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ExoSpaceHab-X: a transportable Moon base for analog missions & outreach

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Abstract

Analog environments are instrumental in simulating Space-like conditions, enabling researchers to pre-empt potential challenges during Space missions and ensure preparedness, thus reducing risks. Additionally, analogs serve as invaluable platforms for engaging the public. Some facilities open their doors to university students, trainees, and PhD researchers, empowering them to conduct experiments, simulate mission protocols, and validate concepts.

EuroSpaceHub, a European funded project under the EIT HEI initiative, led by EIT Manufacturing and Raw Materials, embodies the EuroSpaceHub Academy, an educational program designed to train young students in Space, entrepreneurship, and astronautics [1-4]. Since 2009, ILEWG Lunex EuroMoonMars, one of the founding partners of EuroSpaceHub, has actively organized analog campaigns at various locations, including MDRS (Utah), HI-SEAS base in Hawaii, Iceland (CHILL-ICE), Etna/Vulcano (Italy), Atacama Desert (Chile), AATC in Poland, ESTEC (Netherlands), Eifel (Germany), and others [5-7]. With an increasing demand for analog research, more and more universities and companies seek analog facilities to conduct tests and experiments.

ExoSpaceHab-X is a revolutionary transportable lunar habitat being developed under the EuroSpaceHub Academy by Lunex EuroMoonMars. The innovative design of the project allows interested institutions to rent the habitat upon request, thus promoting resource-sharing among different scientific communities. The ease of logistics and low costs enable the ExoSpaceHab-X facility to be transported to various European locations, accommodating diverse research requirements. The habitat's adaptability allows for both analog missions with four astronauts and outreach activities such as events, short workshops and demonstrations, making it a versatile research site.

The habitation module comprises two distinct areas: a trailer and an integrated inflatable structure. The trailer houses essential functional zones, including a cooking station, sleeping quarters, a multipurpose experiment rack-equipped laboratory, workstations, hygiene compartment and communal recreational areas. The inflatable component acts as an airlock for extravehicular activity (EVA) simulations and it transforms into a reconfigurable open space for outreach to host events and workshops. The habitat's interior effectively isolates astronauts from the external environment, offering an ideal setting to study the effects of confinement. Moreover, the limited interior volume fosters valuable research on interpersonal and group dynamics.

The primary objective of this project is to establish ExoSpaceHab-X as an innovative solution within the existing landscape of analog facilities, serving as a powerful training resource for students as well as an effective tool for outreach with the broader public.

Keywords: Analog simulations, Students training, EuroSpaceHub initiative, ExoSpaceHab-X habitat, Portable Lunar habitation, Public Engagement and Space Outreach.

Acronyms/Abbreviations

AATC: Analog Astronaut Training Center.
EIT: European Institute of Innovation & Technology
ESTEC: European Space Research and Technology Center.
ESH-X: ExoSpaceHab Express.
EVA: Extra-Vehicular Activity.
HI-SEAS: Hawaii Space Exploration Analog and Simulation.
HEI (Initiative): Innovation Capacity Building for Higher Education.
ILEWG: International Lunar Exploration Working Group.
ICE: Isolated and Confined Environment.
ISS: International Space Station.
IMA: International MoonBase Alliance
IVA: Intra-Vehicular Activity.
LSS: Life Support Systems.
MDRS: Mars Desert Research Station.

1. Analog Missions and Space Simulations: Advancing Future Space Explorers' Training through the Utilization of ExoSpaceHab-X, a Versatile and Transportable Lunar Habitat.

In this introductory section, we underscore the strategic role played by Analog habitats in Space Exploration and their significance in training young students in the aerospace sector. Additionally, we highlight their potential for outreach and public engagement in aerospace research. Furthermore, we introduce the subject of this research, the *ExoSpaceHab Express* project, a novel type of transportable lunar habitat designed for simulations and outreach purposes.

1.1 Analog Missions and Space Simulations: Indispensable Tools for Training Future Space Explorers.

Analog Missions and Space Simulations have emerged as indispensable tools in the training of future Space explorers, equipping them with the necessary skills and experiences to navigate the challenges of extraterrestrial missions. These simulated environments replicate Space-like conditions, allowing students to gain practical knowledge and problem-solving abilities while minimizing risks associated with real Space missions. These specialized facilities, situated in diverse terrestrial sites, serve as valuable platforms to investigate various aspects of Space missions and astronaut life. Through their ability to recreate Space-like conditions, analogues empower researchers to proactively address potential challenges that may arise during Space missions, effectively minimizing risks and optimizing preparedness.

The concept of analog missions and Space simulations has a long-standing history in Space exploration. Such simulations were initially employed to test equipment and procedures in Space-like environments before actual missions. Over time, these simulations evolved to encompass a wide array of training scenarios and have become instrumental in imparting hands-on experience to aspiring Space professionals and to better plan missions before real Space flights [8]. Moreover, analog missions have proven their effectiveness in fostering teamwork, problem-solving skills, and psychological preparedness, which are crucial attributes for successful Space missions.

Various analog habitats and research centers have been established worldwide, each offering unique benefits and contributing to our understanding of Space training. Efforts have focused on terrestrial analogs, such as the MDRS in the Utah Desert, the HI-SEAS on Mauna Loa in Hawaii, and the AATC in Poland, to name but a few [1,5-7].

This introductory section highlights the significance and multifaceted nature of analog missions and Space simulations, outlining their vital role in shaping the future of Space exploration endeavors. The discussion categorizes analogues into two main macro-typologies based on their features:

1. *Analogues in Extreme Terrestrial Environments.*
   These analogues replicate Space environments by capitalizing on geological and environmental characteristics, offering similarity to extreme Space conditions. By subjecting crews to simulated extraterrestrial conditions, they gain realistic insights into the difficulties that await them in Space, thereby enhancing their ability to mitigate risks and navigate complex challenges.
2. *Confinement-Oriented Analogues.*
   These analogues focus on complete isolation and confinement, providing ideal settings to simulate and study living conditions experienced by the crew during Space missions. In such environments, crew members develop crucial adaptability and resilience, essential attributes for the next Space expeditions.
   The project presented in this paper is *ExoSpaceHab-X* (ESH-X) a transportable simulator that focuses on simulating isolation and confinement, thus falling into the second typology of analogues according to the previous distinction.

