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Conceptual Structural Design of a Pressurized Inflatable and Deployable Habitat Optimized for Lunar Surface Missions

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Abstract. Inflatable and deployable structures are increasingly recognized as a promising solution for long-duration missions on the Moon and beyond. This study addresses the conceptual design and preliminary assessment of a pressurized habitat intended for lunar surface deployment. Three geometric configurations have been evaluated in terms of mass efficiency, stress distribution, and habitability. The fabric restraint shell, made of aluminized Kapton Kevlar (AKK) and sized with a safety factor of four, was combined with a carbon-fiber-reinforced floor designed to support astronaut loads and internal equipment. The cylindrical configuration proved the most suitable option due to its reduced structural mass, modularity, and ease of deployment. A finite element model was developed to investigate static pressurization and thermal loads, confirming structural adequacy with acceptable stress and displacement levels. A digital habitability analysis using anthropometric mannequins further validated the spatial configuration. Finally, a dynamic inflation analysis with LS-DYNA has been done to capture the stress-strain evolution.

Introduction

In recent years, the colonization of celestial bodies has evolved from a distant goal to a tangible objective. The Moon, as a stepping stone toward Mars, serves as a testbed for life-support technologies and infrastructure. Inflatable and deployable habitats have already proven feasible and reliable in orbit: NASA's TransHab concept, Genesis I and II, and the Bigelow Expandable Activity Module (BEAM) on the ISS [1].

Unlike orbital environments, surface habitats must withstand extreme thermal cycles (from –233°C up to +127°C on the moon), leading to thermally induced stresses. Additional challenges include radiation from galactic cosmic rays and solar flares, and the abrasive, contaminant nature of lunar regolith. The low-density atmosphere requires full pressurization, while lunar gravity (17% of Earth's) influences both structure and human physiology. This study presents the conceptual design and structural assessment of a pressurized, inflatable, and deployable lunar habitat. The design emphasizes the membrane maintaining internal pressure of the restraint layer, sized with a safety factor of four, in compliance with NASA habitability standards NASA-STD: 3000 [2] and 3001 [3].

Geometric Conceptual Design

Three continuous-curvature geometries were selected to ensure uniform stress distribution under internal pressurization, reducing local stress concentrations that may cause fatigue or collapse [4]. The analyzed configurations are: (i) hollow torus, (ii) hollow hemisphere, and (iii) hollow cylinder [1]. For the toroidal and cylindrical cases, a reference internal radius of 1.6 meters was adopted, consistent with existing designs such as HALO (Habitation and Logistics Outpost) [5] and CYGNUS [6].

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A MATLAB code was developed to dynamically link the internal habitable volume (V_{int}) with the geometric parameters of each configuration. The user specifies the habitable volume and the fabric thickness (t); the algorithm then computes the corresponding structural dimensions, ensuring that the required internal volume is maintained.

An analysis was conducted to optimize the floor placement for circular-section habitats such as the cylinder and the torus. The optimization cost parameter (η), shown in Eq. 1, represents a trade-off between the habitable volume and the storage capacity beneath the floor.

$$\eta = \frac{V_{stow}}{V_{int}} \times 100\ (\%). \tag{1}$$

Based on a reference internal diameter of 3.2 meters, the floor position in circular-cross-section habitat varied to maximize habitability, minimize structural clutter, and consequently reduce mass. The optimal floor height was found at approximately 21% of the internal diameter, providing a balanced configuration in terms of usable space and stowage efficiency. Defining the habitable volume as the space above the floor, the cylindrical habitat was chosen for detailed analysis among the three configurations due to its lower mass, modular design, and ease of deployment.

Stiffened Cylinder Sizing

The structural complexity of pressurized extraterrestrial inflatable habitats required resilience against a broad range of loads, primarily including pressurization, thermal, radiation loads, and micrometeoroid impact [1]. The restraint layer sizing focuses on pressurization and thermal loads. In adherence to NASA-STD-3001 [3], a pressurized lunar habitat must maintain an internal condition of 101325 Pa and 20°C and therefore be capable of sustaining a pressure differential (Δp) of 101325 Pa and a thermal differential (ΔT) of approximately 200°C with the external lunar environment. A safety factor (c) of four is applied.

