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Lunar Worm: designing a hybrid class habitation module inspired by Nature

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Abstract

Space exploration has always been a desired field for multidisciplinary teams all over the world. These days more than ever humanity is close to a real step towards extended lunar exploration and possibilities for long-term missions on Earth's satellite. Designing potential habitat solutions that would sustain human presence on the lunar surface represent an important challenge to be addressed. Lunar Worm is a hybrid class II and III module for long-term habitation that aims at increasing human research and settlement capabilities through a biomimetic approach inspired by annelids. The chosen location for the mission is the Shackleton crater which became a target for multiple space and lunar research groups mainly due to the perpetual sunlight and the presence of frozen water. For the initial step of the mission, a proposal of a limited village is determined, which is composed of two deployable modules designed for a crew of 4 members. Inspired by the annelids, Lunar Worm's main feature involves a deployment system based on the expansion of a series of segments of a composite inflatable solution, enclosed between two rigid shells. Regarding the materials, high-strength, impact-resistant, and advanced composite materials are chosen for the envelope: the front bumber is to be made of Kevlar reinforced polymer composites whereas the other layers include Nextel and Kevlar fibers. Overall, the rigitidy and the structural resistance of the module is guaranteed by the aluminum frame, which possesses low mass and high stiffness and minimizes transportation costs and volume. The inner layers of the inflatable system integrate the use of innovative solutions such as mycelium, cyanobacteria, and ice to provide insulation as well as radiation protection. Furthermore, the fabrication through 3D printing of a lunar regolith radiation shielding has been envisioned during robotic precursor missions, aimed at site preparation for human arrival. The organization of the module allows for the deployment both in vertical and horizontal directions, increasing its flexibility. The interior distribution of the modules has similar facilities that offer structurally stable, psychologically comfortable, and mission targeted design solutions, taking into consideration both the technical requirements and suggestions for the optimal physiological performance of the crew. Modularity and redundancy both at a module and at a settlement level are taken as key design principles to create a system that allows for an incremental expansion to serve larger crews over time and become a permanent lunar habitation and research village.

Keywords: space architecture, lunar settlement, lunar habitat, deployable, biomimetic approach, modularity

Acronyms/Abbreviations
National Aeronautics and Space Administration (NASA)
Human Centred Design (HCD)
Human integration design processes (HIDP)

In situ resource utilization (ISRU)
European Space Agency (ESA)
Moon to Mars’s Planetary Autonomous construction technologies (MMPACT)
Technological Readiness Level (TRL)
Low Earth Orbit (LEO)
International Space Station (ISS)
Space Launch System (SLS)

1. Introduction

The goal of this research is to present and investigate the potential of a surface lunar habitat concept, developed following the Space Architecture principles of Human Centred Design and Design across scales. The research focuses on the possibilities that a modular approach to deployable habitats could have if applied across scales. The design strategy involves the modularity and adaptability of interior spaces. A versatile module is the key element of the project, since it can be employed in multiple conditions and can deliver a proper plan of action for incremental aggregation and expansion for a lunar village. In doing so, the goal of this design effort represents the need to ensure the habitability of the module, intended as the required suitability of the environment for daily[1] human life, while satisfying all the technical requirements necessary to ensure the feasibility of such design. This can only be achieved through a multidisciplinary approach, one of the cardinal elements upon which the field of Space Architecture is built. This discipline it embodies the meeting point of the engineering approach in designing habitats and systems for the exploration of off-earth environment such as the Moon, Mars, asteroids and space vehicles, with the complexity of the human factor oriented design, taking into account psychological aspects, as well as subjective considerations and non-quantifiable qualities of the space[2]. Taking into account the precepts of the Millennium Charter, the research has focuses on a series of specific categories for action[3]:

- Sustainability
- Human Interaction
- The User
- Human Factors
- Human Condition
- Social Aspects
- Environmental Conditions
- Education
- Lifecycle
- Humility
- Benefits

These categories of actions set the ground for the new development of a more human centered direction for the design of space structures and systems.

1.1 Intro to Human Centered Design

In order to reach this goal, NASA has developed a methodology within the framework of the Human Integration Design Processes (HIDP). The Human Centered Design is defined as an approach that focuses on making systems usable by ensuring that needs, abilities, and limitations of the human user are met, in a clear shift of the attention towards the figure of the astronaut. This design approach can represent the human user as a functional subsystem of the greater habitat/spacecraft system, making it necessary for the design to accommodate the human in order to increase the chances of mission success[4].