The economic advantages of analog missions are also fundamental when discussing the strategic role played by analog facilities, with potential cost savings being a primary benefit. Conducting research in real Space still implies enormous costs. High launch costs have been the greatest factor in limiting the number and in reducing the range of Space missions [9].

By anticipating and addressing mission challenges on Earth, analogues help safeguard against equipment damage that may otherwise incur higher costs in the unforgiving environment of Space. Moreover, analogues provide an accessible and cost-effective alternative for conducting research and experiments, as conducting research directly in Space remains financially prohibitive for many research programs. Ground-based analogue studies are conducted more quickly and less expensively [10, 11].

The time efficiency offered by analog missions further supports their strategic significance. The strict protocols and lengthy logistics associated with real Space missions demand meticulous planning and forethought. Analogues present a more streamlined approach, enabling faster investigation processes, making them invaluable testing grounds for preliminary research and experimentations.

Beyond training future Space crews, analog missions serve also as powerful tools to engage the broader public in Space research and exploration. Their reduced costs and logistical simplicity allow for large population samples to experience living conditions akin to Space. The resulting wealth of data obtained from such experiences is instrumental in understanding the psychological and physiological effects of Space-like environments on a wider scale. Moreover, public resonance is amplified through social media platforms, generating interest, inspiration, and understanding of Space exploration's challenges and their significance [4].

The promising role played by analog missions and Space simulations in shaping the skills of future Space explorers, optimizing Space research, and fostering public engagement in the journey of Space exploration is evident. The strategic contributions of these facilities span across various dimensions of Space exploration, underscoring their significance in accomplishing the objectives of ongoing Space missions.

1.2 ExoSpaceHab-X: A Versatile and Transportable Lunar Habitat for Analog Missions and Outreach Activities.

ESH-X is an innovative lunar habitat designed to enhance Space training and research capabilities through its portability. The primary objective of this work is to introduce ESH-X and demonstrate its potential as an advanced tool for training students in Space exploration and research. By utilizing analog missions and Space simulations, we aim to prepare the next generation of Space scientists, engineers, and astronauts for the challenges they will encounter during future Space endeavors.

The research project presented here was conducted and funded within the framework of the European project EuroSpaceHub, specifically under the EuroSpaceHub Academy initiative, guided by the EuroSpaceHub partner Lunex EuroMoonMars. The EuroSpaceHub Academy is an educational program specifically designed to provide training to young students in Space, entrepreneurship, and astronautics [1-4].

This research aims to address a significant question: How can we enhance accessibility to analogue experiences for researchers, institutions, students, and aerospace communities without compromising efficiency and cost-effectiveness? The answer lies in the design of a mobile facility, offering easy logistics and reduced costs, being transportable to various locations. This novel concept enables interested institutions to request and rent the ESH-X analog facility for research or dissemination purposes, promoting a formula of "analog habitat sharing”.

The ESH-X project represents a significant advancement in the realm of Space simulations and analog missions. Unlike traditional fixed-location analog habitats, ESH-X is designed to be transportable on the road across Europe, thus enabling its deployment to multiple research centers and universities. This flexibility empowers diverse scientific communities to access the habitat, fostering collaboration, and enhancing the overall utilization of the facility for multiple research projects. By providing an accessible and cost-effective solution, the ESH-X habitat aims to widen the availability of analog experiences for a broader scientific community. The facility is able to cater to diverse activities and it encourages collaborative research initiatives. At the same time, it facilitates outreach endeavors, thus positioning itself as a crucial tool in advancing Space research, preparing future explorers, and promoting scientific engagement in Space exploration.

ESH-X serves as a dual-purpose habitat, catering to both analog missions and outreach activities. Its interior design includes essential functional zones for astronaut training and research, such as a living area, sleeping quarters, a multipurpose experiment rack-equipped laboratory, workstations and others. The inflatable component acts as an airlock for extravehicular activity (EVA) simulations, while its reconfigurable open space facilitates outreach events and workshops. By providing a comprehensive overview of the project, we aspire to contribute to the advancement of analog missions and Space simulations, ultimately enriching the preparation of future Space explorers and fostering scientific progress in Space exploration.

2. Project Development Methodology

The project development followed several phases. Firstly, a strategic analysis and study of existing facilities were conducted, including an examination of the features, strengths, and limitations of existing analog habitats. Subsequently, the target users of the project were defined. Following this preliminary theoretical analysis, we subsequently set the design requirements of the project. Finally, the operational phase of habitat construction took place, followed by the organization of the preliminary public outreach and events.

2.1 Target User Definition and Preliminary Stakeholder Analysis.

The target users of the project were defined encompassing potential beneficiaries who could leverage the use of this facility.

Primarily, universities and research centers closely associated with the aerospace domain were identified. Universities closely linked to aerospace, such as Aerospace Engineering faculties, were identified, since they could use the habitat for analog missions with their students. In addition to faculties like aerospace engineering, other potential interested parties, were considered, including Psychology, Space architecture and Biomedical faculties. These have an interest in investigating crew dynamics, human performance under stress and life in confined environments.

The identified target users comprised Bachelor's, Master's, and doctoral students in these programs, who could capitalize on the simulation conditions offered by ESH-X to test tools, devise and experiment with realistic simulation contexts. Furthermore, universities could also rent the habitat for short periods to host themed events, workshops, and demonstrations, attracting potential stakeholders.

