Helios Lunar: An Analogue Habitat for Future Crewed Missions

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Abstract

To establish a sustainable human presence for lunar settlements, NASA's Artemis program aims to launch missions within the 21st century. In preparation for deep space human missions, developing a simulated habitat in an extreme environment encounters similar challenges that enhance the credibility of the concept. Helios Lunar is an analogue space habitat developed for the surface of the Moon that incorporates space architecture principles from the literature to adapt to modern times infrastructure such as the Artemis lunar base camp. This habitat integrates foldable mechanisms, deployment procedures in extreme environmental conditions, human ergonomics, psychological improvement technologies, and structural aspects for analogue habitats. Helios Lunar integrates structural behaviors from extreme environment habitats to support key technical aspects. These aspects include space-active sustainability and development mechanisms tailored to the needs of modern infrastructure. The vision of the project is to develop a human-centric analogue habitat for the lunar surface exploration phase, which will be built in such a manner that it can be expandable in the future. The prototype is developed as per the payload system criteria of SpaceX's Starship, which enables feasible transportation to remote destinations. The kinematics of the modular segment are also accounted for. The spatial orientation of Helios Lunar is planned considering the effects of operating in an isolated, confined, extreme environment for a human-centric model, and mission functionality. The habitat design further accounts for human factors (ergonomics and psychological) and behavior of the astronauts. For long-term missions, the psychological behavior is addressed by

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implementing neuroarchitecture features in the habitat workplace, which include a combination of natural lighting, plant wave sensors, circadian light systems, and the selection of biophilic design to integrate natural elements into the interior structure. Helios Lunar should first be developed as a sustainable analogue habitat for future crewed missions.

Keywords: lunar infrastructure development, hybrid module, neuroarchitecture, biophilia, active sustainability, foldable habitat, spatial orientation, space geometrics

Helios Lunar: Un hábitat análogo para futuras misiones tripuladas

Resumen

Para establecer una presencia humana sostenible en los asentamientos lunares, el programa Artemis de la NASA aspira a lanzar misiones en el siglo XXI. En preparación para las misiones humanas al espacio profundo, el desarrollo de un hábitat simulado en un entorno extremo se enfrenta a desafíos similares que refuerzan la credibilidad del concepto. Helios Lunar es un hábitat espacial análogo desarrollado para la superficie lunar que incorpora principios de arquitectura espacial de la literatura para adaptarse a infraestructuras modernas, como el campamento base lunar Artemis. Este hábitat integra mecanismos plegables, procedimientos de despliegue en condiciones ambientales extremas, ergonomía humana, tecnologías de mejora psicológica y aspectos estructurales propios de hábitats análogos. Helios Lunar integra comportamientos estructurales de hábitats en entornos extremos para respaldar aspectos técnicos clave. Estos aspectos incluyen la sostenibilidad activa en el espacio y mecanismos de desarrollo adaptados a las necesidades de la infraestructura moderna. La visión del proyecto es desarrollar un hábitat análogo centrado en el ser humano para la fase de exploración de la superficie lunar, que se construirá de forma que pueda ampliarse en el futuro. El prototipo se desarrolla según los criterios del sistema de carga útil de la nave espacial Starship de SpaceX, lo que permite un transporte viable a destinos remotos. También se tiene en cuenta la cinemática del segmento modular. La orientación espacial de Helios Lunar se planificó considerando los efectos de operar en un entorno aislado, confinado y extremo para un modelo centrado en el ser humano y la funcionalidad de la misión. El diseño del hábitat también considera los factores humanos (ergonómicos y psicológicos) y el comportamiento de los astronautas. Para misiones de larga duración, el comportamiento psicológico se aborda mediante la implementación de características de neuroarquitectura en el entorno de trabajo del hábitat, que incluyen una combinación de iluminación natural, sensores de ondas vegetales, sistemas de iluminación circadiana y la selección de un diseño biofílico para integrar elementos naturales en la estructura interior. Helios Lunar debe desarrollarse inicialmente como un hábitat análogo sostenible para futuras misiones tripuladas.

Palabras clave: Desarrollo de infraestructura lunar, módulo híbrido, neuroarquitectura, biofilia, sostenibilidad activa, hábitat plegable, orientación espacial, geometría espacial.