The four major principles that characterise Human-Centered Design are:

- Active Involvement of Users and Clear Understanding of user and task requirements
- Function allocation between users and technology
- Design iteration
- Multidisciplinary Design

Once having defined the approach that is dominant in the field of Space Architecture, a set of case studies from different periods regarding off-earth habitats for humans is brought forth to analyse the integration of the Human-Centered Design principles, and set a background for the presentation of the topic of this research.

1.2 Literature Review on Lunar Habitats

The approach adopted by NASA in classifying the technology development roadmaps for exploring Moon, Mars or other celestial bodies defines different habitat structures based on both the typology of the mission and their reliance on Earth-based technologies and materials for their construction. In a series of progressive stages 3 main habitat classes have been defined[5].

Class I habitats, or pre-integrated, are associated with structures that have been entirely prefabricated or pre-outfitted on Earth before their arrival on the surface. This class of habitat is the first typology that is envisioned to be employed in crewed missions, and will have the primary function of supporting an initial exploration phase of the Lunar (or Martian) surface. Such habitat concepts were already considered for the Apollo program, where enhanced lunar modules were expected to make up for bases for missions lasting up to 14 days.

Class II habitats stand for structures pre-fabricated on Earth, then assembled, deployed, erected or inflated upon arrival. This typology of habitat guarantees the increase of the habitable volume, while still satisfying the payload volume constraints of available launching systems. It can be integrated with ISRU technologies, for example using regolith for the radiation shielding. These habitats, which represent an intermediate step into the development for a permanent off-earth settlement, represent a widely explored solution in the field of Space Architecture and present multiple case studies.

A lunar habitation concept has been developed between 2009 and 2015 as a collaboration between ESA, the international architecture firm Foster+Partners, Alta SpA, Monolite Ltd, and Scuola Superiore Sant'Anna[6]. The research developed introduced a hybrid concept for a habitat that would leverage both the utilization of an inflatable shell connected to a pre-integrated segment for the habitat, and the creation of a radiation shielding through the declination for space of the existing 3D printing technology D-Shape[7].

Another more recent study has been conducted as a collaboration between ESA, Skidmore, Owings & Merrill, and MIT to develop a concept for an international 'Moon Village'. This project includes a detailed design for a deployable vertical habitat with three inflatable bladder systems connected to a rigid shell which supports the loads of launch, transfer and landing[8]. The concept analyses the potential solution for the aggregation of multiple modules; the masterplan which defines the functionalities of the Moon Village clusters which are meant to be developed following an incremental approach. This plan integrates a series of functional areas developed in parallel, which include a habitation band, an infrastructure band, an activity band and the energy generation and transportation band[9].

Class III habitats, are completely ISRU derived, in the sense that they are fully composed by materials and construction systems that are either found or manufactured in situ, such as lunar masonry, lunar concrete or retrofitted caves. This is the most advanced typology of habitat and before becoming a feasible option for construction it requires extensive validation through in situ testing and experimentation. Therefore, this typology, is expected to satisfy the requirements for a Colonization mission typology. Conceptual designs of this habitat class exist and usually rely on the expected validation of ISRU technologies which currently have a lower TRL(Technology Readiness Level)[10]. A significant example of a class III habitat is represented by the Lunar Lantern, developed within the larger Project Olympus by ICON, Search+ and Bjarke Ingels Group (BIG), which falls under NASA's Moon to Mars Planetary Autonomous Construction Technologies (MMPACT). This habitation concept represents a vertical habitat which is completely designed and imagined as an ISRU structure. A protective and illuminated outer shield structure surrounding a continuously 3D-printed pressure vessel is envisioned. Each element of the structure is imagined as a 3D printed component which, with a combination of discrete and continuous elements, this provides a high degree of redundancy and structural efficiency to the harsh loading conditions of the lunar surface[11].