In addition to Universities and Research Campuses, another target often overlooked by other analog facilities was envisioned. Through their work with the EuroSpaceHub Academy, the ESH-X team observed how analog missions could be transformative experiences for developing soft skills in young students participating in these endeavors. Hence, companies, organizations, and private entities were envisaged as potential targets seeking to use the habitat to conduct similar activities with their partners and employees reinforce group dynamics.

Lastly, the dimension of Outreach was embraced by the ESH-X team when defining the target users. The simulation was conceived as a role-playing game, allowing even younger individuals, such as high school students, to enthusiastically engage in Aerospace Research. Among the target users, museum institutions, exhibitions, and similar entities were identified. These actors could rent the habitat for events and short periods to provide their visitors with an innovative Space experience. Therefore, the educational dimension — which aims to raise awareness among a broader audience about the importance of analog missions — finds a point of convergence in ESH-X, along with the experiential dimension.

2.2 Design Requirements and Development Constraints for ESH-X Transportable Lunar Habitat: towards agile and cost-effective Space Simulations.

The design and development constraints of ESH-X were set at the very beginning of the project to ensure the successful production of this innovative prototype.

Firstly, the primary objective was to create a facility that was easily transportable on wheels, and that was capable of being relocated to research centers and universities across Europe. The emphasis was on minimizing transportation costs to make the habitat accessible to a wide range of institutions. Secondly, streamlining logistics and transportation operations was essential. The design aimed to minimize personnel efforts during the relocation process, thus reducing costs and enhancing operational efficiency for all participating entities.

Another requirement that was clearly set at the very beginning of the project was that the facility had to accommodate simulations lasting one week (short term simulations). This timeframe provided an optimal balance between research depth and practical feasibility for the previously defined target users. The habitat was also envisioned to host simulations of varying complexity, ranging in medium-low complexity simulations, catering to University students and researchers alike. By fostering an open and inclusive environment, it sought to facilitate diverse research initiatives.

The accommodation of a crew of four people was also set at the initial stage as a critical requirement. This allowed for an effective emulation of real-life Space missions, facilitating team dynamics and interactivity. Additionally, the performance of the transportable analog had to align with that of permanent facilities. Ensuring consistency in simulation outcomes was paramount to derive meaningful insights from the analog missions. Furthermore, faithful replication of aspects of life in Space was prioritized. The habitat had to emulate Space-like conditions as closely as possible to provide a realistic and immersive experience for participants. The compact space of the module necessitated retaining all basic functions to replicate life in a hypothetical Space base. Despite spatial constraints, basic functional areas and solutions for well-being had to be envisioned on board the ESH-X facility.

At the onset of the design process for ESH-X, it was established as a fundamental requirement to prioritize the well-being and cohabitation of the crew, based on the latest advancements in Space architecture research. The habitat's layout and functionalities were to be crafted to ensure the psychological health of astronauts during analog missions. Incorporating ergonomic configurations, efficient Space utilization, optimal lighting conditions, and considerations on the crew’s well-being were deemed essential to create a pleasant living environment for the crew. The habitat's design had be designed in order to facilitate collaboration among crew members while offering private spaces for personal relaxation and rejuvenation. Drawing upon research in Space psychology, human factors, Space Design and social dynamics, ESH-X aimed to optimize crew well-being and promote successful and productive analog missions [12,13]. Finally, the module's reconfigurability was deemed crucial. It had to accommodate the unique needs of different institutions, allowing for adaptable setups tailored to specific research objectives.

One more requirement was to make the module easily scalable for future developments. One of the envisioned scenarios was to connect a hypothetical second module to be developed in the future, thus creating a Lunar Village for simulations. In summary, modularity was established as a key design constraint, ensuring adaptability for future expansions.

While adhering to the aforementioned constraints, the project aspired to be a premium prototype, to be subsequently upgraded in the future for further refinement. Its purpose extended beyond immediate implementation, serving as a model for studying the concept of "analog sharing" (Section 1.2). The budget allocated for the project was therefore consistent with the development of a premium prototype, aiming to explore the possibilities of this new concept. Consequently, the simulation of Enclosed Life Support Systems and complex architectural implementations was excluded. Instead, the focus was directed towards creating realistic interiors and conducting an ergonomic-functional analysis of the internal spaces to simulate astronaut life.

To summarize, the design requirements and development constraints outlined for ESH-X exemplified an innovative design approach to transportable lunar habitats, by addressing cost-effectiveness, accessibility, and versatility of the facility. A summary table of the previously mentioned requirements is provided below.

Table 1. ExoSpaceHab-X Project Requirements	
1	The facility must be transportable around research centers and universities in Europe, utilizing a cost-effective, wheeled design for easy mobility.
2	Logistics and transportation operations should require minimal personnel effort to reduce costs and complexity, as well as to ensure efficient operations by any institution.
3	The facility must be capable of accommodating simulations lasting one week.
4	The habitat should be equipped to host simulations of low to medium complexity, providing opportunities for students and researchers to engage in diverse experiments.
5	The habitat must be designed to accommodate a crew of four people, mirroring the conditions of future missions to the Gateway or Mars.
6	The transportable habitat should match the performance of permanent facilities, ensuring comparable research outcomes and experiences.
7	The analog facility should replicate various aspects of life in Space with a focus on ICEs, Human Factors and Crew's well-being.
8	Despite the limited space given by transportability, the module should maintain all essential functions necessary to simulate life in a hypothetical Space base.
9	The project outcome should be a premium operational prototype to explore the concept of "analog sharing".
10	The module should feature a high degree of reconfigurability to cater to the specific requirements of different requesting institutions.
11	The habitat should be easily scalable for future developments, such as connecting it to a second module in the future to create a Lunar Village for simulations (Modularity).

Table 1. Preliminary Design Requirements of the ExoSpaceHab-X MoonBase project.

2.2 Portability as a Project Driver and a starting Point for the Concept Definition.

In this section, we highlight portability as a crucial design constraint and the foundation for defining the concept of ESH-X. Making the habitat transportable was a fundamental requirement to achieve the novelty of the concept. The emphasis on achieving cost-effectiveness and minimal personnel effort for transportation on European roads led to the exploration of various concept scenarios.