Helios Lunar：未来载人飞行任务的模拟栖息地

摘要

为了在月球上建立可持续的人类定居点，NASA的阿尔忒弥斯计划旨在21世纪内发射任务。在为深空载人任务作准备的过程中，“在极端环境下开发模拟栖息地”一事面临着类似的挑战，这增强了该概念的可信度。Helios Lunar是一个为月球表面开发的模拟空间栖息地，它融合了文献中的空间建筑原理，并使其适应现代基础设施，例如阿尔忒弥斯月球基地。该栖息地集成了可折叠机制、极端环境条件下的部署程序、人体工程学、心理改善技术、以及模拟栖息地的结构要素。Helios Lunar借鉴了极端环境栖息地的结构特性，以支持关键技术方面。这些方面包括太空活动可持续性和根据现代基础设施需求定制的开发机制。该项目的愿景是为月球表面探索阶段开发一个以人为中心的模拟栖息地，其建造方式使其在未来能被扩展。该原型是根据SpaceX星舰的有效载荷系统标准开发的，旨在实现向偏远目的地的可行运输。模块化舱段的运动学特性也已纳入考虑。Helios Lunar的空间方位规划考虑了“在孤立、封闭、极端环境下运行”对以人为中心的模型以及任务功能的影响。居住舱的设计进一步兼顾了宇航员的人体因素（人体工程学和心理因素）和行为。对于长期任务，通过在居住舱工作场所应用神经架构特征来应对心理问题，这些特征包括自然采光、植物波传感器、昼夜节律照明系统、以及选择亲生物设计，将自然元素融入内部结构。Helios Lunar应首先开发为一个适合未来载人任务的可持续模拟居住舱。

关键词：月球基础设施开发，混合模块，神经架构，亲生物性，活跃可持续性，可折叠居住舱，空间方位，空间几何

Introduction

The quest to extend human presence beyond Earth has driven NASA to develop programs that test the limits of space exploration. NASA's Artemis program aims to establish a sustainable human presence on the Moon through a series of missions planned for the 21st century. The Artemis lunar base camp concept combines principles of space architecture with advanced infrastructure studies to adapt to the demands of modern space missions. To prepare for deep-space crewed missions, NASA is focused on developing simulated habitats in extreme Earth environments that mirror the unique challenges of the lunar surface, adding credibility and value to analogue missions. With its relative proximity to Earth and accessible resources that differ from those found on our planet, the Moon serves as an ideal testing ground for future deep space missions. The groundbreaking discovery led scientists to better understand the survival of humans in deep space. **The ISS is a crucial structure for developing space habitat concepts. However, the ISS was built primarily from an engineering perspective, which has led to feelings of fatigue among crew members due to its confined environment**. This report advocates for the development of Helios Lunar (HL), a lunar analogue habitat designed as a testbed to tackle challenges related to lunar conditions and human factors essential to long-term lunar missions.

Objective

The HL analogue habitat is designed to emphasize human-centric models and foundational surface habitation, aiming to enhance the interaction between humans and machines for superior performance in extraterrestrial environments.

Background

Analogue habitats, designed to simulate extraterrestrial environments on Earth, have significantly advanced in both complexity and functionality in recent years, becoming pivotal in preparing for long-duration space missions. Pioneering research through organizations such as NASA's HI-SEAS has enriched our understanding of the physiological, psychological, and logistical challenges faced by astronauts. These habitats are equipped with technologies that mimic the isolated and confined conditions of space, facilitating studies on crew dynamics, sustainability practices, and life support systems under extraterrestrial-like conditions. The integration of cutting-edge technologies such as virtual reality for psychological health, advanced bio-regenerative life support systems, and robotic assistance has transformed these habitats into comprehensive platforms for interdisciplinary research, providing invaluable insights that inform the design and operation of future space missions. The development of HL is conducted through the analysis of several research stations, see **Table 1**.

Table 1. *Literature Review Phases of Helios Lunar.*

Phases	Intend of study	Case study	Aspects
I Parent habitat	To understand the concern of how a parent's habitat should work	SHEE Lunark	Portability, Self deployable, Interior component foldability, Space orientation and Human ergonomics
II Survival structure	Structure survivability in extreme environment	Halley VI RS Bharathi RS Concordia station	Resource shortage, Material study, Foundation study, Life support system, Human psychology and Space orientation
III Futuristic approach	To grow modular structure to the colony and later to an urban village	Oceanix City Myco architecture off-planet	Modular concept, Extreme environment construction, Radiation protection, Scalable, Biotechnology products and Urban Development

