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ON STRUCTURAL DESIGN OF A MOBILE LUNAR HABITAT WITH MULTI-LAYERED ENVIRONMENTAL SHIELDING

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Introduction

The future human lunar missions are expected to undertake far more ambitious activities than those of the Apollo program with the possibility of some missions lasting up to several months. Such extended missions require the use of large-size lunar outposts to accommodate living quarters for the astronauts as well as indoor laboratory facilities.

The greatest obstacle to the prolonged human presence on the Moon is the threat posed by the harsh lunar environment that is plagued with multi-source high-energy radiation exposure as well as frequent barrage of meteoroids. Hence, for such extended missions to succeed, it is vital that the future lunar outposts be designed to provide a safe habitat for the astronauts.

Over the past few years, a variety of ideas and concepts for future lunar outposts and bases have been proposed. With shielding as the primary concern, some have suggested the use of natural structures such as lava tubes while others have taken a more industrial approach and suggested the construction of fixed structures in the form of inflatable, inflatable with rigid elements, and tent-style membrane. For evaluation of these structural design concepts, Drake and Richter[1] have proposed a rating system based on such factors as effectiveness, importance, and timing. While all of these designs, in general, benefit from in-situ resource utilization (i.e., lunar regolith) for shielding, they share a common disadvantage of being fixed to one particular location that would limit exploration to the region in close proximity of the outpost.

As an alternative to the fixed-base concepts, some have suggested mobile lunar outposts (reminiscing of recreational vehicles). While providing a self-contained habitat, such mobile units can offer the future lunar explorers and workers the freedom to travel from one location to another, and to enhance the exploration and scientific activities on the Moon. At the forefront of such concepts is the notional architecture of HARMONY (Human And Robotic MOdular iNfrastructures/sYstems) proposed by Mankins.[2] As part of his HARMONY architecture, Mankins suggests the use of Modular Integrated Lunar Outpost (MILO) with each module representing a blend of habitat and robotics design referred to as a “Hab-Bot”. The idea is to launch these Hab-Bots, ahead of astronauts, to a desired spot on the Moon. Operating in the autonomous or remotely operated control mode, these modules will link up together to form a larger integrated outpost. As a mission comes to an end and the crew has departed, these modules will walk to another location and establish a new outpost prior to the arrival of the next group of astronauts and space workers.

While mobility and integration of multiple units are the main advantages of the Hab-Bot design, the greatest drawback to this and all other proposed concepts is the need for the habitat wall to provide the necessary environmental shielding. This requirement poses a serious challenge to the design of the structure, and demands the use of innovative solutions.

As part of this research, a Hab-Bot inspired concept for a Mobile Lunar Habitat (MLH) is proposed, which makes use of advanced composite materials to reduce the habitat’s mass and to seek a viable solution to the shielding problem. A modular design is presented for environmental shielding. In addition, a finite-element model of MLH design is developed and analyzed under an operational loading condition.

Environmental Considerations

Radiation Shielding

Unlike the Earth's surface that is protected by a relatively dense atmosphere and the geomagnetic field, the lunar surface is completely deprived of any natural shielding against harmful space radiation. The ambient radiation environment of the lunar surface consists of energetic ionized particles of solar and galactic origins.[3]

The Solar Energetic Particles (SEP) are released from the Sun through sporadic flare events, which are correlated with the periods of increased solar activity. They mostly consist of hydrogen and helium ions (protons and alpha particles) with a much smaller, but biologically more damaging, heavy-ion component (atomic number, $Z > 2$) that can vary from one event to another.

The most energetic form of radiation in free-space as well as on the lunar surface is that associated with the nearly constant Galactic Cosmic Rays (GCR). Reaching energies of 10 GeV, GCR particles travel at nearly the speed of light through the very thin gas of interstellar space. By some estimates, the GCR spectrum consists of approximately 90% hydrogen, 9% helium, and 1% heavier nuclei such as iron (Fe, $Z = 26$) and nickel (Ni, $Z = 28$).[4]

Without any shielding, an astronaut in free space would receive a blood-forming-organ (BFO) dose-equivalent of 0.6 Sv/yr from GCR at solar minimum conditions. This amount is greater than NCRP's limit of 0.5 Sv/yr.[5] For a large solar flare event such as that of August 1972, the free-space BFO dose is estimated at 4.11 Sv (in a span of few days) as compared to NCRP's limit of 0.25 Sv for a 30-day exposure.