Initially, the possibility of transporting the habitation unit on wheels using a truck was considered. The initial scenarios involved the transformation of containers, which showed great potential due to their standardized dimensions optimized for transportation. Moreover, the architectural volume of containers extends lengthwise, visually and spatially resembling the experience of being on the ISS, with its visually elongated volume and square cross-section. However, the preliminary analyses conducted on transporting these container modules revealed very high transportation costs and involvement of dedicated personnel. The stakeholders involved in the project were in agreement about the need for efficient and self-contained transportation and installation, avoiding the reliance on third-party logistics that would hamper usability in different locations.

Given that ESH-X was conceived as a premium prototype focused on studying confined environments, alternative options were explored. The idea of utilizing a caravan with a towing vehicle and integrating it with appropriate modifications was considered and validated. This approach provided the desired portability without compromising on usability and performance. During the preliminary design phase, several concepts were explored, but this latter solution was prioritized due to its significant logistic and economic advantages over other solutions.

Furthermore, the valuable experience gained in the past by Prof. B. Foing — co-author of this paper — with the ExoHab project at ESA ESTEC served as fertile ground and encouraged the pursuit of this direction. Indeed, the research team led by Foing had conducted several exercises and analog mission demonstrations within a caravan, which revealed promising prospects for this approach [12,13]. These preliminary efforts demonstrated the feasibility of conducting analog missions and simulations in a mobile habitat, showcasing the potential of such a versatile platform for future space-related research and training endeavors. Building upon this foundation, the ExoSpaceHab Express project was propelled forward, incorporating the lessons learned and insights from previous experiences to refine and optimize the design, ultimately leading to a novel and adaptable lunar habitat concept.

The decision to adopt a hybrid approach was driven by the aim to optimize transportability and usability, while ensuring sufficient interior space to accommodate a crew of four people comfortably. The Weinsberg 400LK caravan, known for its compact and mobile design, provided a solid foundation for the habitat's structure, making it readily transportable around research centers and universities in Europe, in line with the project's design requirements.

For further flexibility and expansion of the habitat's usable volume, an inflatable structure was integrated into the design. The inflatable component, inspired by advancements in Space architecture, offered a lightweight and collapsible solution that complemented the caravan's rigid structure. This integration significantly expanded the interior space, providing a more spacious and ergonomic environment for the analog missions and outreach activities. The hybrid approach successfully combined the advantages of the caravan's mobility and the expandability of the inflatable structure, thus presenting a cost-effective and versatile solution.

2.3 The Concept Development Phase: Interior Studies, Dimensional and Layout Analysis, Field Research and Concept Design.

During the Concept Development phase, the studies conducted were focused on exploring the interior design and analyzing the layout and functional areas. Simultaneously, efforts were made to enhance the usable volume without compromising the easy transportability of the chosen solution of the caravan architecture. Exploring the realm of inflatable shelters was validated as a valuable approach, as it showed promise due to its lightweight nature and affinity with Space Architecture.

Methodologically, this phase commenced with exploratory sketches and design concepts, followed by 3D modeling for dimensional assessment of the interior elements. This approach also allowed for the generation of precise work plans and preview renders, which were shared with project stakeholders. Multiple concepts were iteratively reviewed and analyzed based on inputs from the involved stakeholders over time.

The concept, at this stage, served as a starting point. Before proceeding with the implementation phase, field research was conducted with the direct participation of the appointed designer, Serena Crotti — who is the author of this paper — and some of the co-authors of this publication, in analog missions aimed at studying confinement dynamics and habitability in existing analog solutions.

2.4 Field Research for Concept Validation.

More specifically, the project team chose to adopt an ethnographic approach to the design process. This methodological decision allowed the team to immerse themselves in the context of analog missions and to experience life as astronauts in confined environments at first-hand. The ethnographic approach provided a unique perspective, enabling the designer to capture the most intimate and meaningful aspects of daily life in Space, as well as the relational dynamics among crew members.

During the ethnographic phase, the team conducted observational studies, interviews, and in-depth dialogues with astronauts and personnel involved in analog missions. These valuable exchanges provided detailed firsthand accounts and insights into the challenges and opportunities associated with life in Space. A profound understanding of social interactions and behaviors in confined environments was critical in informing the design decisions of the ESH-X module, thus ensuring that the structure met the needs of astronauts during analog simulations.The ethnographic approach also allowed the team to grasp emotional and psychological aspects often overlooked in traditional analog facilities. Designing Space habitats requires particular attention to the psychological aspect and group cohesion, as astronauts spend extended periods in confined and isolated environments. Ethnography revealed new insights into emotional resilience, group dynamics, and the importance of recreational activities for the psychological well-being of astronauts. Overall, the ethnographic approach proved instrumental in the concept development phase, informing design choices, ensuring authenticity and realism in ESH-X design, and fostering a deeper understanding of the needs and challenges of Space exploration.

In particular, three distinct analog missions concurred to the design process of the ESH-X module. In the framework of these missions, the observations and studies conducted greatly contributed to the concept ultimately chosen and produced for the ESH-X habitat. Each mission provided unique insights and valuable data that informed the design process.

The first mission was EMMPOL 8 [16-20], which took place at the AATC in Poland in September 2021. This mission focused on confinement within a small lunar base without windows, and with limited sunlight, mimicking the personal and daily living conditions of astronauts (Fig.1). The crew consisted of five individuals (one woman and four men), representing diverse cultures, who lived in isolation for one week with limited external contact and resources. The primary focus was on IVAs and confinement, with no EVAs planned.

The second mission, called the Venus Biogender Mission, was held in November 2022 near Arredondo, Spain. It was organized by Astroland Agency (based in Santander) in collaboration with the Neurotic Lab of the University of Cadiz. The five-day mission involved simulating life in an underground habitat located inside a lava tube. The all-female crew, consisting of five individuals from different cultural backgrounds, focused on the psychological analysis of astronauts and engaged in various EVAs inside the lavatube. The mission habitat also featured a simulated airlock.