Methodology

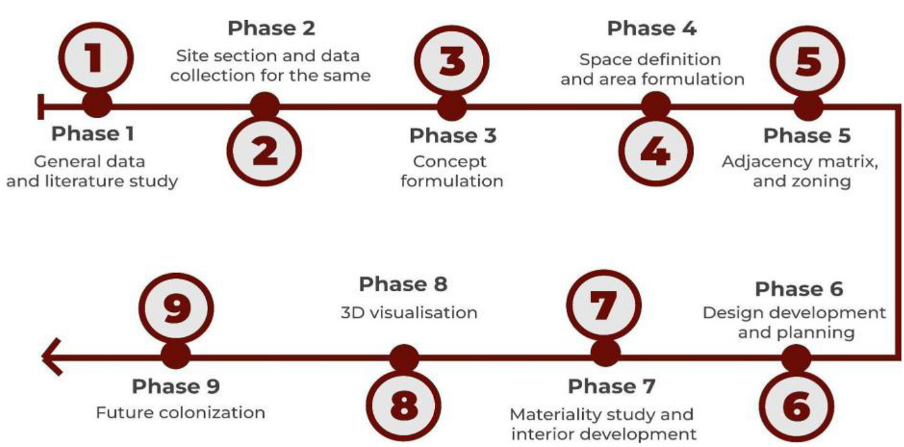


Figure 1. *Methodological Framework for Helios Lunar.*

The research for Helios Lunar followed a nine-phase methodological framework, as illustrated in **Figure 1**. The process began with **Phase 1**, a general data and literature study to establish theoretical and technical foundations. In **Phase 2**, potential sites were selected, and relevant environmental data were collected. This data informed **Phase 3**, where initial design concepts were formulated. **Phase 4** focused on defining spatial requirements and formulating area programs, which led to **Phase 5**, the creation of adjacency matrices and zoning layouts to establish functional relationships. Following this, **Phase 6** involved advancing the design development with detailed structural considerations. Materiality and interior design strategies were then investigated in **Phase 7**. To represent the design, 3D visualizations were produced in **Phase 8**. Finally, **Phase 9** considered the project's scalability and adaptability for future colonization scenarios.

Helios Lunar

By understanding the foundation and limitations of case studies, HL focuses on binding the terrestrial connection within a closed environment without compromising the technical sense. HL aims to demonstrate the enduring factors of deep space missions by adding humans to the system. The prototype was designed considering volume, mass, kinematics, functionality, and material for survival under extreme conditions. The motivation for developing concepts like HL is not just space survivability but also bringing innovative methods for future habitability as our end goal is to build a colony and paper to illustrate the prototype. According to the timeframe of lunar colonization, Helios Lunar is an approach for the Lunar Surface Exploration Phase II. Apart from environmental challenges, the prototype deals with human factors and portability.

Foam generation

Designing for the lunar environment requires resilience against extreme conditions. HL adopts biomimicry, drawing from deep-sea organisms to minimize drag, enhance durability, and adapt to harsh stresses. The habitat is portable, self-deployable, and low-maintenance, supporting remote operations and efficient transport. A shift from curved to octagonal form reduces membrane components, lowering cost and deployment risks, while ensuring scalability for future lunar urban development.

Deployment phases

The foldable HL's kinematics prioritize deployment simplicity and an optimized deployed-to-stowage ratio. The report has delivered in depth detailing of the kinematic mechanism and technical deployment procedure. Structurally, HL is divided into two key components: the pre-integrated space and the foldable space. The deployment process is organized into distinct phases as shown in **Figure 3**.

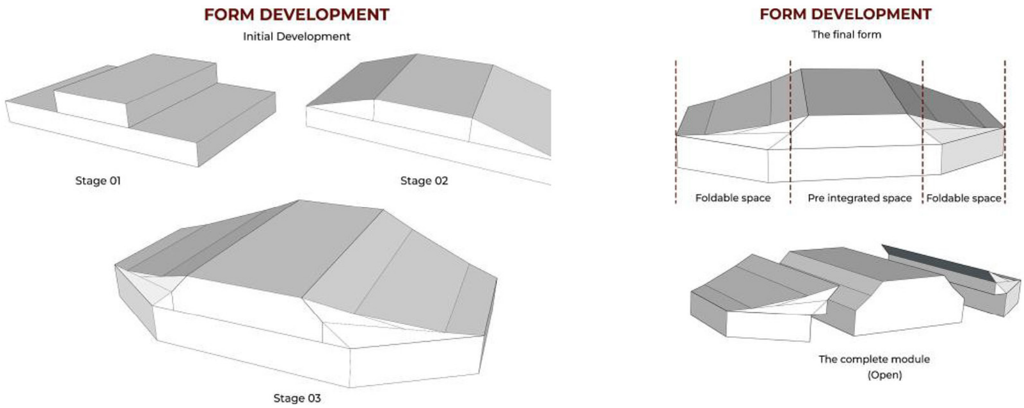


Figure 2. *Foam generation of Helios Lunar.*

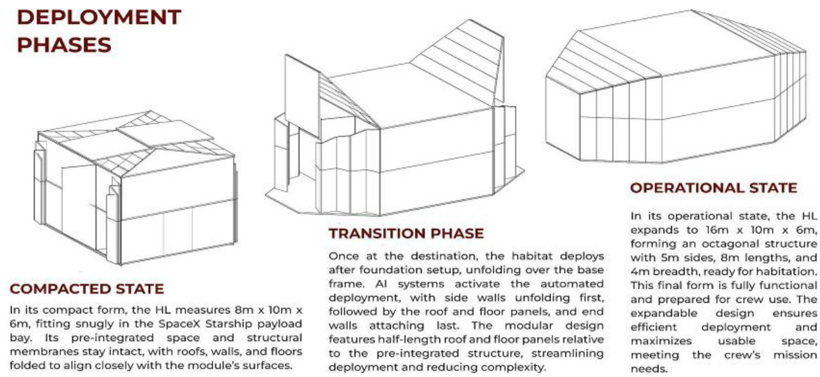


Figure 3. *Deployment phases of Helios Lunar.*

Zoning and adjacency map

HL is purpose-built for Phase II of the lunar surface exploration mission. The team strategically developed functionality and adjacency considerations for each area, as mapped in the adjacency diagram (**Figure 4**). Following the analysis of this proximity chart, zoning plans were prepared to facilitate efficient horizontal and vertical circulation, as detailed in **Figure 5**.

