A mobile habitat for human lunar exploration

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Valentina Sumini[1,5][0000-0003-2315-8786], Claudio Chesi[1][0000-0003-3773-1061], Daniele Florenzano[1,3][0009-0006-5756-5231], Michela Botti[1,3][0009-0003-6063-286X], Lorenzo Calogero[2,3] [0009-0002-6538-6349], Ana Carolina Corrêa Caracas[2,3][0009-0004-0340-3216], Alessandro Caruso[1,3] [0009-0003-9436-1957], Massimo C. Comparini[6], Enrico Ferrone[6], Jeffrey Hoffman[4], Paolo Maggiore[2][0000-0003-0218-0730], Marta Mattioli[1,3][0009-0006-7795-8921], Joseph Paradiso[5][0000-0002-0719-7104], Maria Antonietta Perino [6] [0009-0004-8116-8709], Marco Portolani[2,3][0009-0001-3203-389X], Angela Rizzo[1,3][0009-0005-2868-5261], Giulia Signorotto[1,3][0009-0000-5603-3213]

[1] Politecnico di Milano, Piazza Leonardo da Vinci 22, Milano 20133, Italy
valentina.sumini@polimi.it
[2] Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy
[3] Alta Scuola Politecnica, Italy
[4] Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, USA
[5] MIT Media Lab, 75 Amherst Street, Cambridge, USA
[6] Thales Alenia Space, Str. Antica di Collegno 253, Torino 10146, Italy

Abstract. Since the Apollo missions, there have been significant technological advancements and scientific discoveries in robotic exploration of deep space. Currently, NASA's Artemis Program aims to establish human habitation on the Moon, which remains a considerable challenge. To address this, Alta Scuola Politecnica, Thales Alenia Space and MIT have collaborated to design an innovative and adaptable mobile habitat using a holistic multidisciplinary approach for crewed surface exploration missions. The outcome of the Lunar Architecture Design Exploration (LADE) project is a mobile space architecture system that enables human presence on the Moon, supporting medium to long-term missions. This mobile module serves as a crucial component within a more extensive system of hybrid class II and class III shelters, intended for the development of a lunar village. The primary objective is to facilitate the extended stay of four astronauts near the Shackleton crater, strategically located at the South Pole of the Moon, which offers favorable conditions for surface exploration and potential future permanent settlement. The paper presents an in-depth study of the form-finding process and structural analysis adopted for the LADE mobile habitat.

Keywords: Space Architecture, Mobile Habitat, Structural Analysis, Moon

1 Introduction

After the Apollo missions, the exploration of deep space has witnessed significant technological progress and remarkable scientific breakthroughs. Even now, more than

50 years since the extraordinary first Moon landing, NASA is formulating a vision to establish a human presence on the Moon. This new phase of space exploration revolves around the Artemis Program, which brings together international efforts to accomplish these ambitious objectives. It is worth noting that collaboration among nations in space exploration is not unprecedented, as exemplified by the International Space Station (ISS), a shining example of cooperative ventures that have lasted for over 23 years. The ISS represents the first-ever extraterrestrial society, symbolizing the collective achievements of countries working together in space.

To support the successful human exploration of the Moon and eventual missions to Mars, it is essential to establish a mission framework. From a broader perspective, the project Lunar Architecture Design Exploration (LADE) focuses on initial exploration phases, which are intrinsically connected to the requirement for efficient transportation.

The requirements primarily revolve around ensuring long-term mobility and the well-being of the crew, aligning with the vision of establishing a permanent presence on the Moon. This necessitates the development of a system capable of supporting extended human missions for exploration purposes. Notably, there are significant constraints to consider, including limitations on volume and mass, as well as practical factors such as budgetary considerations and adherence to international law regulations, which are not addressed in this particular article.

In essence, the project aims to design a mobile module that can accommodate four astronauts for a 60-day mission. This module serves as a crucial link between robotic precursory missions for lunar site exploration, specifically the South Pole of the Moon, and the establishment of a human settlement across a network of outposts on the lunar surface.

2 LADE design

Within the LADE project, a variety of mobile modules are envisioned, each designed to cater to diverse mission objectives and requirements based on their unique functions and internal layout. The underlying concept involves offering a selection of mobile modules that can be interconnected through airlocks, enabling the choice of a specific module for a given mission.

