouts are organized around vertical stacking, ladders, and fixed floor-to-floor heights, reinforcing movement patterns optimized for 1g environments. However, in reduced lunar gravity, such configurations can restrict natural human motion, reduce spatial efficiency, and increase physical strain during daily activities. This mismatch between architectural form and human movement behavior in low-gravity conditions limits long-term habitability and highlights the need to reconsider how space, circulation, and bodily interaction are structured in lunar habitats.

2.3 Spatial Confinement & Limited Volume

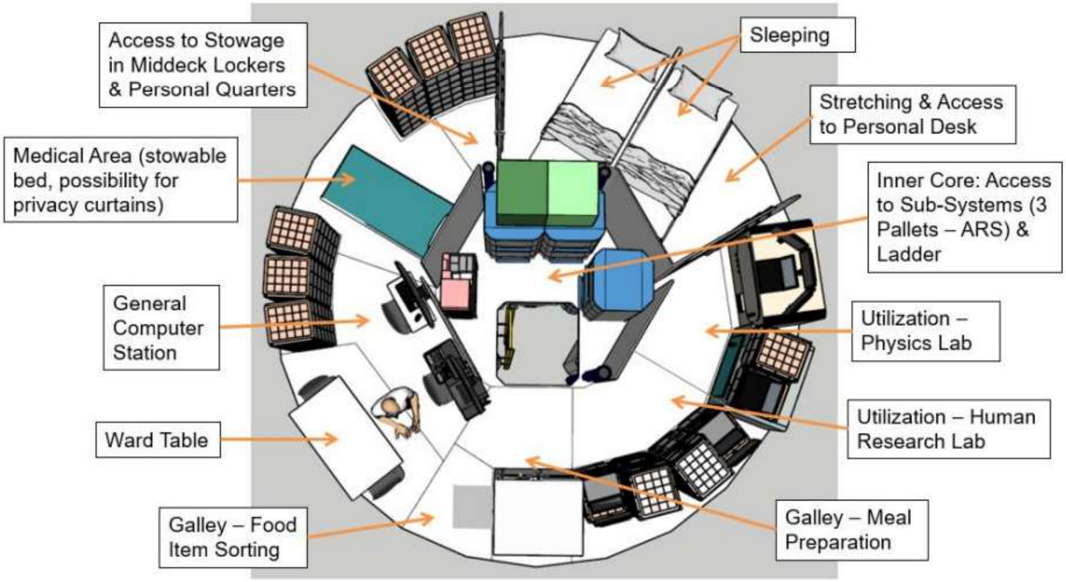


Figure 2.1:Plan view of a representative lunar outpost habitat configuration. NASA Exploration Systems Mission Directorate (NASA/ASU).

Lunar surface habitats are constrained by strict mass, volume, and shielding requirements, resulting in highly compact interior layouts. Functional zones such as work, rest, medical care, and daily living are frequently compressed into shared spaces, reducing opportunities for privacy and personal retreat. This spatial overlap blurs the boundary between collective operations and individual recovery, increasing cognitive load and psychological stress over long-duration missions. The lack of clearly differentiated personal space presents a critical challenge to sustaining crew well-being and performance in confined extraterrestrial environments.

3.0 OBJECTIVE

3.1 Main Objective

This project focuses on ***developing a responsive architectural system*** that can adapt to the dynamic and extreme conditions of extraterrestrial environments. Within this framework, ***human movement as a generator of spatial form*** is treated as a central design driver, informing how space is organized, scaled, and transformed beyond Earth-based architectural norms. At the same time, the research investigates ***how to use in-situ resource utilization (ISRU) and adapt ISRU to architecture***, reframing resource extraction and processing as integral components of spatial and construction strategies rather than isolated technical systems. Through these combined approaches, the project ultimately aims at ***developing strategies for extreme environments***, proposing architectural solutions that are resilient, flexible, and capable of supporting long-term habitation under lunar conditions.

4.0 RESEARCH QUESTION

4.1 Main Research Question

Static architectural solutions are insufficient to address the dynamic challenges of extreme environments. Supporting long-term human habitation therefore requires spatial systems that can adapt to changing conditions and human needs. This leads to the following main research question:

How can a responsive architectural system be designed to replace static spatial configurations and support long-term human habitation in extreme environments?

4.1 Sub Research Question

The main research question can be divided into four sub research questions

How to design a sustainable Lunar habitat?

How can human movement inform the generation of spatial form?

How to design and build the reconfigurable system?

How can human interact with the Building-as-a-Robot System?

These sub-research questions collectively investigate how sustainable lunar habitation can be achieved through integrated architectural, technological, and human-centered approaches. The research explores the design and construction of inflatable systems as adaptable spatial infrastructures suitable for extreme lunar conditions. It further examines how humans can interact with a Building-as-a-Robot system, emphasizing collaboration between occupants, automated construction, and responsive environments. Finally, the study considers how human movement can inform the generation of spatial form, positioning bodily interaction as a key driver in shaping flexible and inhabitable lunar architecture.

5.0 METHODOLOGY

5.1 Case Studies

Experimental Housing Vision

The Shape System developed in the Experimental Housing Vision project, where spatial form is directly linked to human activities. Instead of relying on fixed room layouts, the housing unit adopts multiple sectional shapes that correspond to different modes of use, such as working, resting, and hygiene. The project demonstrates how architectural geometry can be informed by bodily posture and movement, allowing the section itself to become an active design driver. This approach provides a reference for using adaptable shape systems to generate responsive spatial configurations.

Figure 5.1: Experimental Housing Vision – Shape System. AWG – AllesWirdGut Architektur.

Muscle NSA

Muscle NSA project as an example of an inflatable architectural system in which the entire volume operates as a single adaptive body. Rather than relying on rigid structural components, the system achieves stability and spatial definition through air pressure and a networked membrane structure. The project demonstrates how inflatable systems can respond dynamically to external forces and human interaction, offering insights into adaptable construction logics and spatial flexibility relevant to extreme environments.

Figure 5.2: NSA Muscle inflatable system. Oosterhuis, K. (2003).

LIFE Habitat

LIFE Habitat developed by Sierra Space as a large-scale inflatable system designed for microgravity environments. The habitat demonstrates how inflatable structures can support diverse functions, ranging from scientific research to manufacturing, within a single adaptable volume. By combining structural efficiency with internal spatial flexibility, the LIFE Habitat illustrates the potential of inflatable architectures to accommodate evolving programmatic needs. This project provides a relevant reference for designing lightweight, expandable habitats for long-term use in extreme and extraterrestrial environments.

Figure 5.3: LIFE Habitat inflatable system for microgravity applications. Sierra Space. (n.d.).

5.2 Programmatic Study

This programmatic study provides a comprehensive analytical framework based on the circadian rhythms and operational requirements of a six-member astronaut crew. By systematically deconstructing daily routines into a time-based programmatic sequence, the research facilitates the translation of abstract functional activities into tangible spatial parameters. This methodology ensures that diverse behavioral patterns—ranging from collaborative scientific mission tasks to individual restorative practices—are meticulously mapped against structural requirements. Consequently, the study establishes a rigorous nexus between human movement and the organizational logic of the habitat

Figure 5.4: Six-Person Astronaut Daily Program and Movement Mapping (Arthor,2026).

Time (GMT)	Function Category	Mon: System Activation	Tue/Wed: Science Peak	Thu: Core Mission(EVA)	Fri: Sample Analysis	Sat: Station Maint	Sun: Crew Recovery
06:00-07:30	Life Support	Wake-up,Hygiene ECLSS System Check	Hygiene Bio-Med Sampling	High-Calorie intake Suit Bio-Med Prep	Hygiene Health Check	Hygiene Cabin Prep	Sleep-in Personal Care
07:30-08:00	Life Support	DPC (Morning) Weekly Goals	DPC: Science Windows	DPC: Final EVA Safety Brief	DPC: Downlink Plan	DPC Maintenance logic	N/A (Free Time)
08:00-12:00	Sys Assurance Science EVA Ops	FE-1/MS: Power/Thermal Grid Service	SO-1/2:Lab Work:Bio-Culturing	SO-2/MS Lunar EVA Ops CDR/FE-1: IV Command	SO-2/MS: Suit Maintenance SO-1: Lab Ingress	FE-1/2:Deep Maint: Filters/Pipes	Personal Time Family Comms
12:00-13:00	Life Support	Group Lunch Task Sync	Social Lunch	IV Support Team Lunch	Lunch Sample Review	Working Lunch	Social Group Lunch
13:30-15:30	Life Support Logistics	FE-2: Consumables Inventory	FE-2: Lab Resupply	SO-2/MS: Surface EVA Cont.	FE-2: Waste Pack Isolation	All: Logistics: Cargo Reorg	Mandatory Exercise (Slot A)
15:30-18:30	Life Support Sys Assurance	All: 2.5h Exercise CDR: Comm Logs	All: 2.5h Exercise SO: Data Prep	SO-2/MS: Ingress/Dust Rem All: Exercise	All: 2.5h Exercise FE-1: Audit	All: Deep Habitat Cleaning	Psychological Decomp
18:30-19:00	Life Support	DPC (Evening): Daily Wrap	DPC: Data Sync	DPC: EVA Debrief	DPC: Status Report	DPC: Schedule Prep	N/A (Free Time)
19:00-21:30	Life Support	Dinner / Journal / Pod Org	Dinner Entertainment	High-Intensity Recovery Rest	Dinner Research Summary	Social Gaming Bonding	Meditation/Prep
21:30-06:00	Life Support	Lights Out	Lights Out	Lights Out	Lights Out	Lights Out	Lights Out