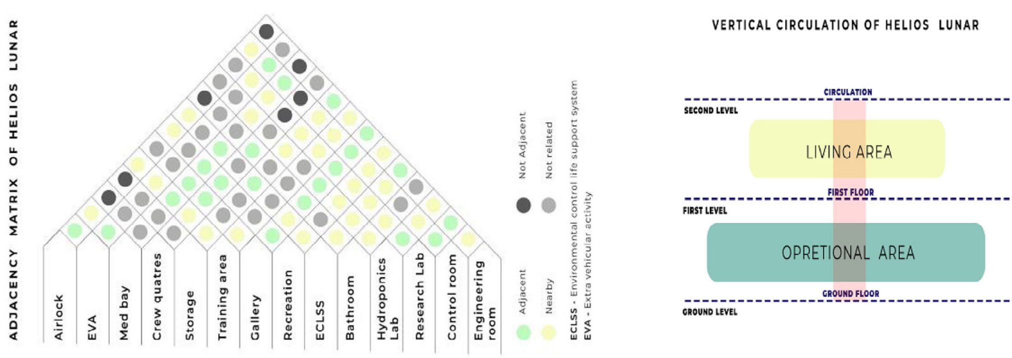


Figure 4. *Adjacency Matrix and Vertical Circulation of Helios Lunar.*

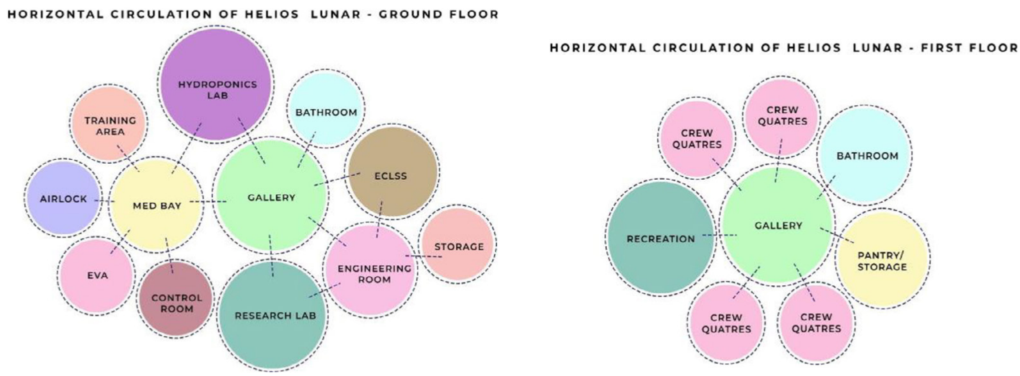


Figure 5. *Horizontal Circulation of Helios Lunar.*

To ensure optimal spatial orientation, a comprehensive understanding of functional requirements was achieved through an extensive literature review. Each critical area was defined as follows.

1	Airlock	:	Balances atmospheric conditions between habitat and external environment
2	EVA prep area	:	Dedicated space for decontamination and maintenance of EVA equipment
3	Med bay	:	Facilitates medical procedures and health monitoring
4	Crew quarters	:	Personal space for crew members to store belongings and rest
5	Stowage	:	Reserved for essential equipment and supplies
6	Training	:	Enable physical exercise to maintain crew fitness
7	Galley	:	Social area designed for meal preparations and informal gatherings
8	Recreation	:	Provides a space for relaxation and leisure
9	ECLSS	:	Houses equipment for water, waste and air treatment
10	Bathroom	:	Designed for crew hygiene and personal care
11	Hydroponics	:	Support crop cultivation and agriculture research
12	Control room	:	Centralized area for mission data management and communication
13	Engineering room	:	Monitors and manages habitat subsystems

Design development and planning

Upon reviewing the zoning layout, the concept developed spaces through adjacency mapping to optimize functional relationships. HL has demonstrated excellence in planning based on integrating social, physical, and psychological factors to blend with habitat. The functional area ranges of HL, formulated from case studies, are listed in **Table 2.** The habitat's compact core incorporates fixed structural interior components, while its expandable octagonal sides accommodate dedicated spaces for research, hydroponics, and sections of the medical bay. After deployment, the first floor of the habitat will be fully intact and ready for immediate use. Spatial organization within HL systematically addresses public-to-private, wet-to-dry, and silent-to-noisy elements, ensuring an architecturally balanced layout. **Figure 6** provides comprehensive plan details and insights.