1.3 Building on the Moon

1.3.1 Environmental Condition

The construction of a habitat in such a harsh and hostile environment like the lunar surface needs to satisfy a series of extremely complex and specific requirements that can allow for the mission success and ensure the survival of its inhabitants. The definition of the Lunar surface environmental condition and its major threats to human safety represent a necessary step; the complexity of these conditions underlines the importance of the multidisciplinary approach adopted in the field of Space Architecture. One of the most important aspects to be considered, which differentiate Lunar construction between Martian construction is the hard vacuum to which the Moon's surface is exposed.

This condition requires the fundamental need to create a safe and artificially pressurized environment to sustain human life. Another primary aspect of related to Lunar construction is the presence of partial gravity compared to Earth. The Moon's gravity accounts for approximately 1/6 of Earth's and although it can be considered an opportunity for structural performance of lunar habitats, it is definitely an aspect to be considered when developing a design for a surface habitat. Another crucial condition which represents a threat to human health is the constant bombarding of solar and cosmic radiation, as well as micrometeoroid impacts and extreme temperature excursions between lunar day and lunar night (which accounts for approximately two Earth weeks). This situation sets as a fundamental requirement a shielding strategy that could protect the astronauts from the abovementioned threats altogether. Lastly, lunar regolith represents a huge hazard due to its electrostatic charge and its extremely high abrasiveness, making it problematic for all mechanical and electronic components which suffer from extremely rapid wear when exposed to this specific agent[5].

1.3.2 Reduce Earth Dependency

An aspect that will act as an enabler for the future of human exploration beyond the Low Earth Orbit(LEO) is the capability to reduce the dependency from Earth-based resources, due to the extreme costs related to payload launch and shipment on the Lunar surface. This goal can only be achieved through the utilization and exploitation of in situ resources to obtain both consumable goods (i.e. oxygen as fuel and as a consumable for life support systems), and viable construction materials[12]. It is crucial for the preliminary exploration missions on the Lunar surface to provide the necessary technological advancements and validations to improve human capabilities on this aspect.

1.3.3 Automation in construction

Plans for designing a surface off-earth habitat require to consider the entire construction and deployment sequence of said structure to be performed in an automated way. It is therefore fundamental for a space architect to place particular importance on the automation aspect of the construction sequence[13], by imagining one or more precursor robotic missions that could establish the correct conditions for human to land and survive on the lunar surface for a continued period.

These preliminary considerations represent a common ground that establishes basic requirements for the feasibility and the successful outcome of any space architecture design effort. The research will therefore be evaluated with the aforementioned criteria to assess its effectiveness.

2. Material and methods

The expected result for the research applied is to create a structure able to satisfy the mission requirements at multiple scales, enabling a high degree of flexibility in all aspects of the proposal, including the internal disposition of the spaces, the deployment capability, and the aggregation and expansion strategy. Therefore the targets related to the general design goal are:

- Compactness of the module
- Capability of transportation
- Flexibility of usage over time
- Modularity of the overall system
- Structural adaptability to different functional requirements

The main design strategies that have been followed, together with the continuous reference to the human centered design, include the importance of the biomimetic approach, the modular approach that has guided the design activity across scales and the computational approach which has been the primary support in the process of form giving and form finding of the detailed proposal.

2.1 Concept Design

The development of the conceptual design for the Lunar Worm habitat was inspired to the natural world, following a biomimetic approach where the analysis of the animal world has guided the design choices and the definition of the idea. Indeed, as the name suggests, the main source of inspiration has come from annelids[14], better known as segmented worm, which is the definition of any invertebrate animal that is characterized by the possession of a body cavity, movable bristles, and a body divided into segments by transverse rings, or annulations. The most interesting characteristic of annelids is related to their locomotion, which is achieved through the extension of their body. This characteristic has been reflected and used as a guiding principle for the definition of the particular deployment strategy of the module, which falls under the class II habitat category. The reasoning behind such strategy comes from the necessity to be able to optimize as much as possible the volume of the module in order to match the payload constraints of the current launching technologies. The lower design limit was