The inspiration behind the LADE project stems from a comprehensive analysis and subsequent interpretation of bees. The inherent characteristics of bees are reimagined in a futuristic context, envisioning a lunar swarm and its interconnected habitat. The project emphasizes the interdependence of both the shelters and the mobile modules, as they are mutually essential for functioning and existence.

The biophilic approach is also applied to the design of mobile modules, where the arrangement of their functions takes inspiration from the body structure of bees. When interconnected, these modules resemble the head, thorax, and abdomen of the bee, with each section serving specific purposes such as navigation, communication, locomotion technologies, and extravehicular activity (EVA) systems in the primary module, and research or storage functions in the secondary module.

Similarly, the method chosen for the movement of mobile modules draws parallels to the coordinated behavior of a bee swarm. These modules form a group of individual units that move together and work towards a shared objective. To ensure order and minimize the need for navigation tools and control equipment within the mobile modules, the project envisions a primary module responsible for navigation and leading the way. The secondary modules, selected for the mission based on computer vision, artificial intelligence (AI), and fleet learning, follow the primary module. Each secondary module possesses its own mobility system.

This approach offers significant flexibility in achieving the desired performance levels depending on the specific mission requirements. Currently, the primary module focuses on navigation and control, while the secondary modules are dedicated to tasks such as research, storage, or transportation.

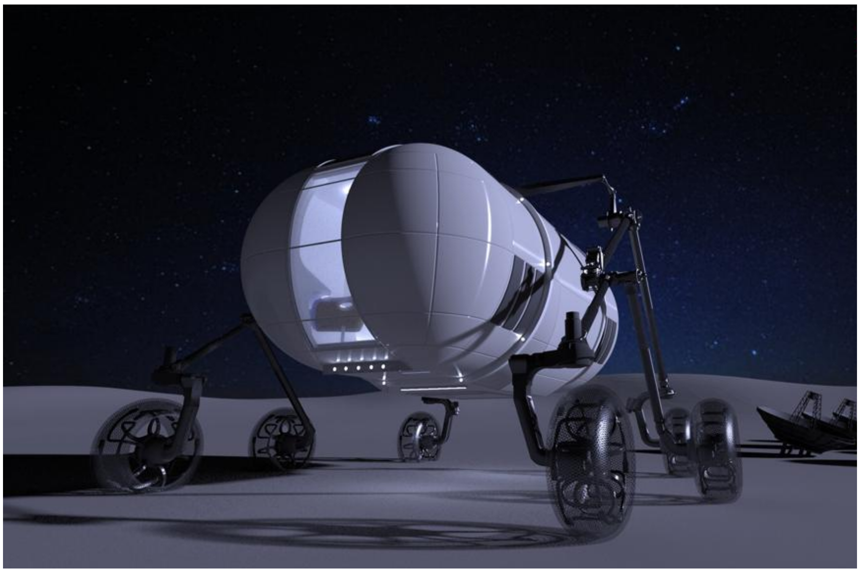

Fig. 1. Render of the exterior.

The primary mobile module's internal layout is structured based on its key functions, divided into three sections: the cockpit, center, and rear. The cockpit is specifically designed for navigation and control purposes, featuring spacious desks equipped with displays, speakers, projectors, and sensors. The chairs are adjustable on rails, allowing astronauts to access all control areas and position themselves in front of the transparent surface of the module's shell. This transparency enables the drivers to have a clear view of the Moon's surface and the surrounding environment.

3 Designing the module shell structure

3.1 General aspects

The geometry of the LADE module has been determined by the current technological and volumetric constraints coming from the payload launch from Earth and the current limitation of the launcher's capabilities. The geometry of the shell has been therefore designed as a simil-cylindrical shape, the section of which is inscribed within a circle 4.5 m in diameter.

The complexity of the structural system for a mobile lunar habitat has been simplified into two main macro-elements: the independent structure of the mobility system, which includes the structural elements composing the modified rocker-bogie mobility system, providing support to the shell, and the shell structure itself, containing the pressurized habitat space. The shell structure is composed of a panel structure reinforced by a network of lightweight beams in the most stressed areas. Structural optimization was performed to define the most efficient configuration of sections of both beam and shell elements. To this purpose, the geometry has been completely developed within Grasshopper© [1], while the structural analysis has been performed with the Grasshopper© plug-in Karamba3D® [2].