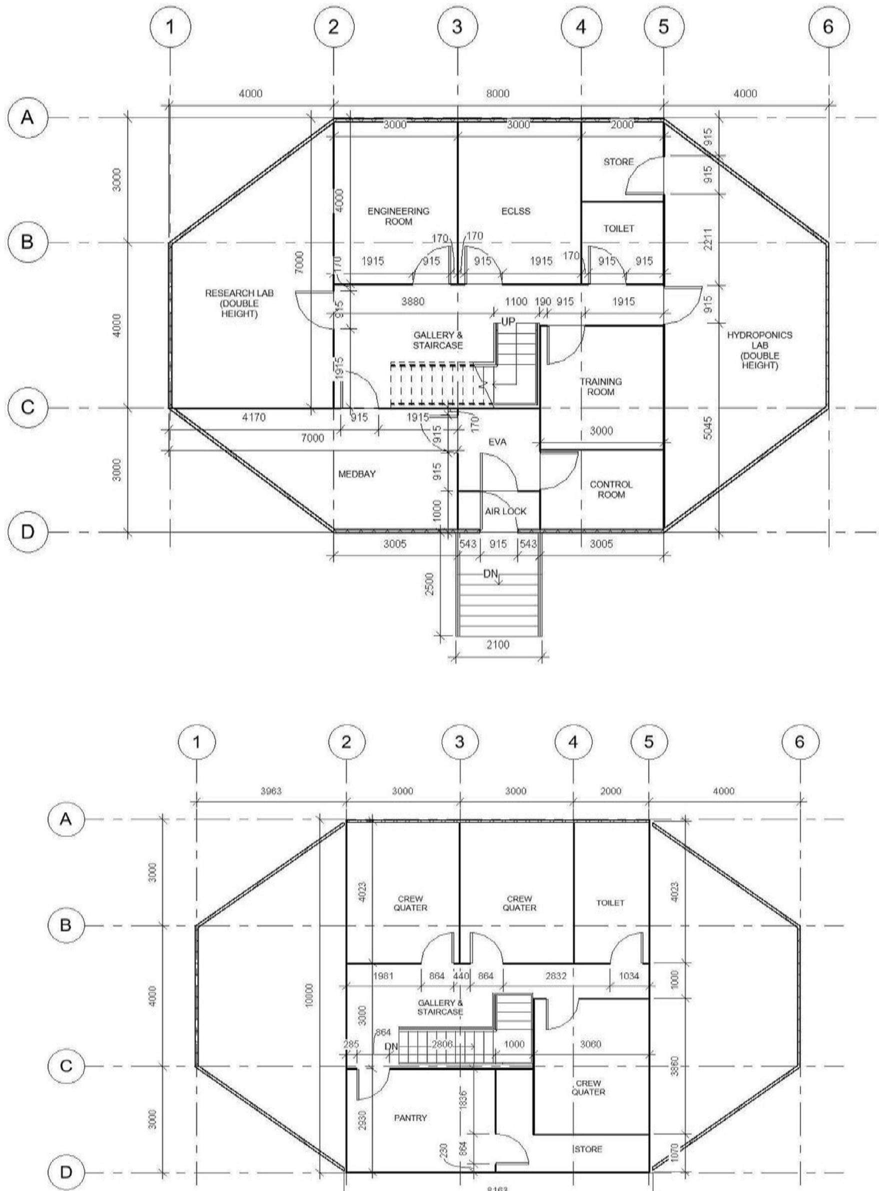


Figure 6. *Ground floor and First floor plans of Helios Lunar.*

Table 2. *Area calculation of Helios Lunar.*

Functional spaces	Average Area of Case Studies (Sebastian & Karl, 2024), (Barbara et al., 2015), (Moreno et al., 2009) (m^2)	Area of HL (m^2)	Percentage Area of Case Studies (%)	Percentage area of HL (%)
Airlock	0.785 – 1.13	2	0.957	1.5
EVA	0.785	2	1.2	1.5
Med Bay	15.19 – 100	16	2.68	12
Training room	1 – 150	9	3.517	6.76
Control room	0.747 – 50.7	6	15	4.5
Galley / Stairs	20.7	18	7.39	13.53
Research lab	6.85 – 14.56	22	10.7	16.5
Hydroponics lab	158.32	26	14.38	19.5
Bathroom	0.25 – 20	4	4.2	3
ECLSS	1.875 – 25	12	13.43	9.02
Engineering room	0.747 – 50.7	12	9.87	9.02
Storage	0.5 – 1.5	4	6.05	3
Total area of GF		133		
Galley / Stair	20.7	18	13.63	20
Crew quarter 1	1.42 – 51.85	12		13.3
Crew quarter 2	1.42 – 51.86	12	24.82	13.3
Crew quarter 3	1.42 – 51.87	12		13.3
Toilet	0.25 – 20	8	4.2	8.89
Pantary	4.75 – 16	12	–	13.3
Storage	0.5 – 1.5	6	6.05	6.67
Total area of FF		90		
Total Area		223		

Structural detailing

In the HL project, structural detailing and material optimization are central to creating a habitat capable of withstanding the lunar's extreme conditions. Structural detailing focuses on precision engineering to ensure stability under irregular terrain, partial gravity and fluctuating thermal conditions.