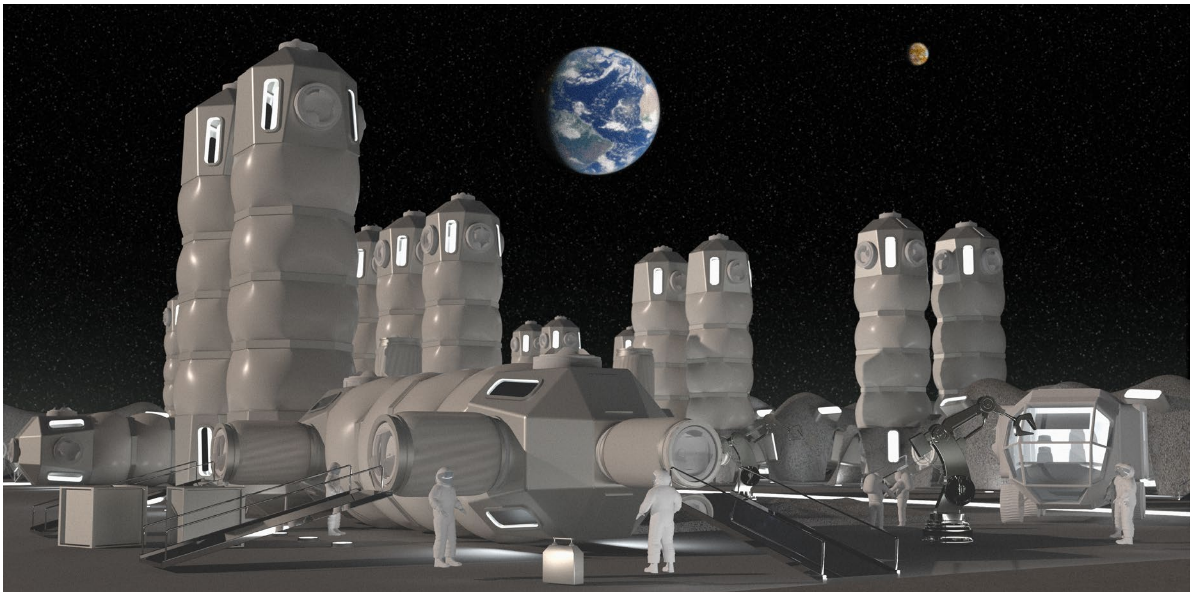

Fig 1. General view of deployed module

based on the volumetric constraints of the SLS Block 1 Cargo launching system, which reports a 5m diameter Fairing class, with a height of 19m approximately and a payload mass of 26tons. A secondary, more flexible option, would be provided by the introduction of the SLS Block 1B Cargo, increasing the fairing class to 8.4m[15]. The design allows for the fitting of 2 stacked modules within the dimension of both selected launchers, allowing therefore for a substantial reduction in costs over time for the expansion of the settlement. This also permits an initial primary set up of the habitat as a dual module configuration, providing multiple habitat solutions depending on the mission requirements.

3. Design Proposal

This section will be devoted to an extended discussion on the surface habitat concept Lunar Worm. To ensure the successful development of the proposal and to address all challenges related to the off-earth construction and the satisfaction of all habitability requirements over extended periods of time, it is fundamental to define a mission scenario within which the module is deployed and contextualized.

3.1 Mission and Location

Six Apollo missions sent explorers to the surface of the Moon and collected 382 kilograms of samples to return to Earth for study however, the time spent on the Moon was limited[16]. Moreover, half a dozen robotic missions have been performed in the last decade[9].

The mission definition that will see Lunar Worm as the enabling habitation technology is defined as long term mission with the goal of permanent settlement to perform the extraction of resources. This will involve NASA as the main institutional stakeholder, in partnership with the private company Shackleton Energy Company[17], interested in the field of resource extraction, in particular for water and metals such as titanium, present on the Lunar surface. This mission condition set the requirement for an iced water rich location to be selected for the development of the mission.

The location of the settlement is chosen to be along the rim of Shackleton Crater in the South Pole where it would be possible to build an ever-developing settlement and which is also considered as the region that will have the center of operations by the USA, China and Europe[18].

The rim of the crater is preferred due to continuous exposure to sunlight that results in higher temperature, relatively easier access to the crater where natural resource explorations will be done, and a visual connection with the surroundings, possibly the Earth that will result in psychological benefits in the long run.

The mission consists of 3 main phases: the first one, covering the first 6 months, will be a robotic precursor mission which will prepare the arrival of the astronauts by defining the site conditions and later support the positioning and the deployment of the module; the second phase will include the first launch which will involve 4 crew members to be hosted in the first paired modules on the surface to perform experimentation and validation of resource extraction technologies. The third and final phase will allow the continuation of research activities on nature and distribution of natural resources with the mining procedures and finally working on the prolongation of future missions, allowing for an incremental expansion of the settlement to serve larger crews over time and become a permanent lunar habitation and research village.