Figure 5.5: Programmatic Astronaut Schedule and Task Allocation Based on Functional Category

The mission schedule divides operational responsibilities into three distinct categories to ensure habitat stability and scientific productivity. The Commander and Flight Engineer focus on critical infrastructure, including ECLSS health assessments, power grid synchronization, and maintenance logic implementation. The Science and Mission Group manages specialized research tasks such as bio-med sampling, lunar EVA operations, and lab ingress/egress protocols. To maintain crew well-being and operational alignment, Collective Crew Tasks—including daily planning conferences, physical exercise, and psychological decompression—are integrated into the routine for all personnel.

5.3 Computational Design

Force Driven Organization

The architectural organization is established through a multi-dimensional computational workflow that translates complex human behavioral data into a responsive, three-dimensional environment. The process begins with Program Definition, where functional requirements are digitized into a data matrix of spatial generators. These generators initiate a Planar Force Iteration, simulating the tension between Adjacency (Attraction) and Boundary (Repulsion). The spatial intimacy of the habitat is governed by the shifting ratio of these vectors: where Boundary > Adjacency, the system maintains distinct spatial independence; as Adjacency overrides, the algorithm drives programmatic fusion, creating integrated functional clusters. This ensures that the layout is not a fixed geometry, but a dynamic result of relational rules.

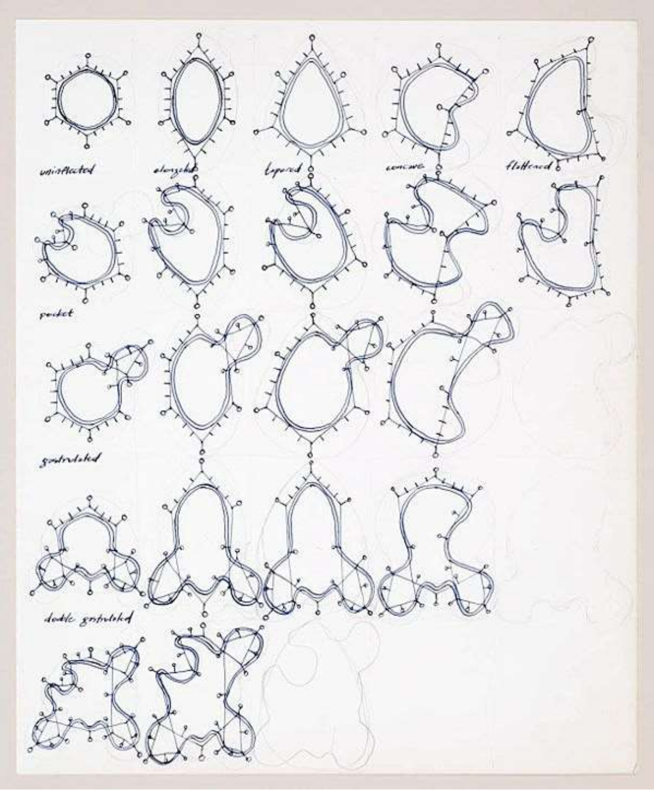
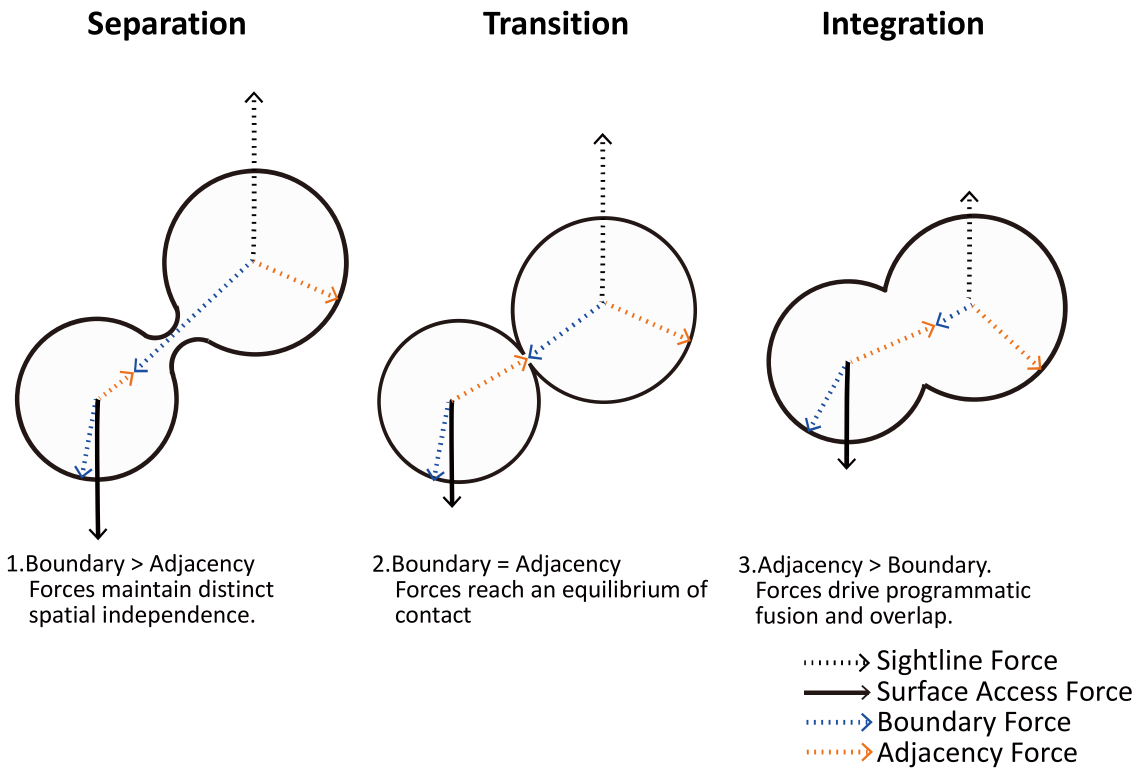


Figure 5.5: Lynn, G. (2000). Embryological house. Princeton Architectural Press.



Separation

Transition

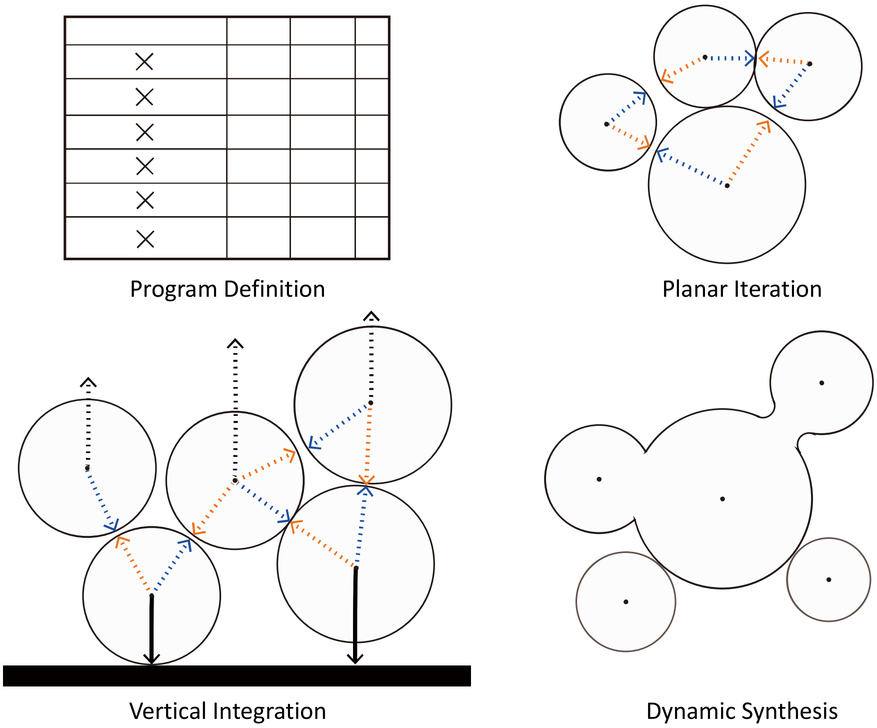
Integration

1.Boundary > Adjacency
Forces maintain distinct spatial independence.