Foundation

The structural foundation consists of an injection pile with anchorage, designed to maintain stability and immobility within the structural development area. The base layout and configuration of HL follows.

a. **Installation Base:** The foundation rests on a hexagonal plane, supported by an arrangement of horizontal and vertical beams. This hexagonal framework forms the support system for the pile foundation.

b. **Pile Specifications:** The pile foundation is 1,000–1,300 mm high, with a total foundation depth of 1,600 mm. The base is 300 mm thick, and 1,300 mm of the pile extends below ground level.

c. **Anchorage Plate:** Positioned at the intersection with ground level, this plate is situated between the pile and the injection grout, ensuring a stable connection.

d. **Plate Dimensions:** Each anchorage plate measures 100 mm x 100 mm and is anchored within the central part of the pile.

e. **Z-Clamp Anchoring:** Z clamps to secure the anchorage plate in position. These clamps are affixed to the ground via screws that extend downward, further stabilizing the foundation.

f. **Grouting Material:** The pile injection is filled with grout using lunar regoliths, sintered via solar energy, providing a solidified bond to support the foundation's integration with the surrounding soil.

This foundation system effectively transfers structural loads through the securely anchored plate and the solar-sintered grout layer. The arrangement of the hexagonal beam plane and pile anchorage, combined with the embedded plate and Z-clamp system, ensures enduring stability for the structure. The foundation system optimizes materials by using in-situ lunar regolith (Grout) and lightweight alloys (Aluminum alloys), reducing Earth imports while ensuring durability and structural integrity in the lunar environment.

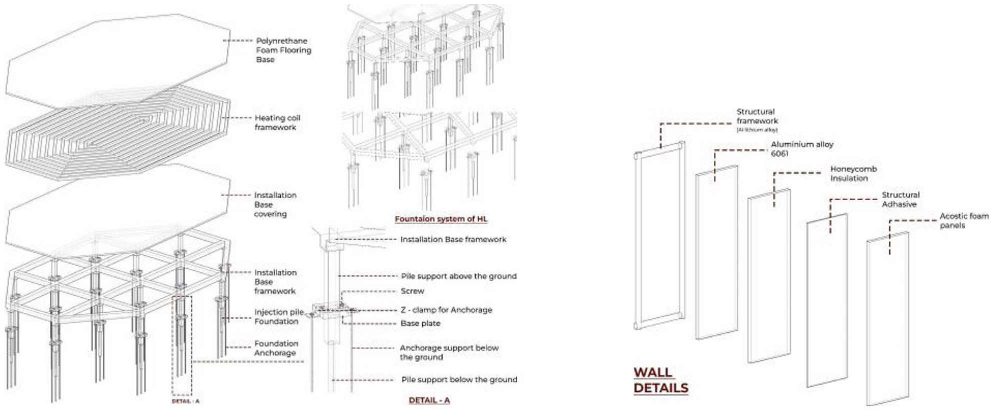


Figure 7. Close-up view of the foundation system for Helios Lunar.