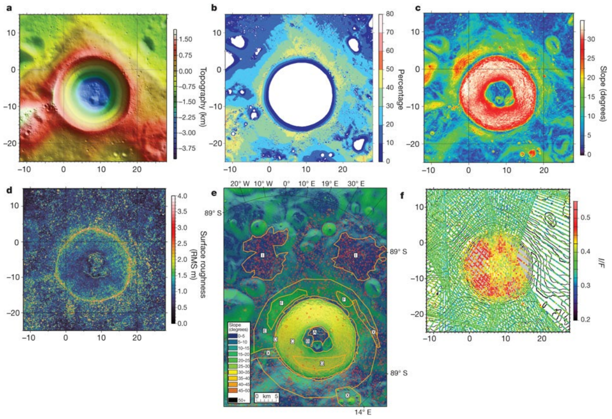

Fig. 2 Characterization of Shackleton Crater. Source: https://sservi.nasa.gov/articles/detailed-characterization-of-shackleton-crater

3.2 Module Design

3.2.1 General Composition

As previously described, Lunar Worm is a hybrid class module for long-term habitation that aims at increasing human research and settlement capabilities through a biophilic approach. Inspired by annelids lunar worm's main feature involves a deployment system based on the expansion of a series of segments of a composite inflatable solution, enclosed between two rigid shells. The organization of the module allows for the deployment both in vertical and horizontal directions, increasing the module's flexibility. This is possible thanks to the organization of the spaces in different segmented areas, the opening for which can serve both as a corridor with a series of opening in the horizontal organization of the module, as well as a vertical mobility support in the vertical configuration. The selection between the horizontal and the vertical configuration is based upon the mission requirements and the necessities for floor plan area, ceiling height, functional activities of the module. Each rigid shell, which is specular at each end of the module, presents multiple airlocks, which allow for multiple combinations for the physical connection between two modules, improving at the same time the redundancy of the whole system. The main structural elements are composed by the two rigid shells, which are connected to the structural rings separating each central segment by a foldable aluminum structural framing, which also provides structural support for the inflatable portions of the system. The geometry of the shell and the structural rings enclosing the inflatable spaces were designed in a parametric fashion, and have been optimized through a multi objective optimization process performed with the Grasshopper© [19] plug-in named Octopus[20].

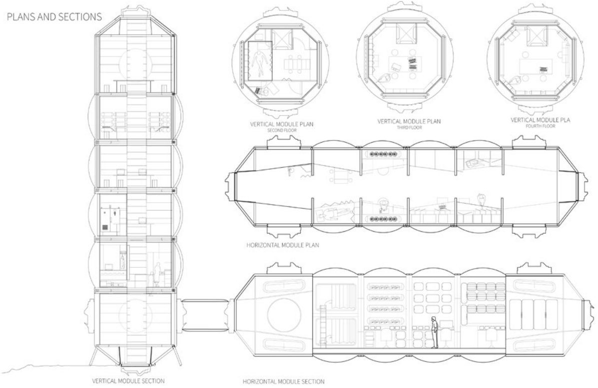

Fig. 3 Structure and internal distribution of vertical and horizontal module

3.2.2 Deployment Strategy

The deployment strategy of the module can be subdivided in a series of consequential steps to be performed automatically or with the support of robotics elements. The first stage of the deployment represents the fully stacked conformation, which extends from launch up until the landing phase. In this condition both modules are fully compacted and stacked on top of each other. Once landed, the modules are removed from the lander capsule and are disposed in their first deployment conformation, where the one module is connected in horizontal disposition with the other placed in vertical position, with both modules still fully non deployed. Third phase represents the progressive deployment, which happens so that each segment is inflated and expanded fully before moving onto the next one. The fourth stage is the fully deployed stage, which involves the realization of a 3D printed radiation shielding made of regolith, which will then make the module pair fully functional for long term use.