Because of its smallest atomic weight and lack of neutrons in its nucleus, liquid hydrogen is considered as the best radiation shielding material. However, hydrogen-rich polyethylene has been studied as a more practical shielding material, and that is the material considered for shielding the MLH against harmful radiation at a linear thickness of approximately 10 cm.

Meteoroid Impact Shielding

The meteoroid environment near earth and the Moon consists mainly of ice particles of cometary sources. Meteoroids are classified into periodic streams (nearly identical orbits to the source comet) and sporadic (random orbits). The sporadic meteoroids can hit the lunar surface from different trajectories relative to the ecliptic plane. In the interplanetary space, the meteoroids travel at speeds between 11.1 to 72.2 km/s.[6] With the average mass density of 0.5 g/cm^3 and mean speed of approximately 30 km/s, meteoroids and micrometeoroids pose a serious threat to the MLH and the crew working on the lunar surface. At such high velocities, meteoroids can easily penetrate the habitat's wall if it is not adequately designed. Hence, shielding against meteoroid impacts is a major design requirement.

Ground-based projectile testing facilities have been able to shoot meteoroid-size projectiles at speeds reaching no higher than 11 km/s. Therefore, there is significant uncertainty about shield performance at impact speeds beyond 11 km/s, as the shield performance predictions obtained from various hydrodynamic codes cannot be experimentally verified.

More advanced meteoroid shielding designs incorporate a double or multiple-wall configuration.[7] Once a meteoroid crashes into the front wall, it will melt and vaporize. If the front wall is penetrated, then a cloud of hot gas and debris from the front wall is generated. The objective of the rear wall is to stop this high-energy debris cloud from damaging or penetrating the pressure wall of the habitat.

Previous research involving hypervelocity impact testing of composite shielding shows that neither the number of plies in the laminate nor the impact angle has any significant influence on the diameter of the entry crater in the front wall. However, the Nextel layer is shown to be very effective in stopping the debris fragments coming from the front wall, and that its effectiveness increases as it is moved farther behind the front shield.[8]

In design of MLH, a modular meteoroid-impact-shielding (MIS) configuration is used; its front wall is made of Kevlar-reinforced polymer-matrix composite, and its rear wall—at approximately 10 cm away—is made of two tightly woven blankets of Nextel (primary layer) and Kevlar that are stitched together to enhance the rear wall's penetration resistance. The MIS is covered on the inside by multi-layer insulation. A more detailed computational analysis is necessary to determine the exact thickness of individual MIS layers as well as the wall spacing.

Conceptual Design of MLH

The proposed design for MLH, as shown in Fig. 1 (b), is derived from the ISS US Lab module with a diameter (pressure vessel only) of 4.22 m (166 in) and length of 8.66 m (341 in). For greater mobility over the lunar terrain, MLH is equipped with six independently controlled mechanical legs. The overall size of MLH is constrained by the interior dimensions and clearances of the single-manifest payload fairing of the Delta IV family of rockets. One of many possible options for an expanded lunar outpost is shown in Fig. 1(a). A closer view of the modular MIS design is shown in Fig. 1(c).