The third mission, the "Hana Hou" EMMIHS 2023, took place in Hawaii and was attended by ESH-X designer and by Prof. Bernard Foing [21-22]. This mission simulated life in a Martian base located on the Mauna Loa Volcano at the HI-SEAS habitat (Fig. 2). The crew — consisting of individuals of diverse ages and nationalities — included both men and women. The simulation lasted five days, during which a crew of six conducted intense EVAs in the realistic volcanic terrain surrounding the base.

These missions facilitated a comprehensive exploration of human interactions, psychological well-being, and practical considerations that significantly influenced the final design of the habitat.

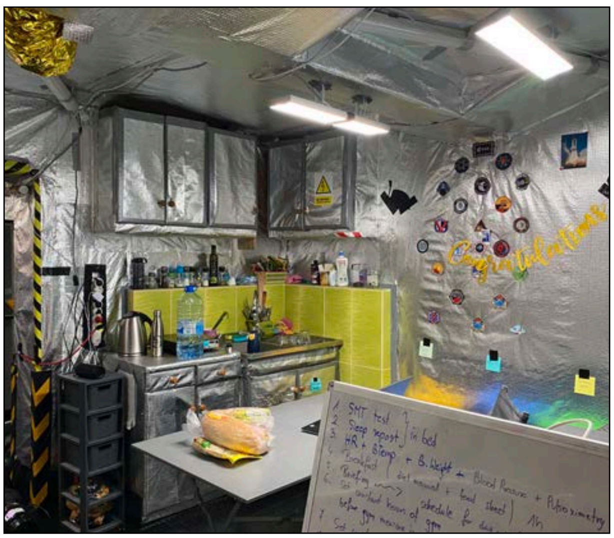

Fig. 1. Interiors of the AATC simulated Moon Base in Rzepiennik Strzyżewski (Poland) during the EMMPOL 8 Mission (September 2021, Serena Crotti / AATC)

Fig. 2. The HI-SEAS Habitat on Mauna Loa Vulcano (Hawaii) during the EMMIHS 2023 Hana Hou Mission (March 2023, EMMIHS 2023 Crew, IMA)

2.5 Implementation and Prototyping phase: Building the Transportable Lunar Habitat ESH-X.

The implementation phase of the ExoSpaceHab-X project took place in Italy, more specifically in the province of Monza Brianza, where the manufacturing operations were conducted. The primary individuals responsible for overseeing and executing the project were the designers Serena Crotti and Michele Zanchi.

Spanning from January to May 2023, the implementation phase involved a comprehensive and meticulous approach to transforming the chosen concept into a tangible and functional lunar habitat. By the conclusion of the implementation phase, the ESH-X prototype had materialized into a functional lunar habitat, ready to undergo preliminary testing and evaluation in preparation for its future applications in analog missions and outreach activities.

Execution works proceeded simultaneously for both the rigid module (Weinsberg 400LK) and the inflatable structure (Fig. 3). A collaborative effort was established with the Italian company Nasoallinsù, a specialized manufacturer of inflatable structures, based in Varese. The company was selected due to its extensive experience in producing inflatable shelters for emergency situations and related applications. The close collaboration between the ESH-X team and the company was instrumental in achieving an efficient and seamless integration of the inflatable structure with the main module. The goal was to strike a balance between structural integrity, low weight and compressibility of the inflatable, water resistance, ease of inflation, thereby creating a robust and reliable inflatable extension for the habitat. Acknowledging that the habitat would need to be rapidly deployed and set up in diverse locations, the implementation phase focused on streamlining the installation process without compromising on functionality and safety.

3. Results and discussion

In this section, we present the results obtained during the implementation and prototyping phase, as well as the considerations and reflections of the research team regarding the obtained outcomes.

3.1 Detailed overview on ExoSpaceHab-X features.

In this section, the main features and characteristics of the ExoSpaceHab-X habitat are presented in detail.

In plan view, the habitat has overall dimensions of approximately 7x7 meters when the inflatable module is installed, with an indicative height of 2.50 meters externally from the ground. The usable internal height is 2.20 meters in the inflatable module and 1.95 meters in the rigid module. The two units, the rigid module, and the inflatable module are integrated into a single structure (Fig. 3,4). The inflatable component surrounds the rigid module, providing additional living volume. The layout is depicted in Fig. 4, which illustrates the planned zones on board.

The rigid module (trailer) houses essential functional areas, including a living/cooking space, sleeping quarters, a multipurpose experiment rack-equipped laboratory, workstations, and hygiene facilities. The inflatable component serves as an airlock for extravehicular activity (EVA) simulations and transforms itself into a reconfigurable open space for outreach, accommodating events and workshops. It can be easily and quickly reconfigured as a communal space for mandatory crew training or activities that foster group cohesion.

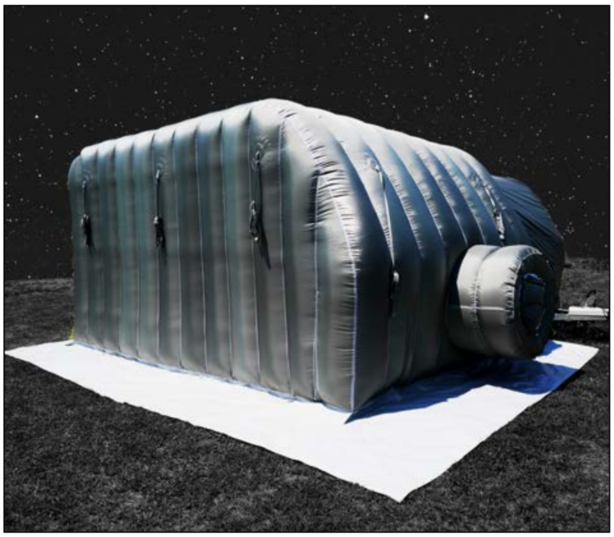

Fig. 3. Artistic photographic collage of the ESH-X module with the inflatable element in place and the rigid trailer in the back.