3.2.3 Radiation Shielding

Due to the particular conformation of the module design, which grants the possibility to have both vertical and horizontal development, the requirement of radiation shielding becomes a strictly necessary step in the design process. In order to ensure crew's safety two different radiation shielding solutions were selected.

a. Mycelium & Algae

The first solution is pre integrated in the module deployment strategy. The inflatable component of the module is in fact composed by a multilayer material composed by a mix between Kevlar and Netxtel fibers, iced water and organic material, which leverages the capability to construct structurally efficient materials from fungal bio-composites within the layers of the inflatable shell elements[21]. This process, which is activated first through an inflation of the membranes, followed by the filling with bio-composites which are necessary to the cyanobacteria embedded within the inflatable. These bacteria are fed water, nitrogen, carbon dioxide and other nutrients which are sourced in situ. When heat is supplied to the cells it creates the right conditions for growth, which results in the production of oxygen. Once the cyanobacteria reach the critical biomass, the substrate is dehydrated and oxygenated to become fit for feeding a fungi branch which activates a process of solidification and fusion between the algal biomass and the mycelium at a cellular level. This process creates a solidified material with structural capabilities and with a secondary effect of radiation

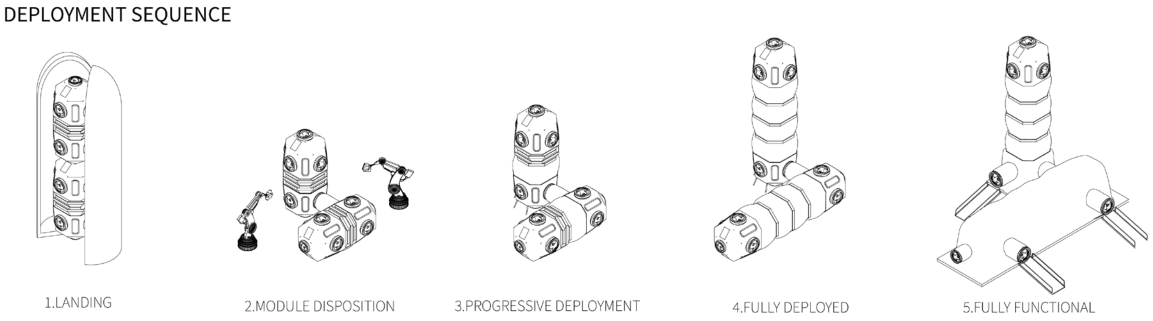

Fig. 4 Deployment sequence diagram

shielding due to the high quantity of hydrogen produced.

Another process that can be analysed for radiation protection is related to the capability by melanin-rich fungi to shield from ionizing radiation, at efficacies comparable to lead (Pb) and with higher degree of efficiency compared to charcoal. These fungal organisms are able to sustain approximately 1.6 million times the radiation dose considered lethal for humans, opening up interesting opportunities for the integration of these biological processes within the inflatable systems as previously described.

This type of radiation shielding solution is integrated within the proposed segments of the module, in order to provide protection to the crew members even in the vertical disposition of the module.

b. Regolith Shield

A second radiation shielding strategy was adopted to ensure a better performance for long term duration. A 3D printed radiation shield constructed in regolith was developed to protect the horizontal modules and the lower hard shell of the vertical modules. The form-finding strategy of the shield was obtained through a computational approach, following simple hanging model [22] structure developed with the support of the Kangaroo [23] plugin for Grasshopper. The solution was integrated with an extension of the openings on the hard shell modules, in order to still provide a visual continuity with the exterior space. The regolith shielding is meant to be aggregated and offer a series of arched openings to allow the entrance inside the module. Another important aspect is the decision to develop a shielding that is not directly in contact with the module surface as to avoid increased wearing rates due to the contact of the surfaces with the lunar regolith.

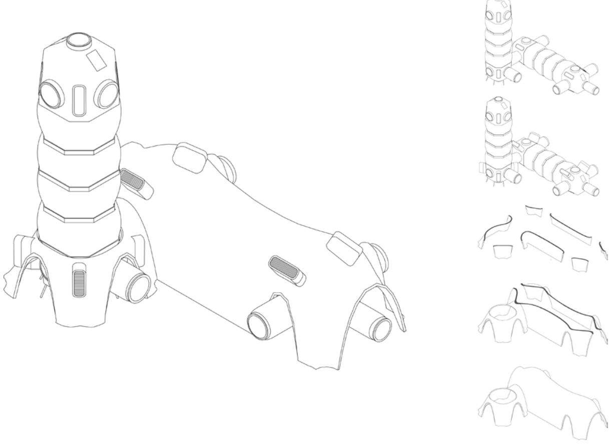

Fig. 5 Radiation shielding conformation

3.2.4 Interior Spaces

The psychological well-being in a long-lasting mission is an issue and a challenge for space architects to address due to the complexity of human neuro system and a degree on unpredictive reaction to lunar environments that have never been analysed for a long stay. Multiple studies suggested there are several main issues that can heavily access the well-being of crew members which are[24]:

- Social tension, interpersonal conflicts and increased annoyance and sensitivity
- Somatic complaints, especially insomnia and sleep disturbance
- Motivation decline cause by prolonged isolation
- Non-changing and tasteless food
- Absence of privacy
- Noise and vibration, produced by the habitat
- Absence of day - night change
- Extremely clean environment
- Macro to microsociety challenge

Psychological disturbance in the different forms and ways can affect the well-being of the crew members, but also the results of work they performed. All issues should be addressed in the final design proposal so that it can eliminate or significantly decrease the effects of environmental condition on the human psycho and overall success of the mission.

One of the biggest challenges is the privacy and sleep issue[25]. These two aspects can boost some somatic complaints, social relations within the crew and integration onto the micro-society. The study of On-orbit sleep problems of astronauts and countermeasures, by Bin Wu*, Yue Wang, Xiaorui Wu, Dong Liu, Dong Xu and Fei Wang developed by Military Medical Research, has addressed the issue of lack of sleep and its effect on cognitive functions of the brain, stress resistance and emotional sensitivity of humans in extreme environments. As the study suggests, sleep insufficiency, can negatively affect not only cognitive abilities of the crew, but also immune system and the overall health of the human being.

Another key issue of psychological tiredness and stress increase for long term spaceflight[26] is addressed in the study of Prospects for Psychological Support in Interplanetary Expeditions, by Vadim Gushin, Oleg Ryumin, Olga Karpova, Ivan Rozanov, Dmitry Shved, and Anna Yusupova. The study shows the importance of psychological well-being on orbit and for long missions, specifically stressing on the tiredness of the module environment. The research tackles the disappearing earth phenomena which can be connected to the absence of greenery on board. Multiple experiments and observations showed that a greenhouse was not only an element of closed life support system, but also a mean to restore the image of Earth, important for human emotional state. The greenhouse, located in vicinity of private rooms and leisure areas positively affects the psychological well-being due to active involvement into plant care, and image of organic life within module or a spacecraft.

Considering the aspects and issues listed above, the set of rules for interior design was developed, that should fulfil all requirements imposed by the mission. According to *Architecture for Astronauts, An Activity-based Approach* the main rules are the following:

- Each crew member has an equipped personal room, with working area and personal storage (notice: In case of emergency one module however should serve for the entire crew of four)
- Vibration mechanisms, noise and garbage collectors are in the opposite side of the module from the private area for sleep and leisure
- For autonomous food production, each module should have a greenhouse, that is located in between private area and working area, by which serving also as a buffer zone for noise and vibration reduction
- As the module is foldable, the majority of furniture fixtures should be foldable as well and located within the surface of the module.
- Each single module should be completely autonomous
- Defined “Up” and “down” of the cabin even while using all surfaces of the module
- Leisure and dining area should be spacious enough to fit the entire crew simultaneously, so that the entire crew can share a meal
- Hygiene cabin should be located within private – leisure section of the module

These guidelines were successfully implemented into the design proposal, so that the module would consist of 6 parts:

1. Private zone with personal sleeping units, kitchen, dining foldable table and bathroom and sanitary unit
2. Greenhouse with laboratory facilities
3. Office and laboratory facility
4. Mechanical room with medical and sport equipment
5. Airlock and corridor with storage for the connection to the neighbouring modules
6. Leisure room with windows for visual contact with the environments

Fig. 6 Leisure room with windows to visually connect to Earth to improve psychological well being

Facilities are located linearly along the module’s axis, with private area on one end and the mechanical room, office on the other divided by the greenhouse unit. This composition supposedly decreases effect of noise, vibration and stresses on crew by division work and leisure spaces, allocation adequate space for leisure activities and private cabins, introducing the greenhouse as common ground for planting and research, giving the crew opportunity to scatter along the module while performing daily routine. This setup allows the integration of different strategies that offer high performance of interior space for mission goals and research together with positive environments for emotional and psychological health of the crew members.