2.Boundary = Adjacency
Forces reach an equilibrium of contact

3.Adjacency > Boundary.
Forces drive programmatic fusion and overlap.

Figure 5.6: Space Organization Workflow (Arthor,2026).



Program Definition

Planar Iteration

Vertical Integration

Dynamic Synthesis

Figure 5.7: Space Organization Workflow (Arthor,2026).

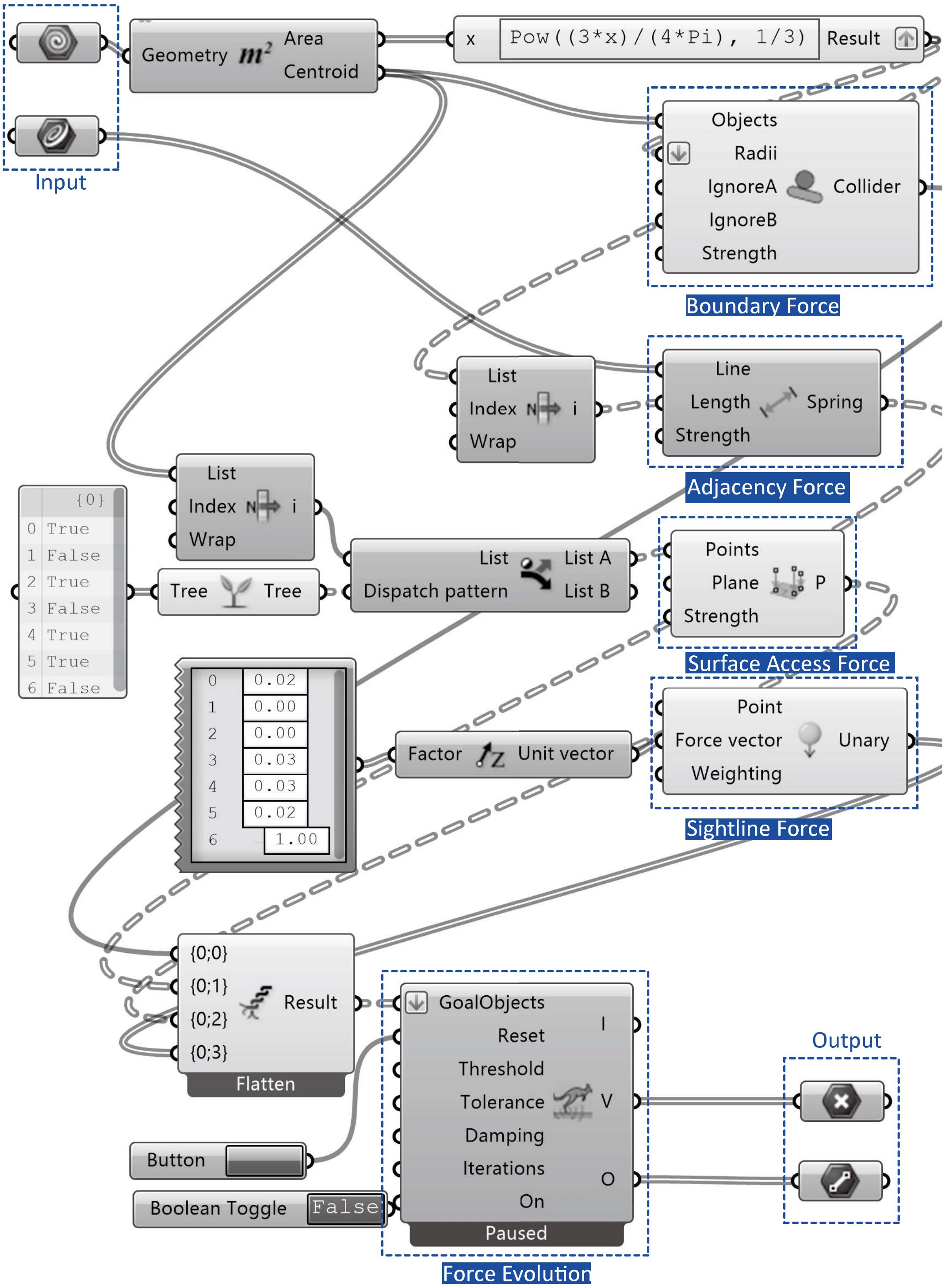


Figure 5.8: Script(Arthor,2026)

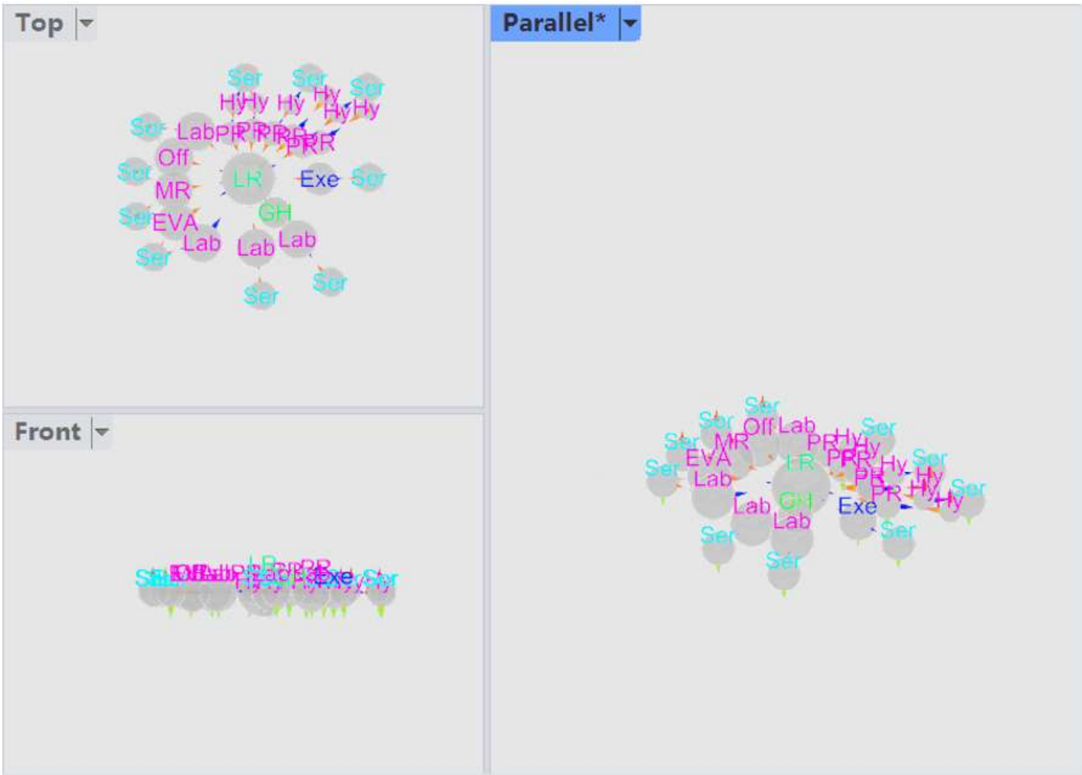


Figure 5.9: Itertion Output (Arthor,2026).

The spatial configuration is established through a force-driven generative process, where human behavioral patterns are translated into a dynamic, reconfigurable organization. By treating functional programs as particles influenced by attraction and repulsion vectors, the system undergoes a series of computational iterations to reach an optimal equilibrium. This iterative logic allows for the seamless fusion of functions, where separate programmatic units merge into integrated clusters based on real-time activity intensity. The result is a fluid architectural framework that responds to human flux, constantly recalibrating its layout to balance programmatic proximity with operational efficiency.