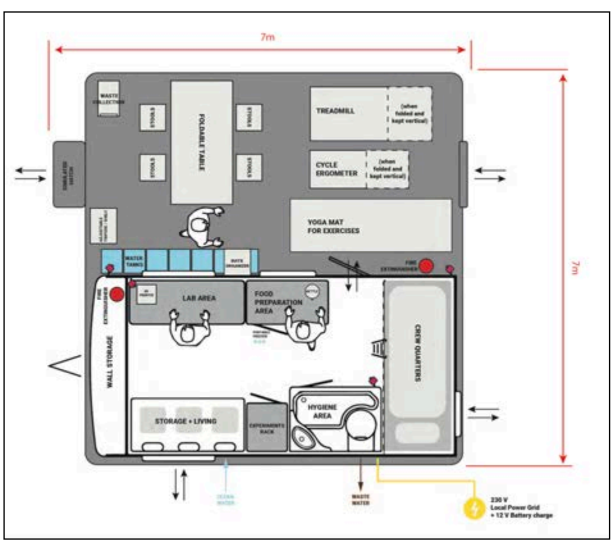

Fig. 4. Plan view of ExoSpaceHab-X habitat with the rigid module and the inflatable module attached to it.

The habitat is equipped with a dual electrical system based on the usage scenario. It can operate while connected to a 220V power supply using the local electrical infrastructure, or it can switch to an energy-saving mode with 12V circuits powered by batteries.

The habitat's interior effectively isolates astronauts from the external environment, providing an ideal setting for studying the effects of confinement. The inflatable structure integrates with the rigid module to create light obscurity from sunlight. Consequently, astronauts' circadian rhythms are altered when inside, allowing for studies on stress and performance under these conditions. The specific features are individually presented in the following subsections.

Galley and Service Area (Fig. 5) The designated meal preparation area is situated within the rigid module. This section is equipped with ample storage space to accommodate dehydrated food rations for a four-person crew for a week. For the hypothesized analog missions, it is envisaged that astronauts will rely on rehydratable freeze-dried meals, prepared using boiling water. The meal preparation area also serves as a storage location for cooking utensils, cutlery, water bottles, and other daily-use items on board. Additionally, during transportation, foldable water tanks can be stored in this area.

Fig. 5. Overview of the interiors of the rigid trailer unit: meal preparation area with storage on the left, crew quarters in the background and hygiene compartment access door on the right. Rack laboratory and working tables in the front.

Laboratory and Working Area (Fig. 6) The laboratory area has been designed to maximize tool storage and work surfaces. Spacious storage compartments have been integrated in the interiors to accommodate bulkier items. Storage solutions have been incorporated throughout the space, not only through traditional means such as built-in storage compartments but also by utilizing vertical surfaces and the ceiling. This approach was necessary not only to

Fig. 6. Laboratory Area with storage solutions and working surfaces for the crew. A modular rack housing instruments and experiments is located on the left.

optimize storage capacity but also to emulate the spatial perception experienced in the ISS, deliberately disorienting users (Fig. 7, Fig. 8). Elastic cords suspended from the ceiling create grid-like storage compartments, while velcro strips, shelves, lightweight pockets, and elastic bands adorn the walls.

Within the laboratory, a module simulating an ISS work rack is installed. This rack comprises several shelves with lateral lighting and houses various scientific instruments. At an ergonomic height, a shelf doubles as a work surface. The envisioned concept for this zone involves modular experiments housed in removable boxes within the rack, facilitating essential work. This concept has been developed by students of the EuroSpaceHub Academy and TU Dublin.

The laboratory can comfortably accommodate up to three crew members simultaneously, with two stationed at the worktable and one utilizing the adjacent seating-storage area near the rack or conducting experiments directly within the rack.

Additionally, the laboratory features a compact refrigerator for preserving biological samples. The refrigerator operates both in full-power mode (220V) and emergency mode with reduced power consumption (12V battery-powered).

Hygiene Compartment This area is equipped with a toilet and a compact sink, catering to the crew's primary personal hygiene needs, such as teeth brushing and hand washing. During missions, water is a precious resource and carefully rationed. During short-duration analog missions, ground-based astronauts refrain from taking showers to fully simulate the experience in Space. Instead, they use hygienic wipes for personal care.

As a result, designated collapsible tanks are utilized to store water for drinking and food preparation within the inflatable module, ensuring efficient use and conservation. On the other hand, the onboard integrated tank which provides water to the hygiene compartment holds emergency water supplies, ensuring preparedness for unforeseen situations.

Virtual Space View and settings (Fig. 7, Fig. 8) One innovative feature of ESH-X is the incorporation of a simulated window, designed to recreate the sensation of being in Space or to adapt to various scenarios based on specific requirements. The window can replicate the awe-inspiring views of outer Space, natural

Fig. 7. Ceiling storage solutions and virtual displays both to optimize storage capacity and also to simulate the spatial perception experienced in the ISS.

Fig. 8. Virtual window simulation with captivating visuals, replicating Space experiences and various scenarios. Exposed cables on the ceiling enhance the immersive feel, resembling the ISS.

environments, or any desired setting, enhancing the psychological well-being of the astronauts during confinement.

To ensure an authentic and realistic feel, a deliberate choice was made to leave cables exposed on the ceiling, resembling the distinctive aesthetics of the ISS. The exposed cables contribute to the overall ambiance, further enhancing the psychological simulation and training experience within the habitat.

Crew Sleeping Pods (Fig. 9) ExoSpaceHab-X features two designated sleeping pods to accommodate the four-member crew during analog missions. A crew rotation schedule is implemented to stagger circadian rhythms, with two crew members asleep while the other two are awake, promoting uninterrupted operation and efficiency. Great attention has been given to the design of these sleeping quarters, considering their role as personal spaces for the astronauts. Each pod is equipped with a sliding partition that completely obscures light, providing the crew with the flexibility to adjust privacy levels as desired.