3.2 Definition of design loads

Multiple load conditions must be defined when designing a structure that is meant to be operated in space, considering all the different mission phases. A main issue is related to the Moon's gravity, which accounts for roughly 1/6 of Earth's gravity, impacting the calculations of structural dead loads. Another factor to be accounted for is the lack of a consistent atmosphere, which results into the pressurization of the interior spaces to 1 atm, creating an outward directed load on the whole pressurized surface of the shell. Along with these considerations, another crucial aspect from a structural standpoint is the exposure to extremely harsh temperature excursions, which could impose a heavy thermal loading condition on the structures [3].

The design of the shell structure has been based on a simple static analysis, with the purpose of optimizing both the shell shape and cross sections; further research would require performing a dynamic analysis, considering both launch and operating conditions.

3.3 Choice of materials

In order to limit the module weight, an Al-Li alloy, AA2060-T8, has been selected for the shell structure, which is required to sustain the pressurization load of the interior spaces of the module and its own weight [4]. An additional material, the borosilicate glass, has been selected for the transparent portions of the shell, due to its high resistance to thermal shock and its optimal mechanical properties for space uses [5]. Tab.1 provides information on the mechanical properties of such materials.

Table 1. Mechanical properties of structural materials.

Element	Material	Young's modulus [GPa]	Tensile strength [MP]	Compres- sive strength [MPa]	Poisson ratio
External shell	Al-Li alloy AA2060-T8	76.5	476	470	0.33
Glass window module	Borosilicate Glass	64	81.6	914.7	0.20

3.4 Geometrical configuration

Several requirements have been considered in the search for a suitable geometrical configuration. First of all, due to the conformation of the mobility system [6], a symmetrical shape has been adopted [7]. In addition to this, sharp edges have been avoided, in order to reduce stress concentration and improve manufacturability.

The resulting geometry is composed by 3 portions, which include a central segment, symmetrical with respect to the center of mass of the structure, and two quasi hemispherical shells which host on the one side the airlock dedicated to the physical connection with the secondary module and on the other one the opening nearby the navigation cockpit. These three segments are connected to each other by a transition segment with the cross section composed by two half circular arches and two horizontal beams, in order to expand the horizontal floor surface of the module and increase the usable interior space for the astronauts. Figure 2 shows the parametrically modelled geometry of the shell.

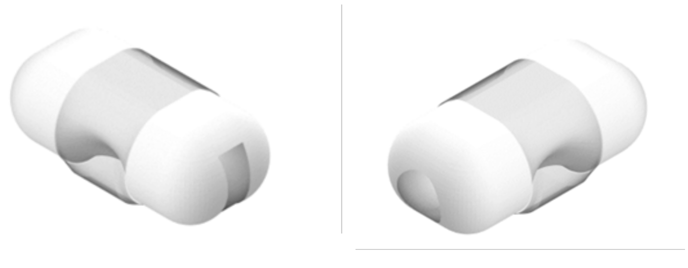

Fig. 2. The shell obtained from a parametric model.

3.5 Structural analysis and design optimization

The design of the pressurized shell has been based on numerical analyses performed by Karamba3D. To achieve this, the computational procedure has included the following steps:

1. modelling of the shell structure, which has also required the integration of the cockpit opening and the airlock opening. The Rhinoceros® [8] native NURBS [9] geometry has been then transformed into a mesh of variable density to be compatible with the Karamba3D environment.
2. setting up of the structural model. This step has included the definition of design loads and load combinations, as well as the constraints representing the connections with the rocker-bogie structure; also, the cross sections for both the structural panels and the supporting light beams have been defined. The applied loads include: gravity loads, the operation pressurization load of 1 atm, and additional loads corresponding to the weight of the permanent elements of the structure, in particular the shielding elements and the batteries. For beams, hollow square cross sections with a 10cm side and a thickness of 1.2cm have been adopted, whereas the shell sections, being the object of optimization, are variable. Both structural elements have been applied the same Al-Li alloy as previously described.
3. lastly, the static analysis of the model, including shell and beam elements, has been conducted. Typical results consist in the graphical representation of stress distributions and displacements. Fig. 3 shows displacements occurring on the structure, from which it can be noticed that maximum values occur by the cockpit opening. In relation to this, it has to be mentioned that in this model the collaborative effect of the borosilicate glass window was not accounted for. It has also to be considered that high displacement values are present in the upper central area of the shell, in the vicinity of the supports. Looking at Fig. 4, the spherical structures show uneven distribution of section utilization at both ends, with a reduced value for the spherical elements. Overall, the displacement and section utilization diagrams show a comparable behavior.