5.3 Computational Design

Evolutionary Morphology

The morphology evolves through a Social Force Model, where human movement trajectories are converted into kinetic force vectors. These vectors act as the primary drivers for geometric deformation by manipulating the boundary control points in real-time. This algorithmic feedback loop enables a Multi-User Response, where the spatial boundary deforms simultaneously to accommodate the collective flow and density of multiple occupants. Furthermore, the system facilitates Sectional Evolution: by applying varying intensities of "push" and "pull" forces at different heights, the algorithm generates complex sectional variations, tailoring the 3D volume to specific task-related clearances and ergonomic requirements

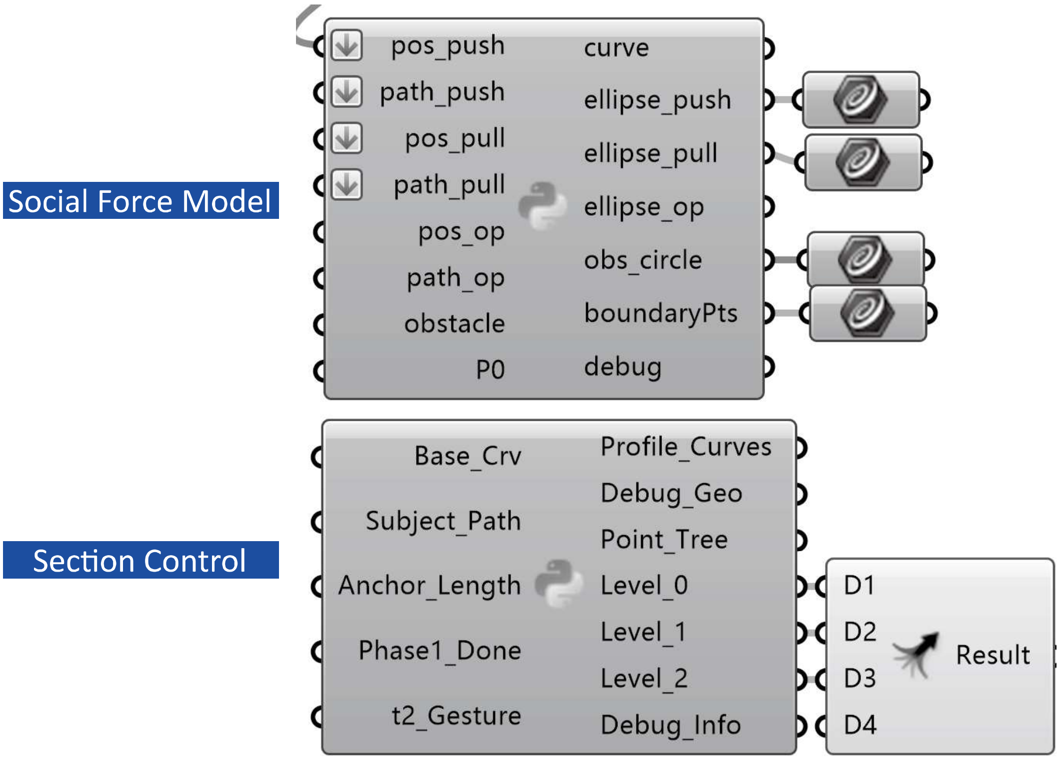


Figure 5.10: Script

The generative sequence illustrates the transformation of a static Initial Boundary into a responsive, high-performance shell through a continuous computational feedback loop. The process begins by mapping human movement trajectories as kinetic force vectors that act directly upon the boundary’s control points, initiating a non-linear deformation of the primitive. This interaction facilitates a simultaneous Multi-User Response, where the perimeter deforms in real-time to accommodate the collective flow and density of multiple occupants. Finally, the morphology culminates in a Sectional Synthesis, where variable "push" and "pull" intensities are applied at different heights, generating complex 3D sectional variations that tailor interior clearances and ergonomic volumes to specific behavioral requirements.

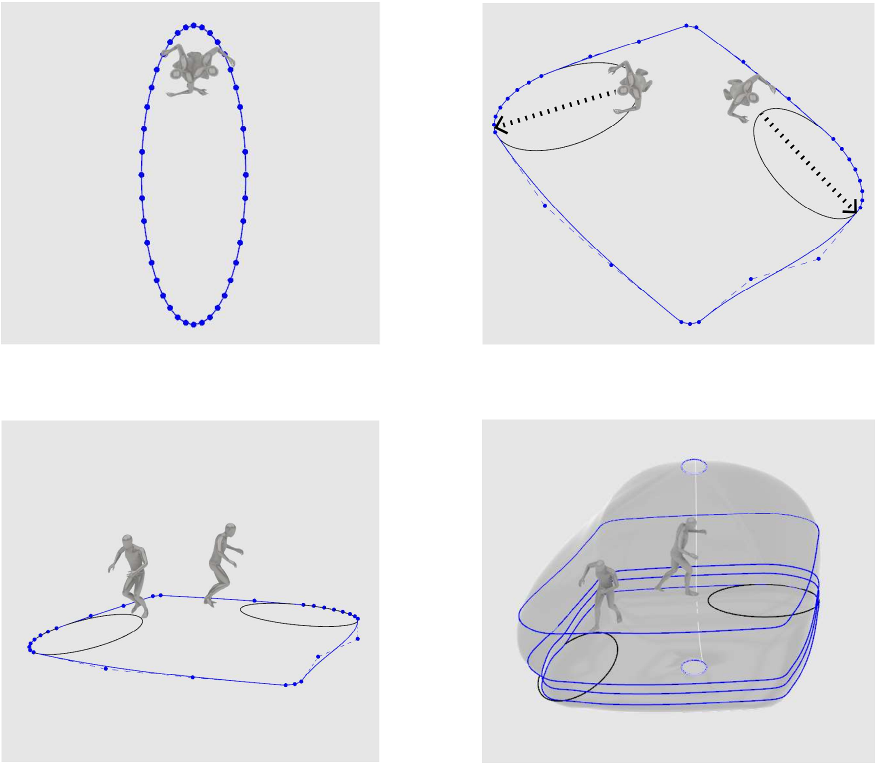


Figure 5.11: Behavior-Driven Morphogenesis(Arthor,2026)

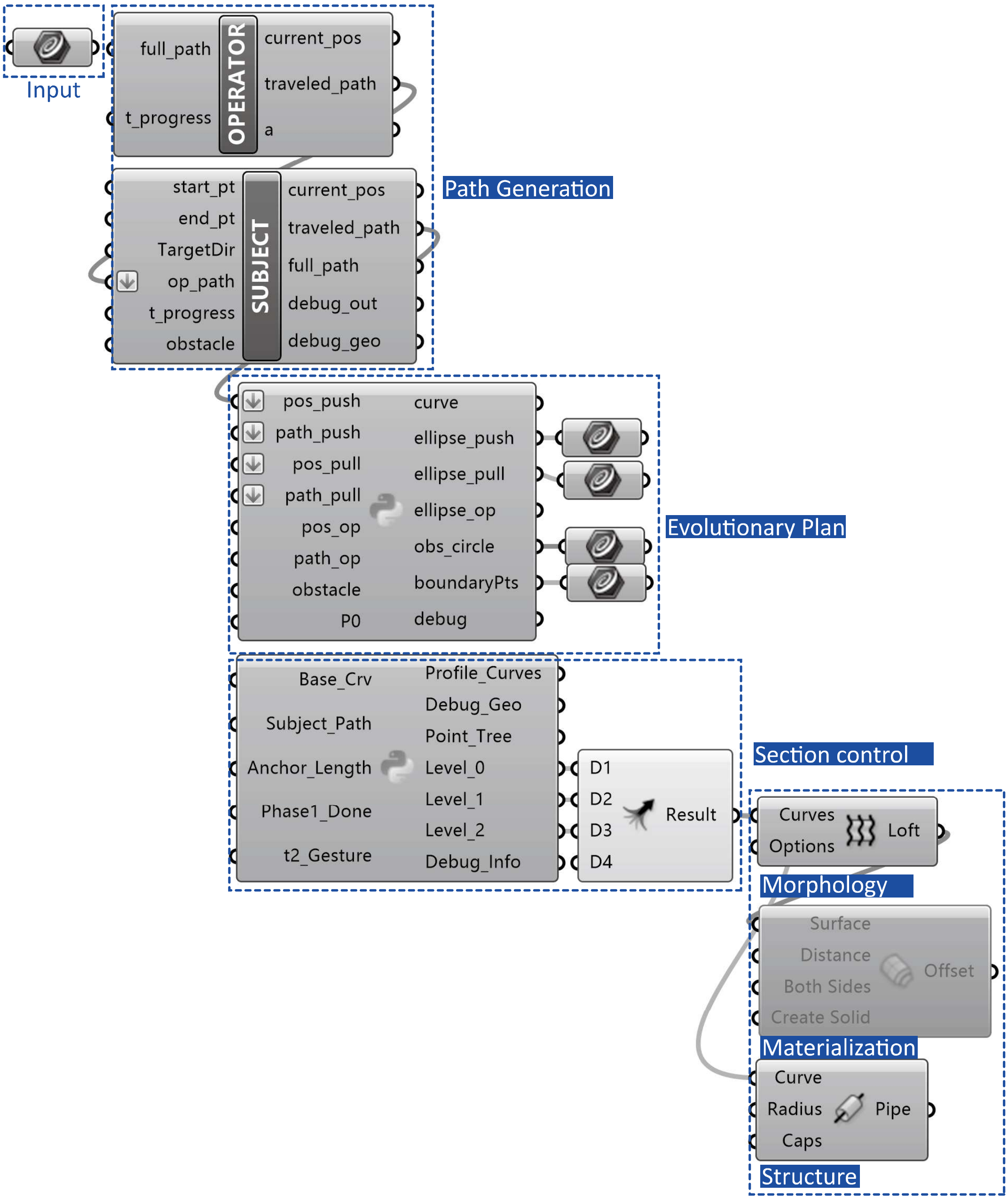


Figure 5.12: Script(Arthor,2026)