The flexible shell material selected is aluminized Kapton-Kevlar (AKK), which has a yield stress (σ_y) of 3000 MPa and a Poisson's ratio (ν) of 0.36. The combined stress condition for a thin-walled shell under pressure (σ_p) and thermal (σ_T) loading is expressed as follows:

$$\frac{\Delta p \cdot r}{t} + \frac{E \cdot \alpha \cdot \Delta T}{1-\nu} \leq \frac{\sigma_y}{c} \tag{2}$$

From Eq. 2, a wall thickness of 0.8 mm is selected. The reinforced cylindrical shell has two open ends: one interfaces with a docking system connected to a main structure (rover, base, or launcher), while the opposite end can connect modularly to other habitats or terminate with an endcap. According to Niu [7], three endcap types are possible: flat, hemispherical ($\varphi = 90^{\circ}$), and semi-spherical ($\varphi < 90^{\circ}$).

The flat configuration causes stress concentrations, whereas curved geometries ensure smoother load transfer. Owing to deployability, the hemispherical endcap with tangential continuity to the cylindrical body offers the most efficient stress distribution and compact stowage. The total external restraint layer mass of the cylinder connected to the endcap is 107 kg. The floor placement analysis identified an optimal position at 21% of the habitat diameter, providing a 2.5 m width, an efficiency factor (η) of 17%, and a maximum habitable height of 2.56 m. For a two-astronaut pressurized habitat, an internal volume (V_{int}) of 50 m^3 was imposed, yielding to 7 m in length.
The floor was sized for two occupants from the 95th percentile of the ANSUR database: a 101 kg male and a 79 kg female; with an additional 1400 kg representing equipment and furnishings. The load was modeled as uniformly distributed over a 2.5 m × 7 m area. A carbon fiber/epoxy prepreg (T700/epoxy) was selected for its foldability under both equal or opposite-sense methodologies [8].

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The sizing resulted in a 3.6 mm laminate of 12 plies (0.3 mm each) with stacking sequence $[0/90/0/90/0/90]_s$ and a total mass of 103 kg. Eight circular supports for membrane deployment and eight supports for the floor yielded a preliminary total habitat mass of 219 kg.

Habitability Analysis

The CAD model of the pressurized, inflatable, and deployable habitat in its fully deployed configuration was created in CATIA and subsequently imported into Siemens NX to perform a preliminary habitability assessment.

Two digital human mannequins were positioned within the habitat, both representing the 95th percentile of the ANSUR anthropometric database: a male subject weighing 101 kg and standing 187 cm tall, and a female subject weighing 79 kg and standing 174 cm tall.

The mannequins were placed in a virtual environment populated with volumetric placeholders simulating operational equipment and material usage.

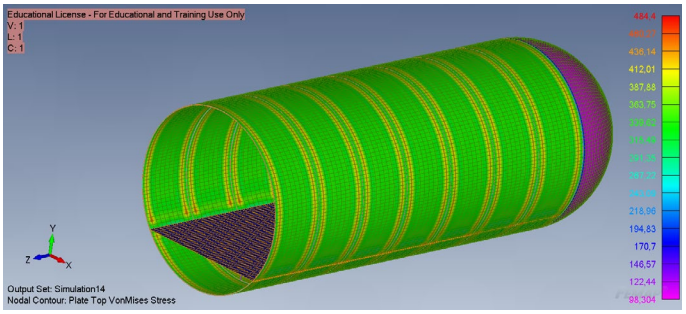


Figure 1: Isometric rendering of the fully deployed pressurized inflatable habitat, showing two digital mannequins and operational equipment placeholders.

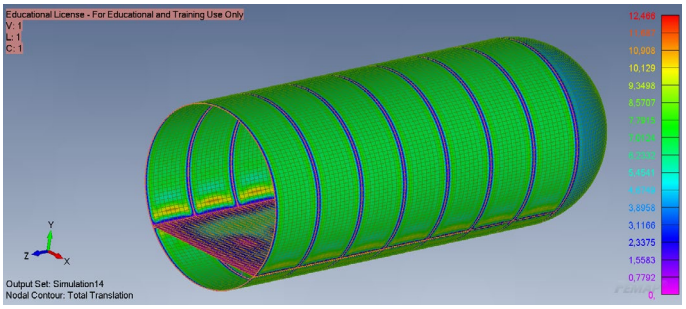
As shown in Fig. 1, the analysis indicates that the dimensions of the habitat are found to be suitable for the designated purpose, thereby confirming that the internal spatial configuration is adequate to meet the requisite habitability criteria.