Fig. 7 Interior view of the Greenhouse with laboratory facilities

3.2.5 Settlement Aggregation & Expansion Strategy

Safety practicality and the potential for further expansions were the main elements to consider for the settlement aggregation and expansion strategy.

A modular, interconnectable system of structures is created to achieve separate elements with 2 exits that can be easily detached from the rest of the system in case of an emergency.

The modular system also increases the adaptability to the irregular terrain of the location while making it easier to further expand the habitats of the settlement thanks to the repeatable pattern of the modules.

The modules with different functions come together according to the needs of the required system to create self-sufficient groups of structures that are repeated as the settlement expands. These conglomerations of modules are:

- the resource extraction facility, composed by 3 horizontally disposed modules connected head to head in a continuous way;
- the research facility, which comprises 2 vertical modules next to each other and 2 horizontal modules disposed with an L shape
- the greenhouse facility, composed by 3 vertical modules and a single horizontal one
- the crew district, which includes two vertical modules and 2 pairs of head to head connected modules placed one next to the other, in order to allow a more effective radiation shielding protection.

The facilities such as the launching pads and the energy production centers are located at least 1km away from the habitat portion of the settlement, keeping the safety measures into consideration. Their connection is granted by a series of horizontal sintered regolith surfaces which serve as roads to improve the transportation.

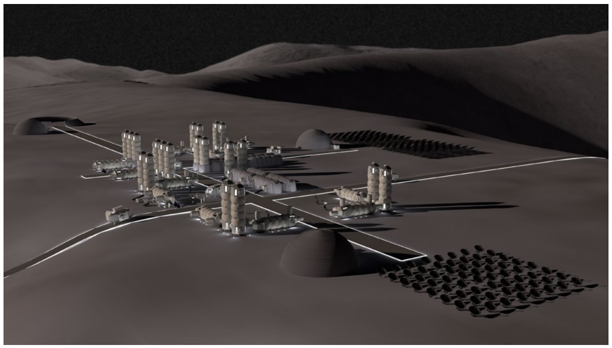

Fig. 8 Aerial view of the settlement expansion with functional clusters

4. Results & Discussion

The goal of the presented research was to design and validate the potential of a surface lunar habitat concept following a clear methodology rooted in the Human Centred Design approach and the Design across scales. The evaluation of the concept has been performed based on a series of design goal criteria analysing the compactness of the module, its modularity and flexibility, as well as its structural adaptability. The biomimetic, modular and computational approach followed during design activity guided every choice regarding the development of the module. The proposal consisted in envisioning a mission scenario that could fit within the current framework of surface exploration and that could define the needs and requirements for the habitat to be designed. The selection of a public-private joint research mission set the perfect scenario for the development of a class II /class III habitat that could sustain extended mission. The module design reflected the intention to develop a highly flexible, reconfigurable and modular solution, able to act as a building block in the incremental development of a future lunar settlement. Technological aspects such as the deployment strategy taking inspiration from the world of annelids and the hybrid radiation shielding solution involving 3D printed regolith structures and biological components present an interesting prospect, even if currently at a low TRL, on the future technological developments that could be unlocked by the first phase of crewed mission on the Lunar surface. The development of the interior spatiality of the hybrid vertical and horizontal habitat options address the requirements for habitability and tackle some issues related to the habitat deployment and construction.

5. Conclusions

The results obtained within the context of this research open up to a wide range of future research opportunities. In particular, increasing the level of detail within the context of the current design proposal is an imperative step to validate the technological readiness of the solution. Further research on radiation shielding solutions, as well as detailed procedures on management of construction and deployment processes in robotic precursor missions would establish a solid background for further validation of the conceptual design. An in depth structural analysis of each different structural element, along with a general structural analysis of all components assembled would test the performance of the habitat under the extreme lunar conditions. The upcoming Artemis missions are a fundamental step in validating the potential of the solutions presented in this paper, as well as highlighting the most suitable solutions that will allow a sustainable and prolonged permanence of humanity on the Moon and, in the future, on Mars.

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