Internally, a smart lighting system has been integrated to cater to individual preferences. Crew members can customize the lighting to simulate natural sunlight with a full spectrum or utilize RGB colors that can be independently controlled for each compartment. (Fig. 9, 12, 13). This allows for personalized lighting settings and even chromotherapy, aiding relaxation and potentially mitigating the impact of confined environments. Each crew quarter is also equipped with multiple storage pockets, accommodating personal items like clothing and personal effects. Two storage pockets are placed within each crew quarter, enhancing organization and accessibility for personal belongings.

Beneath the lower crew quarter, a designated storage area is allocated to cater to additional personal items, such as backpacks or belongings the astronauts may wish to have close at hand during their stay on the habitat. The features of the sleeping quarters contribute to the crew's overall well-being and help ensure their comfort throughout the mission, while also considering the need for efficient space utilization within the confined environment of ESH-X.

Inflatable Module The inflatable module of the ExoSpaceHab-X is an integral component of the habitat and it is attached externally to the main unit, expanding its space and capabilities. This module features two distinct access points, each serving functions during analog missions and outreach events.

The first access point is a simulated porthole, designed with a cylindrical shape and multifunctional capabilities (Fig. 10). During Extravehicular Activity (EVA) simulations, it serves as a simulated porthole, providing a passage on the outside environment. Additionally, it doubles as a simulated "pressurized" element for resupply missions, with two layers of fabric creating an internal air chamber. This allows for the safe storage of resupply equipment without direct contact with the crew. Moreover, the module's future potential is envisaged as a connector for linking another identical

Fig. 9. Private Sleeping pods with customizable lighting features and privacy partition dividers.

Fig. 10. Simulated porthole in the inflatable structure of the ESH-X habitat.

Fig. 11. Interior view of the inflatable module with foldable tables and chairs installed to provide extra workspace for the crew.

module, enhancing the habitat's modular design, a crucial requirement in the initial concept.

The second access point is a standard visitor's door, incorporated to facilitate events and outreach activities. This door ensures accessibility for all, including individuals with reduced mobility, making the ESH-X an inclusive space for diverse audiences.

The inflatable module also serves as an open space with versatile applications. During analog simulations, it can be converted into an additional working area, featuring foldable tables to accommodate various activities (Fig. 11). It can transform into an airlock for EVA simulations, providing an open-space environment for training purposes. Furthermore, it offers a recreational space for group activities, fostering camaraderie and enhancing crew dynamics during prolonged confinement.

During outreach events, the inflatable module becomes an engaging venue for small workshops and demonstrations, facilitating educational interactions with the public.

Smart Lighting System The lighting system installed on board ESH-X was designed to serve three crucial functions, each contributing to the well-being and productivity of the astronauts within the confined environment:

1. Providing Optimal Work Conditions: The lighting system ensures excellent visibility for various work activities carried out by the crew members. Adequate lighting in workspaces is essential for efficient task execution and safety.
2. Supporting Astronauts' Circadian Rhythms: The system plays a vital role in regulating the biorhythms of the astronauts. By simulating natural light conditions with varying color temperatures from warm to cool, it influences the internal body clocks, promoting better sleep patterns and overall health under conditions of confinement (Fig. 12).
3. Customizing the Environment: Recognizing the importance of personal well-being, the habitat is equipped with an intelligent LED lighting system provided by the Italian company LEDPRO. Crew members have the freedom to customize the lighting conditions in their individual quarters using dedicated remote controls. The full spectrum RGB lighting allows astronauts to choose colors based on their preferences and needs, creating a personalized and intimate space within the confined environment (Fig. 13).

In common areas, the lighting system simulates sunlight with adjustable color temperatures, aligning with the Mission Time. This simulation positively affects the circadian rhythms of the crew, providing a sense of normalcy and natural rhythm despite the isolated setting. Moreover, the color temperature of the light, closely resembling sunlight, offers a natural stimulus to the astronauts, enhancing their well-being and mood during their time in the habitat. Furthermore,

Fig. 12. Smart Lighting System in Solar Light Mode with Warm or Cool Light Spectrum to replicate daylight conditions at different times of the day and positively reinforce circadian rhythms. Remotely controllable from the Mission Control.

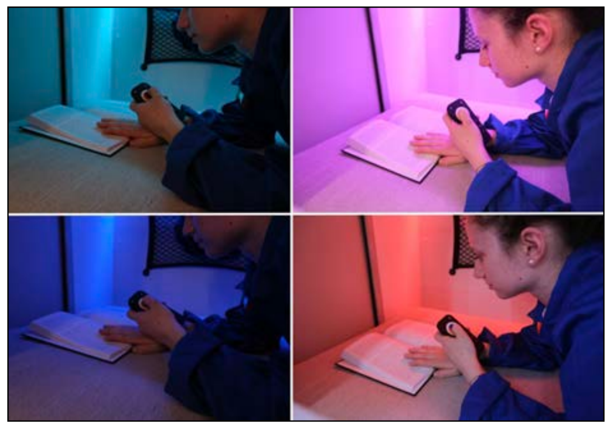

Fig. 13. Full spectrum RGB lighting to choose colors based on analog astronauts' preferences and needs.

the system can be utilized to create custom scenarios, enabling researchers to analyze the influence of different lighting conditions on astronaut performance and circadian rhythms as part of mission experiments. This adaptability and versatility highlight the habitat's capability to support diverse research objectives and simulations.

The ESH-X lighting system operates in dual mode, depending on the power supply. When connected to the standard 220V power source (generator, external unit, or local power grid), the system functions at full capacity as described above. In the event of an emergency or low power scenario, such as reliance on battery power, the system switches to standard temperature 12V LEDs, ensuring the habitat's continuous operation with minimized power consumption.