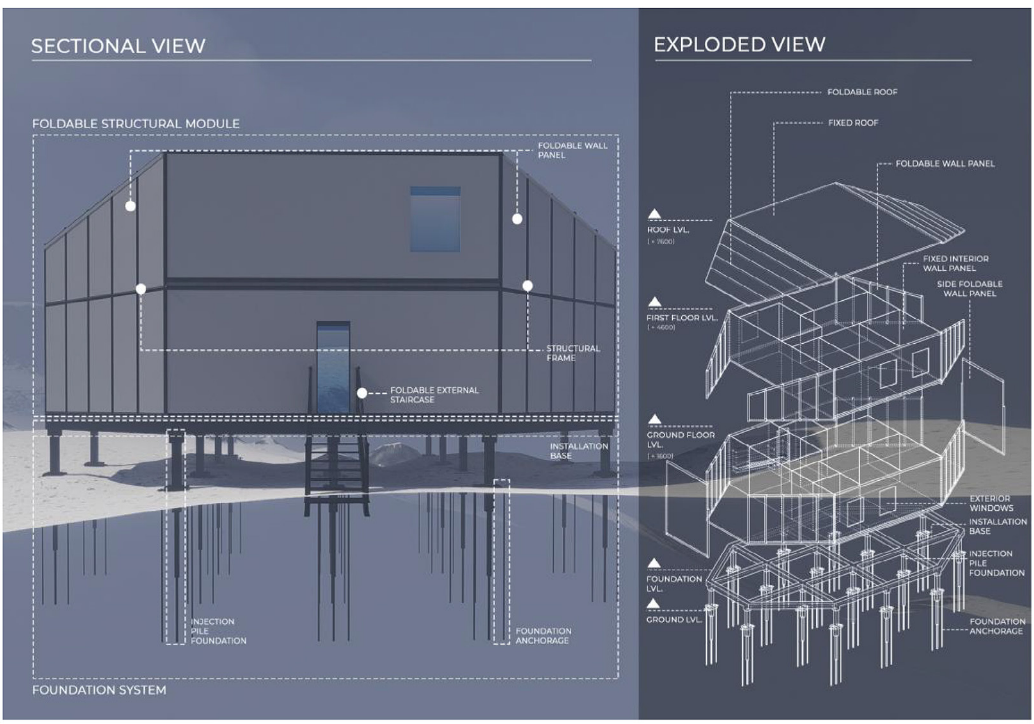


Figure 8. Sectional and explosive views of Helios Lunar.

Habitat ancillary systems

Ancillary systems are the essential support system that ensures the habitat operates smoothly, providing a safe sustainable environment for its occupants. As a Biological-Regenerative Life Support System (Bio-LSS), HL adopts a Micro-Ecological Life Support System Alternative (MELiSSA). MELiSSA consists of five main compartments:

1. The liquefying compartment (CI)
2. The photoheterotrophic compartment (CII)
3. The nitrifying compartment (CIII)
4. The algae compartment (CIV.a)
5. The high plant compartment (CIV.b)
6. The crew compartment (CV)

Apart from the main compartment, it requires secondary support systems are Biomass Pretreatment Unit (BPU), Urine Treatment Unit (UTU), Carbon Dioxide Concentration Assembly (CCA), Carbon Reduction Assembly (CRA), Food Treatment Unit (FTU), Air Recovery System (ARES), Gray water recovery unit (GWRU), Common equipment and Interface Buffer (IB&CE). These compartments will be attached to HL using United Technology Aerospace System (UTAS) ECLSS pallets (Jones, 2021) for a user-friendly interface. Analyzing existing requirements HL consciously integrated existing systems to its biosphere. **Table 3** explains the adopted mechanisms.

Table 3. *Helios Lunar Ancillary System.*

Sl.no.	Subsystems systems	Ancillary systems
1	Power system	Active source - Solar panels attached to habitat panel Passive source - Rechargeable batteries
2	Thermal Control System (TCS)	Active TCS - Thermal conduct system Passive TCS - Outer shell layer
3	ECLSS	MELiSSA
4	Communication system	Internal communication - Secure WIFI networks, Headset with push-to-talk radios, Alarm and notification system External communication - Combination of Laser and High Frequency Radio communication
5	Radiation Control system	Active layer - Outer shell layer Passive layer - Interior wall material with high Hydrogen composition
6	Structural integrity monitoring	Advanced smart pressure sensors

Human Factors

HL prioritizes human-centered design alongside structural integrity, ensuring optimal workflow, accessibility, and comfort through proximity chart planning.

a. **Ergonomics**

HL adopts a fully pressurized module to counter physiological effects of partial gravity (bone loss, muscle atrophy, vision issues, cognitive illusions). Ergonomic considerations include spatial use of floor/walls/ceiling, work surface height, force and leverage needs, and orientation references. Interior design applies color theory and dimensions for comfort. Table 5 outlines survival ranges: gravity (0–1G), temperature (23–27°C), humidity (40–60%), pressure (10–15 psi), sound (0–60 dB), circadian rhythm (12h awake/12h sleep), light (0–750 lux), radiation (0–50 rad), and complete shielding from debris/regolith.

b. **Psychological Aspects**

Isolation, confinement, and stress demand design solutions. HL provides private crew spaces (34.58 m^3 per person vs. 20 m^3 standard), bedrooms/washrooms on the first floor, and windows for external connection. Interior design ensures air quality, lighting, noise control, color use, and AR integration.

Innovative Features

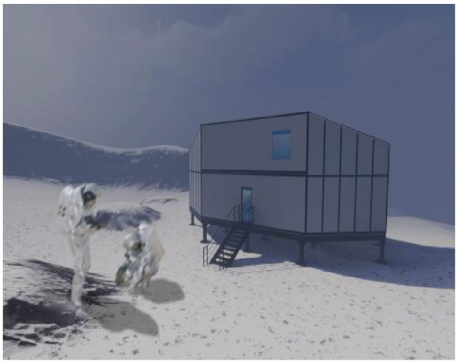
- *Circadian lighting*: artificial daylight to regulate hormones.
- *Plant wave sensors*: convert plant transpiration into music for nature connection.
- *Biophilic elements*: natural materials, aromas (teak beds, salt lamps).
- *Neuroarchitecture light path*: colored emergency lighting for orientation.