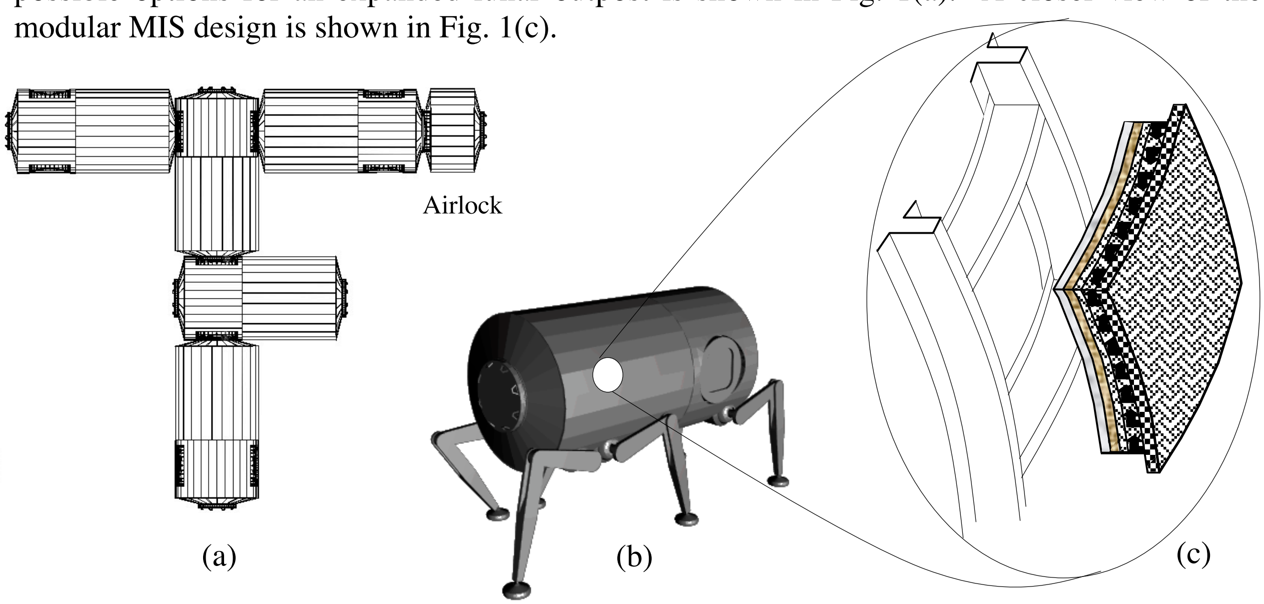

Figure 1: (a) Multi-unit lunar outpost, (b) MLH module, (c) MIS panel

Finite-Element Structural Analysis

Space structures encounter severe vibration and dynamic loads during launch and the initial flight phase. In most instances, these transient mechanical loads are more critical than the operational loads. However, in the absence of launch-specific loads data at this time, the internal pressure of 14.7 psi, as a representative operational loading condition, was used for the preliminary structural analysis.

The FE model, as shown in Fig. 2, was obtained by modifying a previously developed model of ISS US-Lab module. The major modification task involved the extension of its length and addition of two lateral ports. The design geometry of the lateral ports was taken from the ISS Node 1 model. The new model has a diameter of 4.5 m and a length of 9.3 m.

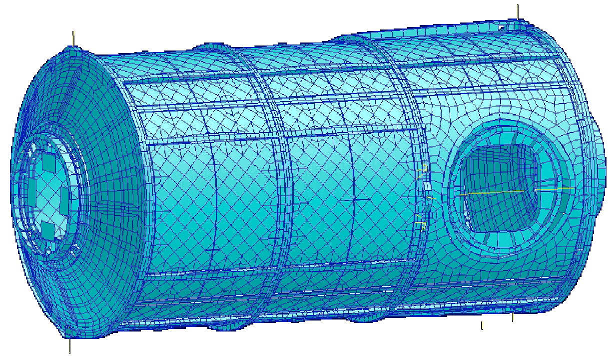

Figure 2: FE model of the MLH structure.

As a baseline design, the model (without the lateral ports) was analyzed for strain energy using 2024-T3 aluminum properties and the specified loading condition. The material in the cylinder portion of the habitat was then changed to AS4-3502 carbon-epoxy with quasi-isotropic properties, and the wall thickness was adjusted until the strain energy nearly matched (< 1% diff.) that of the baseline design. Having nearly the same structural stiffness, the hybrid model was found to weigh 16,435 lb, 2.4% lighter than its aluminum counterpart.

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