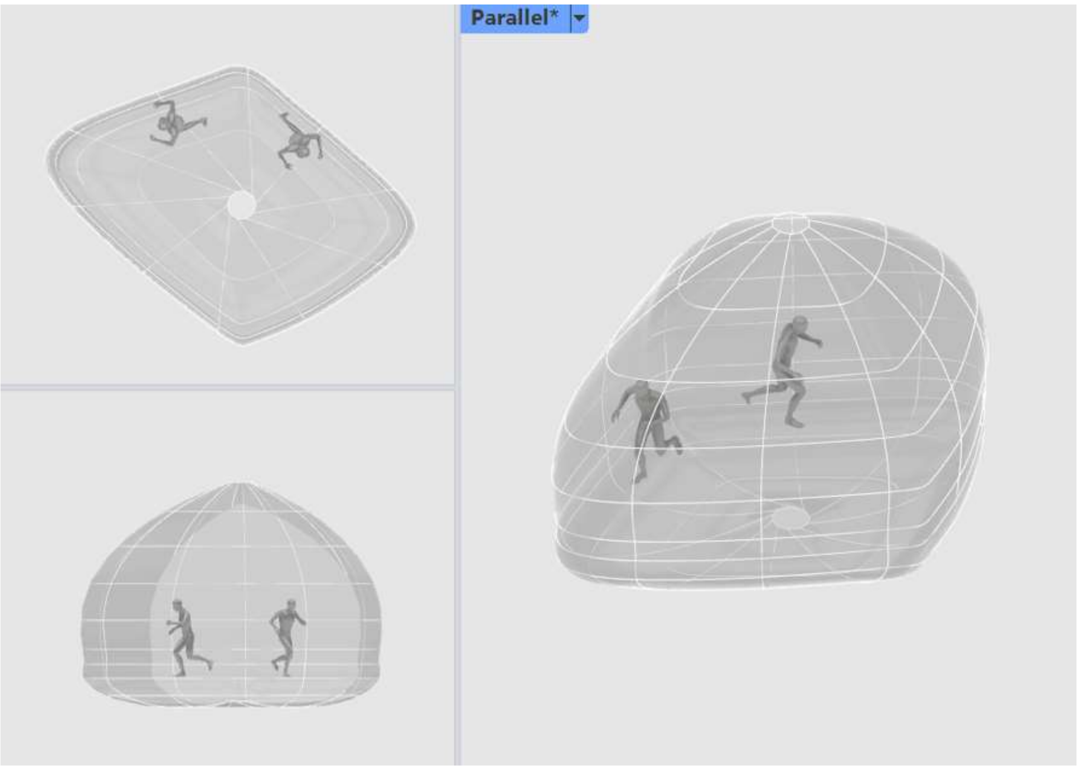


Figure 5.13:Design Output(Arthor,2026).

To bridge the gap between behavioral simulation and physical construction, a specialized script operationalizes the evolutionary logic of the habitat. The process begins with Section Control, where the algorithm decodes the varying intensities of the social force model into a series of differentiated profile curves. These curves are then synthesized into a continuous, non-linear Morphology via a Loft operation, ensuring a fluid spatial transition that follows human movement.

In the final Materialization phase, the script translates this geometry into a buildable system: Offset parameters define the primary skin’s thickness for atmospheric shielding, while Pipe components automate the embedding of the pneumatic framework. This technical workflow ensures that the "Pneumatic Muscle Matrix" is precisely mapped onto the evolved form, effectively transitioning the design from an abstract simulation into a materialized, load-bearing lunar architecture.

5.4 Human Movement Study

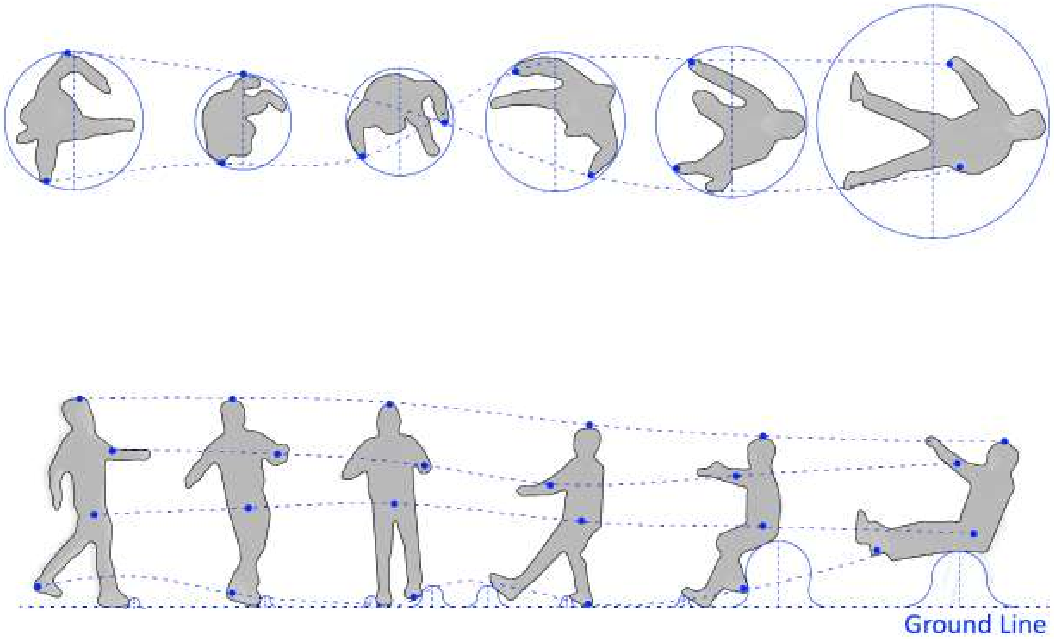


Figure 5.14: Lunar Seated Movement Envelope and Body Posture Analysis (Arthor,2026).

The seated movement study examines body posture and spatial envelope under lunar gravity. Reduced gravity affects balance and center-of-mass control, requiring extended arm reach and additional buffer space during seated transitions. These conditions indicate increased spatial demands compared to terrestrial seating.

The turning movement study focuses on directional changes during movement in reduced gravity. Turning involves larger rotational trajectories and delayed stabilization, resulting in a greater buffer zone around the body. This emphasizes the need for increased turning clearance within architectural spaces.

The sit-down motion study analyzes posture sequences during the transition into a seated position. Overlapping movement envelopes identify critical buffer zones that must remain unobstructed. Together, these studies demonstrate how lunar-specific movement patterns inform spatial clearances and architectural design decisions.

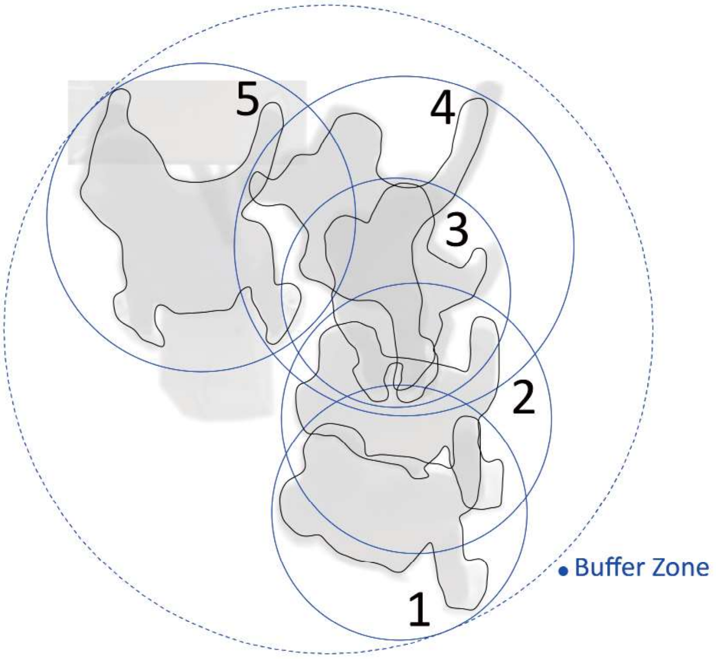


Figure 5.15: Movement study of sit-down motion and buffer zone under lunar gravity. (Author, 2026).