Static Analysis

Based on the geometric information obtained from the conceptual design and sizing phases, a finite element model (FEM) of the habitat was developed in FEMAP. The model includes plate elements for the cylindrical membrane and the hemispherical endcap, beam elements of various sizes and shapes for the telescopic linear guides and supports, and laminated plate elements for the floor. Thermal loads of 200 °C and a pressure load of 0.101325 MPa were applied to the membrane, while a pressure load of 0.0013 MPa was applied to the floor.



(a) Plate Von Mises stress



(b) Total displacement

Figure 2: Results of the preliminary static analysis for the fully deployed pressurized inflatable habitat: (a) Von Mises stress distribution on plate elements and (b) total displacement field.

The resulting stress analysis indicates a pressure accumulation at the cylinder-endcap interface corresponding to 22.62% of the AKK yield strength (σ_y) when evaluated using elemental contour data.

For the nodal contour representation, shown in Fig. 2a, the corresponding value is 16.14%. Stress concentrations are primarily observed near the circular and linear stiffeners, while the membrane region exhibits a nearly uniform distribution with lower values on the hemispherical endcap, confirming the effectiveness of its geometry.

The maximum displacement is 12.466 mm on the flexible cylindrical membrane mainly occurring between the circular frames and near the linear stiffener and 9.345 mm on the stiffened floor. The observed stress and displacement increments are not sufficient to warrant additional stiffening, and in real configurations they are expected to be further reduced due to the non-perfectly rigid interaction between the structural frames and the membrane.

Conclusion

This study presented the conceptual design and preliminary structural and habitability assessment of a pressurized, inflatable, and deployable lunar habitat. Among the configurations analyzed, the cylindrical geometry proved most efficient in terms of mass, modularity, and stress distribution. Finite element simulations confirmed the structural adequacy of the membrane and floor under combined pressurization and thermal loads. The habitability evaluation validated the internal configuration for a two-astronaut crew. Future work will focus on dynamic simulations using LS-DYNA, experimental tensile testing of fabric materials to derive stress-strain curves to insert in numerical solvers, and experimental validation on scaled prototypes.

References

[1] Caiazzo, Alfonso, et al." Structures for Extraterrestrial Habitat: A Review". Acta Astronautica Vol. 238, pp. 471-493, 2026. ISSN: 0094-5765. https://doi.org/10.1016/j.actaastro.2025.10.029

[2] Connolly, J. H. and Arch, M., 2005, "NASA Standard 3000 Human Systems Integration Standards (HSIS) Update," Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Vol. 49, SAGE Publications Sage CA: Los Angeles, CA, Paper No. 23, pp. 2018-2022. https://doi.org/10.1177/154193120504902304

[3] Whitmore, M., Boyer, J., and Holubec, K., 2012, "NASA-STD-3001, spaceflight human system standard and the human integration design handbook," Industrial and systems engineering research conference, 19-23 May 2012, Paper No. JSC-CN-25695.

[4] Naser, M. Z., Redmond, L., Chen, Q., and Rangaraju, P. "Habitats for Space Exploration: Construction Materials, Design Concepts, and Future Directions." In The Planning and

Execution of Human Missions to the Moon and Mars, Chapter 8, pp. 229-266, AIAA, 2023. https://doi.org/10.2514/5.9781624106545.0229.0266

[5] Smith, Marshall, et al." The Artemis program: An overview of NASA's activities to return humans to the moon." IEEE Aerospace Conference, 7-14 March 2020. IEEE, 2020. https://doi.org/10.1109/AERO47225.2020.9172323

[6] Davis, Chad L., and Ken Peek." Feasibility study for using Cygnus as a habitat in deep space exploration." AIAA SPACE, 13-16 September 2016, Long Beach, California. eISBN: 978-1-62410-427-5.

[7] Niu, M. C. Y. "Airframe Stress Analysis and Sizing." Adaso/Adastra Engineering Center (2011): ISBN 978-9627128083.

[8] Liu, Tian-Wei, et al." Folding behavior of thin-walled tubular deployable composite boom for space applications: Experiments and numerical simulation." Acta Astronautica, 209, (2023): 159-171. https://doi.org/10.1016/j.actaastro.2023.05.010