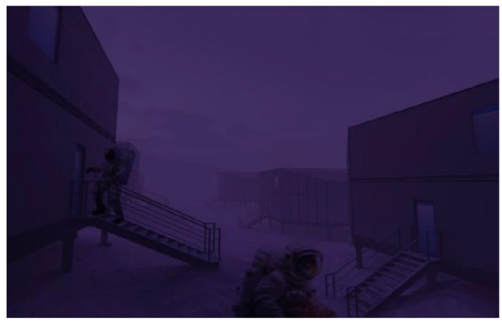
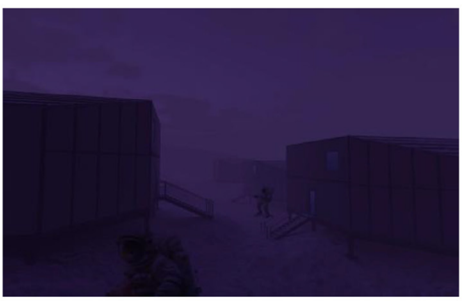
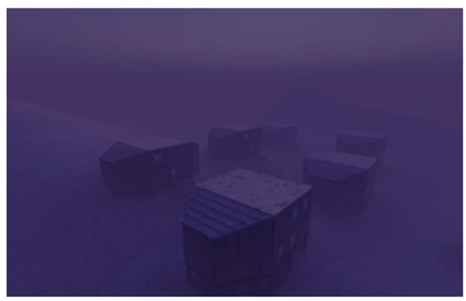
By integrating ergonomic, psychological, and biophilic elements, HL elevates human well-being and mission efficiency, setting it apart as a human-centric habitat design.

Conclusion

This paper presents the design and development of HL, an advanced, human-centric analogue habitat conceptualized for deployment in the lunar environment, specifically near Shackleton Ridge. HL is a modular, foldable structure designed to meet the challenges posed by extraterrestrial habitation through an emphasis on both technical and human-centered factors. As a deployable habitat, HL addresses a range of requirements for extraterrestrial living, including structural resilience, kinematics, and integration of space subsystems, while prioritizing human physiological and psychological needs. The design incorporates a unique material selection strategy to ensure structural integrity in extreme conditions, thereby supporting long-term human presence in space. The habitat's compact, folded dimensions (8 m x 10 m x 6 m) allow it to be efficiently transported within the payload capacity of SpaceX's Starship,

3D conceptualization



expanding to 16 m x 10 m x 6 m upon deployment. Zoning and adjacency mapping informed the spatial orientation of HL, which is designed with a streamlined structure to reduce environmental friction drag. HL incorporates advanced human-centered design features, such as a circadian lighting system, plant wave sensors, biophilic design elements, and neuro architectural lighting to support crew psychological and physiological well-being.

The HL project aims to serve as an analogue habitat for future crewed missions, creating a platform for testing and validating technologies and protocols essential for sustainable, long-term lunar exploration. Its design has broader implications for terrestrial architecture by integrating sustainable, resilient architectural practices that could influence both extraterrestrial and Earth-based building strategies. By advancing architectural and engineering paradigms, HL contributes to the ongoing development of sustainable habitats, enhancing human exploration capabilities on the Moon and fostering a deeper understanding of human adaptation to extreme environments.

Limitation and Bias

The Helios Lunar analogue habitat concept, while advancing deployable and human-centric lunar infrastructure, has several limitations that must be acknowledged:

1. **Deployment Assumptions** – The foldable modular system assumes optimal AI-assisted kinematic deployment and precise foundation anchoring, but these processes remain untested in real analogue or lunar conditions.

2. **Incomplete Engineering Detailing** – Detailed Mechanical, Electrical, and Plumbing (MEP) schematics for life support systems and structural integration are not yet finalized, leaving potential uncertainties in system efficiency and resilience.

3. **Cost and Feasibility Gaps** – Comprehensive cost estimation and logistics analysis for full-scale deployment have not been conducted, making economic feasibility and scalability difficult to assess.

4. **Material and Environmental Testing** – The selected materials (e.g., composites, aerogels, regolith-based grout) require extensive in-situ testing under lunar-like radiation, thermal fluctuation, and dust conditions to validate performance.

5. **Psychological System Validation** – Human-centric design strategies such as circadian lighting, plant-wave sensors, and biophilic features have strong theoretical potential but lack validation in long-duration isolation and confinement missions.

6. **Potential Bias in Design References** – The HL design heavily relies on lessons from specific analogue habitats (SHEE, Lunark, Halley VI, Concordia). While informative, this dependency may bias the design toward existing models rather than entirely novel solutions.

Conflicts of Interest

The authors declare that there are no conflicts of interest related to this work. No financial support, external funding, or sponsorship was received for the development of the Helios Lunar (HL) analogue habitat concept. The research was conducted independently as part of the authors' academic and professional contributions to the field of space architecture. The manuscript has not been submitted elsewhere, nor has it been previously published.

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