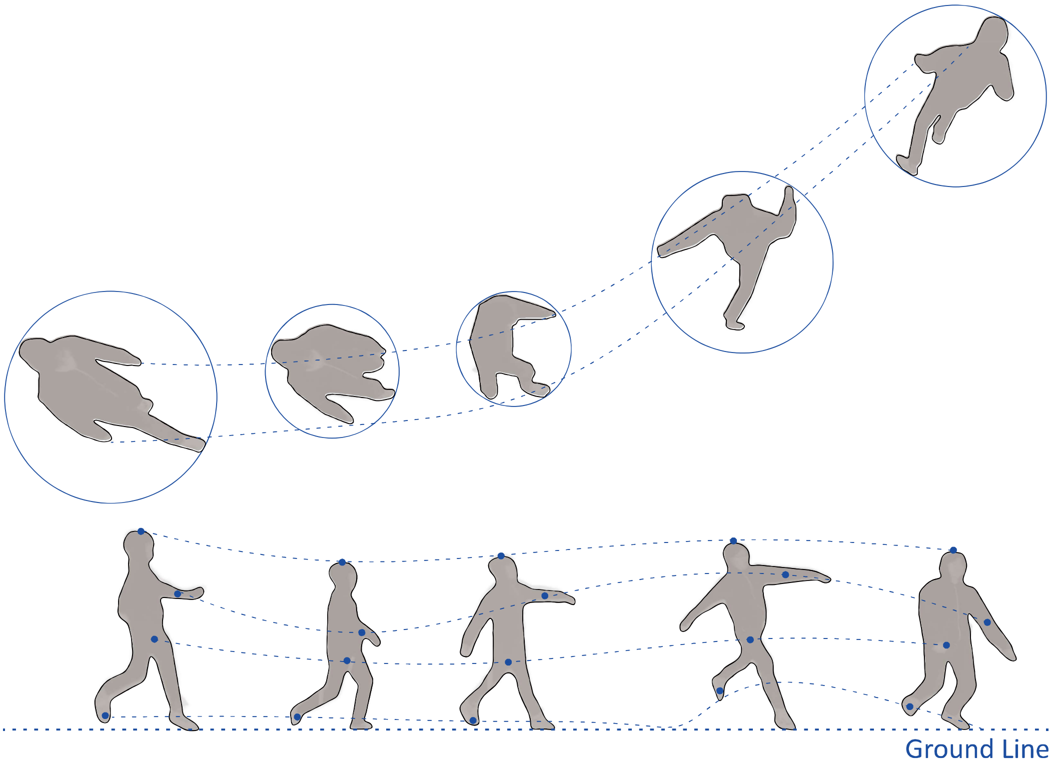


Figure 5.16: Lunar Seated Movement Envelope and Body Posture Analysis (Arthor,2026).

5.5 Lab Research

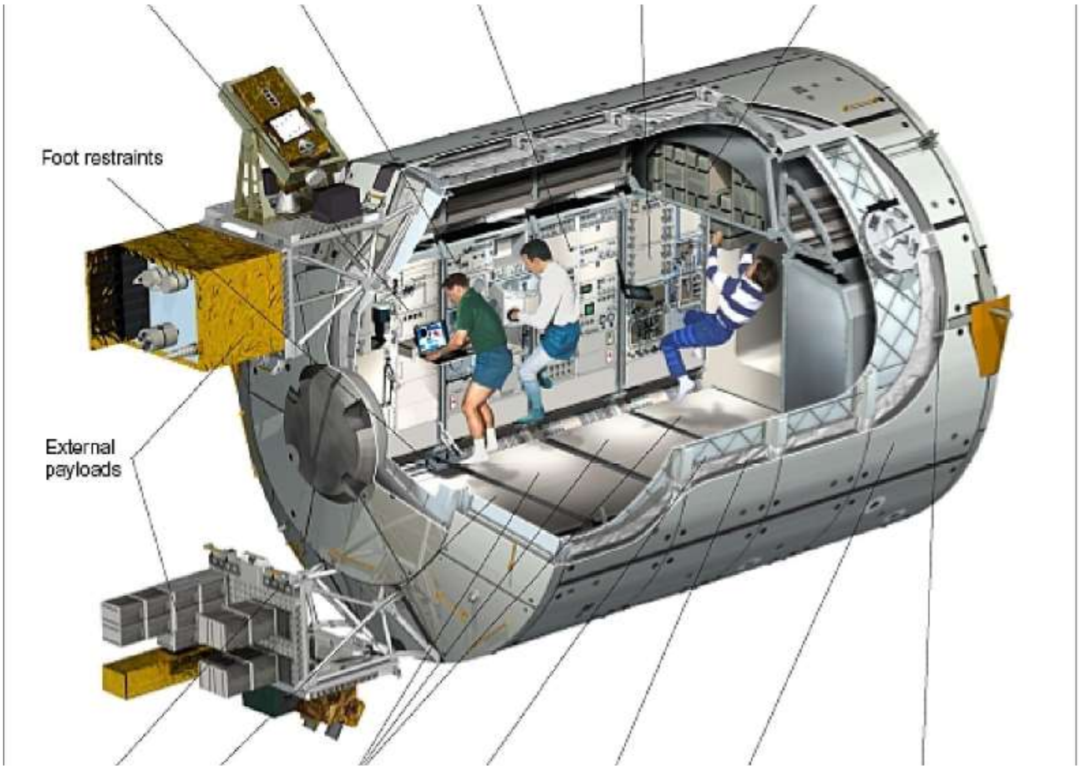


Figure 5.17: Programmatic Laboratory Classification Based on Scientific Research Discipline

The mission's scientific capabilities are organized into a multi-disciplinary Labs Category designed to support a comprehensive range of exploration goals. This laboratory suite includes specialized facilities such as the ***Biology*** and ***Human Research Labs*** for studying organic systems and crew health, alongside ***Physics*** and ***Geology Science Labs*** for analyzing physical phenomena and lunar/planetary samples. A General Lab provides a flexible workspace for cross-functional experiments, ensuring the habitat can adapt to diverse research requirements during the mission.

Human Research Lab

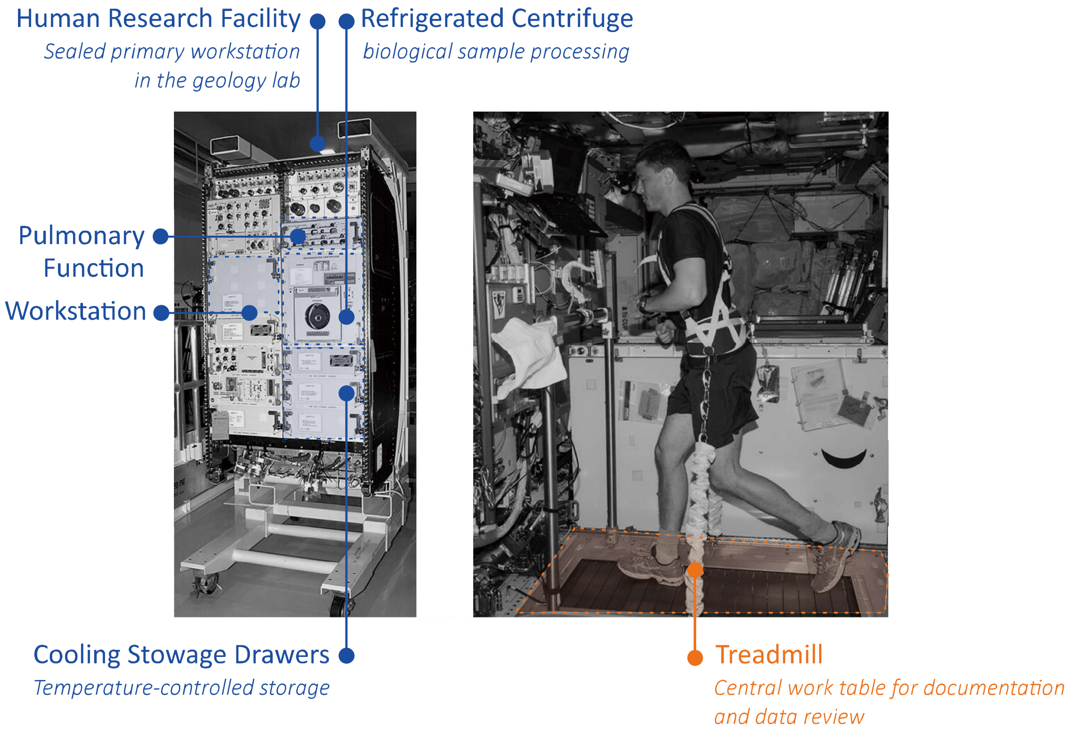


Figure 5.18: Programmatic Human Research Lab Infrastructure Based on Physiological and Environmental Stressor Analysis