Ventilation System. The ventilation system of ExoSpaceHab-X comprises both inlet and outlet components, ensuring proper airflow throughout the habitat. Operating at 12V, the system allows for continuous and efficient ventilation, even in emergency scenarios when standard power supply might be limited. Strategically positioned ventilation grilles are installed in key areas, including crew quarters, bathroom, and living area, to facilitate optimal air circulation and maintain a comfortable and habitable environment for the astronauts.

A control panel with clear and intuitive instructions enables the crew to easily manage the ventilation system. From a single station, they can control the activation and deactivation of the ventilation, as well as adjust its intensity through dimming options.

3.2 The Role of ExoSpaceHab-X to advance Space Education and Outreach

ExoSpaceHab-X plays a pivotal role in advancing Space education and outreach, offering a unique platform for engaging the public, inspiring future scientists, and fostering a deeper understanding of Space exploration. As a transportable lunar habitat with innovative features and adaptability for research and outreach activities, ESH-X opens new horizons for Space education and public engagement initiatives.

The habitat's versatility allows it to cater to a diverse range of educational programs and outreach events. Universities, research centers, and aerospace faculties can leverage ESH-X to conduct analog missions with students, enabling hands-on experiences and immersive simulations that simulate real-life Space conditions. The habitat's interior design, inspired by ethnographic research and astronaut experiences, fosters a realistic and intimate environment for participants, enhancing the educational impact of the simulations.

Beyond academia, ESH-X extends its outreach to the wider public, including high school students, museum-goers, and enthusiasts of all ages. By adopting a role-playing game approach, the habitat transforms educational experiences into captivating adventures, allowing participants to step into the shoes of astronauts and embark on simulated Space missions. Through interactive workshops, demonstrations, and themed events, ESH-X provides a memorable and enriching Space experience, igniting curiosity and passion for Space exploration among a broader audience.

Moreover, ESH-X serves as a powerful tool for raising awareness about the importance of analog missions and the challenges of living and working in confined environments. As visitors engage with the habitat's unique features and functionalities, they gain insights into the complexities and opportunities of Space exploration, fostering a deeper appreciation for the endeavors of astronauts and Space agencies worldwide.

The habitat's portability, cost-effectiveness, and modular design further enhance its suitability for outreach activities in various locations. Whether stationed at universities, museums, exhibitions, or public events, ExoSpaceHab-X brings Space education and outreach directly to communities, breaking down barriers and fostering a sense of wonder about the cosmos.

ExoSpaceHab-X stands as a transformative asset in advancing Space education and outreach. Its immersive simulations, ethnographically-informed design, and adaptability for diverse research scenarios make it an invaluable tool for inspiring the next generation of Space explorers.

3.3 Limitations of the project and possible future developments.

While the ExoSpaceHab-X represents a significant milestone in the design and implementation of a transportable analog habitat for simulations and outreach purposes, it is essential to acknowledge some inherent limitations of this project.

One of the primary constraints of the ESH-X project lies in its external architectural replication of a realistic Space module. While the interior design and functionalities aim to simulate a Space-like environment, the external appearance does not faithfully reproduce the features and appearance of an actual Space module. Enhancing the exterior architectural fidelity would require further research and innovative solutions to align the habitat's appearance more closely with real Space modules, contributing to a more immersive analog experience for astronauts.

A second limitation lies in the Life Support Systems (LSS), which lack in terms of realism. While the habitat is equipped with essential functionalities for analog missions, it does not fully mirror the complexity and redundancy levels required for Space exploration. Future developments in this area would involve more investment and funds, as well as collaborative efforts with specific industry partners to provide technological support.

In terms of future developments, the modular design of ESH-X opens up possibilities for future expansion and adaptation. It can be modified and augmented to accommodate various missions, environments, and specific research objectives. Leveraging this modular approach, additional components and functionalities can be integrated to further enhance the habitat's versatility and effectiveness for diverse analog scenarios.

Looking ahead, the ExoSpaceHab-X project will continue to evolve through collaborative efforts between Space agencies, researchers, and industry partners. By addressing the identified limitations and incorporating feedback from analog missions and crew members' experiences, future iterations of the habitat can be optimized to provide even better support for astronauts during analog missions and contribute valuable insights for future Space exploration endeavors.

4. Conclusions

Analog environments play a crucial role in simulating Space-like conditions, assisting researchers in anticipating challenges and mitigating risks during Space missions. The ExoSpaceHab-X project, developed under the EuroSpaceHub Academy, represents a groundbreaking transportable lunar habitat with innovative features and adaptability for research and outreach activities. Its flexible design allows interested institutions to rent the habitat, promoting resource-sharing across scientific communities. The habitat's ability to accommodate both analog missions and outreach events makes it a valuable and versatile research site.

The project's ethnographic approach to the design process has provided a deep understanding of astronaut experiences in confined environments, enabling the effective interior design of the habitat to meet the needs of analog simulations. While the project successfully addresses several design constraints, there are still some limitations to be considered. These include the external architectural replication of a realistic Space module and the realism of Life Support Systems, which require further research and improvement. Nevertheless, the ESH-X sets a significant milestone in the field of transportable analog habitats, fostering collaboration and exploration in analog research.

ESH-X not only serves as a research facility for analog missions, but it also plays a crucial role in advancing Space education and outreach. The habitat provides a versatile platform for immersive and engaging public events. Its adaptable design allows universities and research centers to conduct realistic simulations with students, while interactive workshops and demonstrations captivate a broader audience, inspiring passion for Space exploration. With its portability and modularity, ESH-X brings Space education directly to communities, igniting curiosity for Space and analog missions.

Looking at the future, the ESH-X project team aims to continue collaborating with Space agencies, researchers, and industry partners to enhance the habitat's capabilities and improve the experience for analog astronauts on board as well as for visitors. With its portability, cost-effectiveness, modularity, and potential for expansion, ESH-X stands as a promising model for the future of analog research.

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