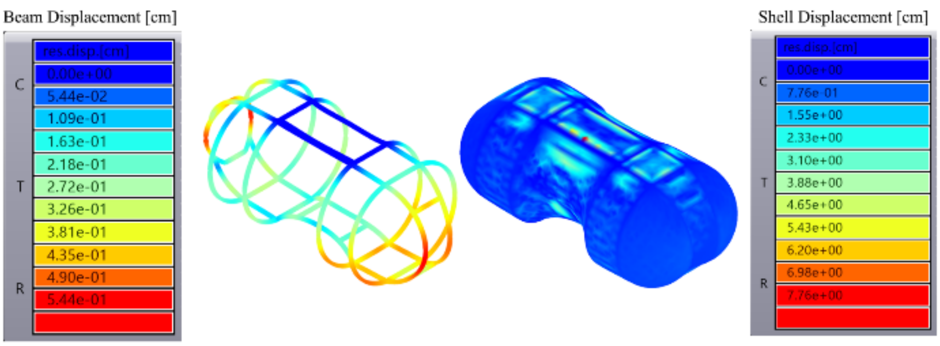

Fig. 3. Displacement levels for both the beams and the shell structure.

3.6 Final design choices

The structural analysis of the pressurized shell has revealed the necessity to modify the element cross sections to obtain a more regular response of the structural system to the applied loads.
In particular, two actions have been undertaken to the purpose of improving the structural performance: first, additional segments of supporting light beams have been introduced in highly stressed areas; then the shell portions subject to maximum displacements and with the highest section utilization have been modified increasing the shell thickness by a factor of two, going from the initial value of 1.25 cm to a double layer panel of 2.50 cm.

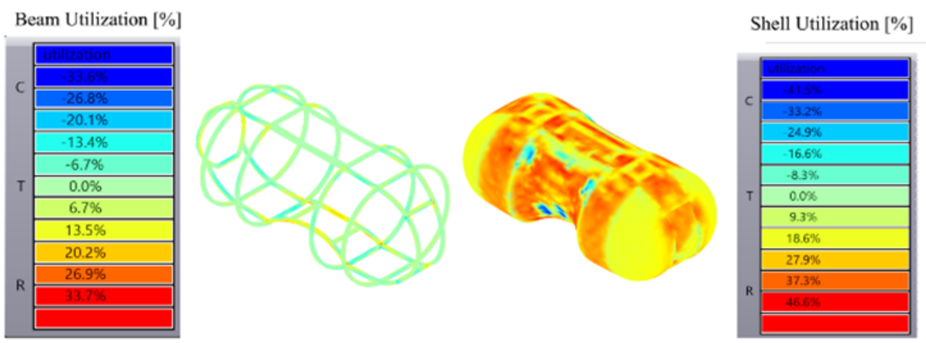

Fig. 4. Section Utilization on the beam and shell structure

4 Conclusions

This paper presents a study on a mobile space architecture system designed to enable human presence on the Moon for medium to long-term missions. The LADE research began by identifying the needs and requirements of the mobile habitat and its subsystems through a holistic approach. The objectives include ensuring robust structural support, efficient mobility and speed for lunar surface travel, self-sufficiency in energy under various conditions, hazard shielding, and landing site analysis [10].

Two key concepts served as references for developing a unique solution. The "wagon train" concept involves the primary mobile module leading the way in navigation, followed by secondary modules guided by computer vision. The biophilic approach draws inspiration from the body of bees, with the head module housing navigation and communication systems, the thorax module encompassing life-sustaining functions, energy, and locomotion systems, and the abdomen representing the specific function of the secondary module selected for each mission.

In this paper a focus on some structural aspects is presented since the research aimed to identify cutting-edge materials for the module's design and utilized computational analysis through tools like Grasshopper© and Karamba3D® software to ensure a safe and structurally efficient solution.

LADE, in its entirety, goes beyond being a mere design endeavor for an innovative surface exploration and habitability solution. It strives to establish a firm foundation upon which a new era of enduring Lunar exploration can be built.

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