The Human Research Lab is dedicated to studying the long-term effects of deep-space missions on the human body. The facility is equipped to investigate critical stressors, including Gravity variations, Radiation exposure, and the psychological impacts of Isolation and Confinement within a Hostile/Close Environment. Key instrumentation includes a Human Research Facility workstation for clinical monitoring, a Pulmonary Function Workstation, and a Refrigerated Centrifuge for biological sample processing. For physical health and data collection, the lab incorporates a Treadmill and temperature-controlled Cooling Stowage Drawers, alongside an Incubator / Growth Chamber to support auxiliary life science research

Static and Flexible part

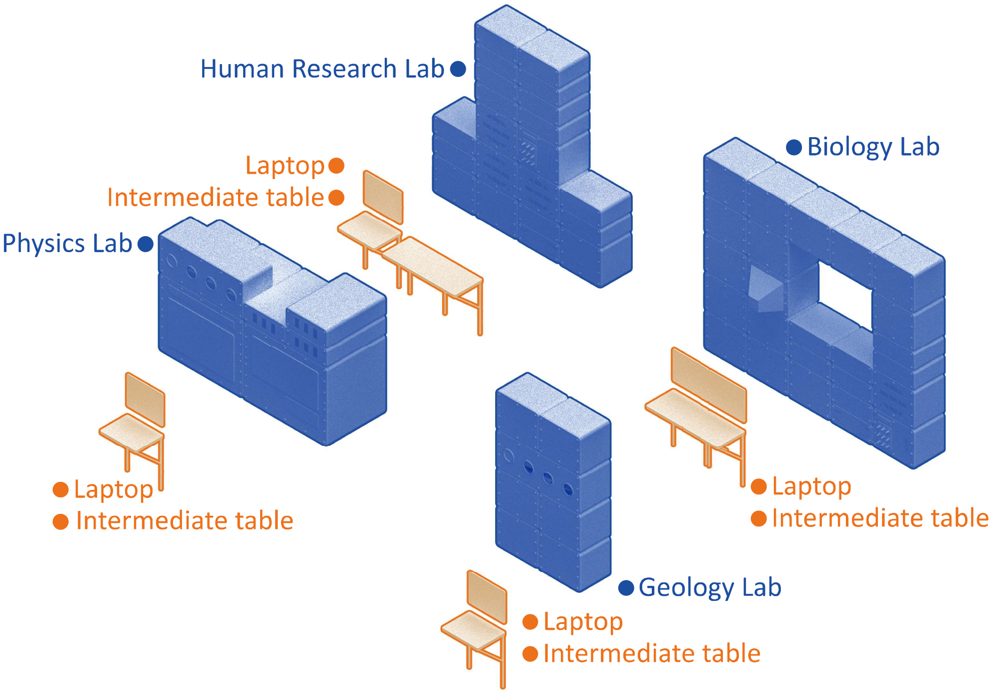


Figure 5.19: Programmatic Infrastructure Configuration Based on Static Equipment and Flexible Modular Workspace

The laboratory environment is engineered with a dual-tier configuration to balance mission-critical stability with operational adaptability. The Static Part comprises permanent, high-mass Research Equipment—including the core modules for the Human Research, Physics, Biology, and Geology labs—which provides the foundational technical infrastructure. Complementing this is the Flexible Part, a modular layer consisting of mobile Intermediate Work Tables and portable Laptops. This agile setup allows the crew to reconfigure secondary workspaces dynamically, facilitating collaborative data review and tactical shifts in research focus across the different scientific disciplines.

6.0 APPROACH

6.1 Concept

The bubble concept proposes the habitat as a responsive, inflatable system that behaves as a single adaptive body. Rather than relying on rigid boundaries, the architectural envelope expands and contracts in response to programmatic and spatial needs. Within the habitat, inflatable modules form flexible bubble spaces that can accommodate different functions and movement patterns. This approach allows space to remain soft, adaptable, and continuously reconfigurable, supporting dynamic use in extreme environments.

Figure 6.1: Inflatable bubble-based spatial concept illustrating responsive and soft architectural environments. Gab. (n.d.). Pinterest.

Figure 6.2: SKUM Pavilion inflatable installation. BIG – Bjarke Ingels Group. (2016). Retrieved from https://big.dk/projects/skum-pavilion-12388

6.2 Prototype

This prototype test focuses on the information flow between sensing, interpretation, and actuation within a responsive inflatable system. As illustrated in the right-hand diagrams, user input is first captured through sensors such as microphones, enabling voice-based interaction with the prototype. These inputs are processed through a language model that interprets user intent and translates it into actionable commands. The commands are then transmitted to the air-robot system, which controls pneumatic actuation and adjusts the form of the inflatable module accordingly. Through this closed-loop interaction, information continuously flows from human input to robotic response and back to the spatial environment, demonstrating how inflatable architecture can function as an interactive and adaptive system rather than a static enclosure

Figure 6.3: Inflatable prototype (Bubblebotics team,2026).

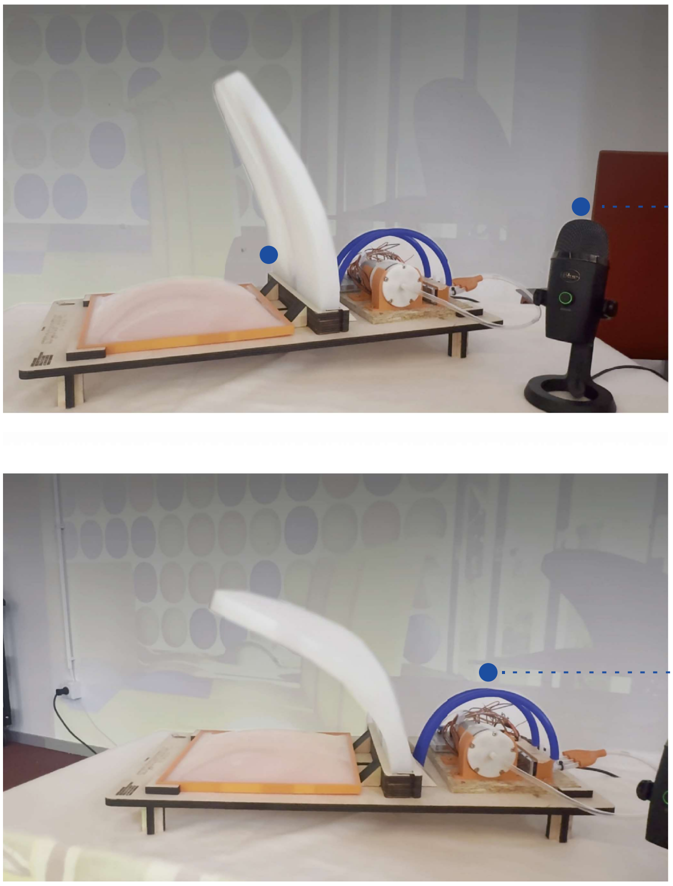


Figure 6.4: sensor–robot interaction test (Bubblebotics team,2026).

The prototype functions as a responsive interface that connects human intent to physical form through a sensing-actuator loop. The interaction begins with the MIC sensor, which captures voice input as raw environmental data. This information is then interpreted by an LLM-based brain to generate specific commands for the Air-Robot System. As the primary actor, the robotic system executes these commands by routing air into the inflatable "muscles," driving a visible change in the module's shape. This closed-loop process ensures the structure is not just a static enclosure, but a living system that senses, interprets, and physically adapts to its users in real-time.

6.3 Soft Robotics Study

The mechanical behavior of soft robotic actuators is determined by the equilibrium between internal driving forces and structural resistance. Under a constant pneumatic Pressure (P) and a fixed hyperelastic modulus (mu), the movement is dictated by a Geometric Driver: an offset-driven torque or Driving Moment (MP). This driving force is opposed by the Structural Resistance, which consists of the material's stiffness (Resistive Moment, MS) and the radial constraint provided by reinforcement (Mf). The ultimate goal of the predictive algorithm is to solve for Equilibrium (MP = MS + Mf), allowing for the simulation of precise trajectories and bending angles (theta) based on the actuator's cross-sectional geometry (a, b) and wall thickness (t).

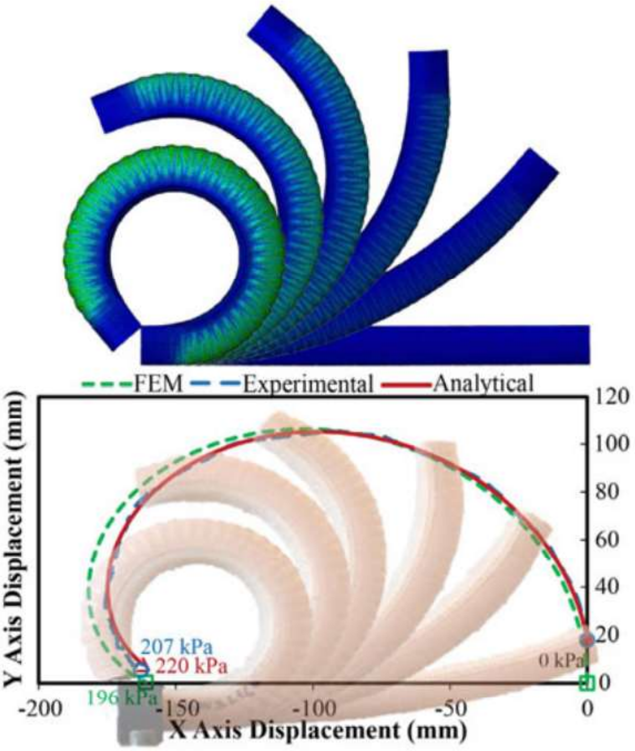


Figure 6.6: Soft Robotics Study Based on Pressure-Dependent Displacement and Computational Trajectory Validation

Flexible Matrix Composite (FMC)

Flexible Matrix Composite (FMC) cells are engineered to convert fluidic energy into predictable mechanical motion through a strategic multi-material architecture. The actuator consists of a dual-material body featuring rigid end caps for airtight sealing and a soft elastomeric sleeve that facilitates expansion. A high-strength helical fiber layer provides radial reinforcement to prevent bursting, while an inextensible base layer creates the necessary strain asymmetry for bending. This synergistic coupling of internal pressure, material properties, and wall geometry results in coupled actuation, allowing the cell to achieve repeatable bending or twisting paths essential for complex soft robotic tasks.

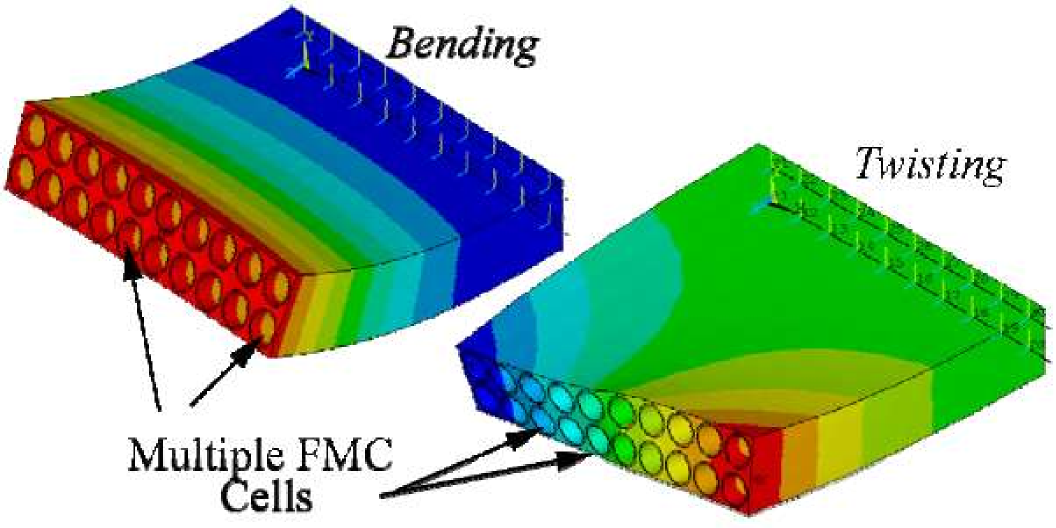


Figure 6.6: Soft Robotics Study Based on Flexible Matrix Composite (FMC) Kinematics and Adaptive Stiffness Control

6.4 Structure

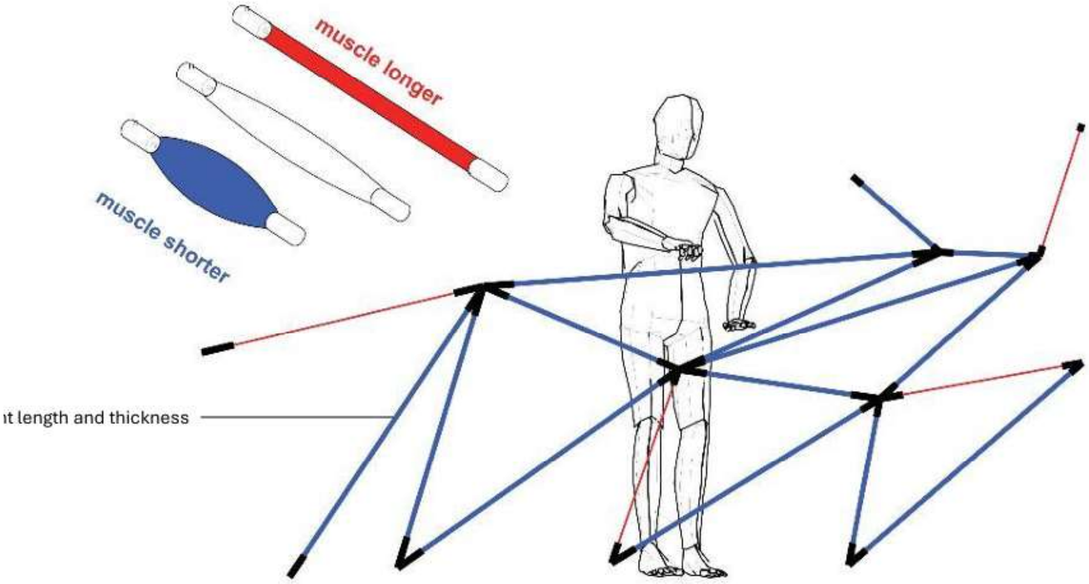


Figure 6.7: Walter. (2025). Adaptive architecture on the moon: Integrating mobile and inflatable approaches to address changing human needs on the moon (P5).

The structural framework is conceived as a Pneumatic Muscle Matrix, directly inspired by the contraction and extension mechanisms of biological musculoskeletal systems. Stability and movement are not achieved through rigid joints, but through the dynamic redistribution of pressurized air within an integrated network of internal tubes. By precisely routing airflow to specific modular "cells," the system generates kinetic force vectors that act as synthetic tendons. This pneumatic flow allows the structure to modulate its geometry in real-time—stiffening to provide robust load-bearing support or flexing to enable adaptive bending and twisting. This fluid-driven equilibrium ensures the habitat can dynamically respond to both human activity and the extreme environmental pressures of the lunar surface.

7.0 Relevance

This research can be closely connected to ***human-centered habitat design***, ***in situ resource utilization (ISRU)***, ***the robotization of architecture***, and ***sustainable design***. By placing human movement, posture, and bodily interaction at the core of spatial generation, the project redefines habitat design as a responsive system shaped by occupants rather than fixed programs or static layouts. This human-centered approach is particularly relevant in extreme environments, where conventional architectural solutions often fail to accommodate long-term habitation.

At the same time, the research explores inflatable and adaptive systems as a strategy aligned with ISRU, reducing dependence on Earth-based construction by emphasizing lightweight structures, material efficiency, and spatial adaptability. The integration of sensing technologies, robotic actuation, and soft inflatable modules reflects the growing robotization of architecture, where buildings can perceive, interpret, and respond to human behavior in real time. Through this framework, the project proposes a sustainable architectural model in which spatial transformation, resource efficiency, and human well-being are closely interlinked.

8.0 Scope

This research is scoped to the exploration of ***responsive interior architectural systems*** for extreme environments, using a lunar habitat scenario as a conceptual and experimental context. The scope is limited to ***human-scale spatial design***, focusing on interior environments rather than exterior structures, urban planning, or territorial settlement strategies. The study addresses habitats intended for **small crews (six occupants)** and does not extend to large populations or long-term urban growth models.

The research scope centers on the relationship between ***human movement, bodily posture, and spatial adaptability***, examining how architecture can respond to human presence and behavior through form transformation. It is confined to ***conceptual design, spatial logic, and system interaction***, rather than full technical resolution. Engineering aspects such as structural optimization, material durability under lunar conditions, life-support systems, and construction logistics are outside the scope of this study.

In terms of technology, the scope includes the ***conceptual integration of sensing, computation, and actuation*** as part of an architectural system, without aiming to develop or validate complete robotic or AI systems. The research is positioned within architectural design inquiry, using prototypes and diagrams as exploratory tools rather than as deployable solutions.

Overall, the scope defines this project as an ***architectural investigation into adaptability, human-centered space, and robotic mediation***, framed within the broader relevance of ISRU, architectural robotization, and sustainable design, while deliberately excluding detailed engineering, biomedical analysis, and operational mission planning.