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Enhancing Lunar Habitat Construction: An Experimental Evaluation of Thermal Performance and Durability of FBG Sensor-Embedded Lunar Bricks

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Abstract

More than five decades have elapsed since Apollo 17 astronauts last set foot on the lunar surface, underscoring the enduring significance of space exploration for our technological and scientific advancement. National and international space agencies have prioritized lunar colonization and the establishment of a sustainable lunar economy as critical objectives. The utilization of local resources is recognized as a crucial strategy for reducing reliance on Earth. As such, the construction of future lunar bases will necessitate materials that are sourced and processed on the Moon. Additionally, the maintenance of surface outposts will demand the fabrication of spare parts, everyday tools, and safety-critical components from local materials. The harsh lunar environment poses unique challenges and objectives, necessitating innovative design methodologies and the implementation of effective monitoring systems.

The increasing interest in lunar habitation underscores the importance of developing intelligent construction materials that leverage local resources while reducing the dependency on imported binders. In this framework, efforts were made to develop a composite material, maximizing the weight percentage of lunar regolith and prioritizing a simple and low energy demanding manufacturing process. After having demonstrated the mechanical performances of standardized structural elements (bricks) produced with this approach, we moved to integrate Fiber Bragg Grating (FBG) sensors inside them to evaluate their thermal characteristics and structural integrity in an environment that closely simulates lunar conditions. This research focuses on the thermal performance of the bricks. The experimental framework subjected these sensor-integrated bricks to severe temperature variations and vacuum conditions. The results demonstrate that the embedded FBG sensors deliver precise and reliable data, highlighting their suitability for continuously monitoring and evaluating lunar habitat structures. This investigation confirms the practicality of incorporating FBG sensors into lunar building materials and emphasizes the advantages of smart components for the efficient use of in situ resources. The results pave the way for the development of advanced, autonomous construction elements, marking a significant step toward creating more sustainable and robust habitats beyond Earth

Keywords: Human spaceflight, Moon, Lunar exploration, regolith, ISRU, FBG

Acronyms/Abbreviations

Compressed Earth Block (CEB)
Deutsches Zentrum für Luft- und Raumfahrt - German Aerospace Center (DLR)
European Astronaut Centre (EAC)
European Large Logistic Lander (EL3)
European Space Agency (ESA)
Fiber Bragg Grating (FBG)
In Situ Resource Utilization (ISRU)
Lunar Regolith Brick (LRB)
Negative Poisson Ratio (NPR)
Technology Readiness Level (TRL)

1. Introduction

The resurgence of interest in lunar exploration has spurred the development of increasingly sophisticated mission scenarios, focusing on establishing long-term, self-sustaining bases on the Moon[1], [2], [3], [4], [5]. One of the key challenges in this endeavour is the utilization of local resources, particularly lunar regolith, to construct essential infrastructure. In this context, In-Situ Resource Utilization has emerged as a crucial area of research [6], [7], [8]. The harsh lunar environment, characterized by extreme thermal variations, demands innovative, smart structural solutions capable of monitoring their operational health and ensuring mission safety.

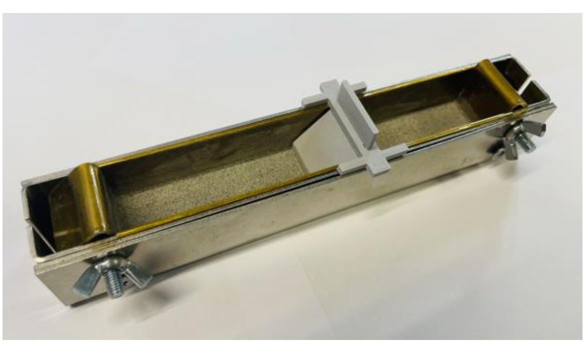
This paper investigates the integration of Fiber Bragg Grating optical sensors into lunar regolith-based sintered bricks to monitor internal temperature. FBG sensors, known for their precision in harsh environments and immunity to electromagnetic interference, offer an ideal solution for non-invasive, real-time remote monitoring of thermal and mechanical properties[9], [10], [11], [12], [13]. The study presents the experimental evaluation of the direct embedding of these sensors in regolith simulant bricks during the sintering process. The final goal, therefore, is to sensorize a well defined geometry of a regolith-made tile for in situ buildings development.

This research is a collaborative effort between Politecnico di Torino, the European Space Agency's European Astronaut Centre, and the German Aerospace Center (DLR) combining expertise in optical sensor technology and regolith-based construction materials[14].

The following sections outline the fabrication of the sensorized specimens – starting from a baseline brick geometry and moving to a specifc tile's development – the experimental setup, and the key findings of the testing campaign.

2. Low binder content smart brick manufacturing

The manufacturing process of lunar regolith bricks combines lunar regolith simulant with Polyether ether ketone (PEEK) as a thermoplastic binder. The process begins with a drying phase, where the regolith is heated at 250°C for two hours, and the PEEK at 50°C for twelve hours, to eliminate moisture and ensure consistent material properties. Following the drying step, the materials are sieved to achieve a uniform grain size distribution, which is critical for the mechanical performance of the final product. The regolith and PEEK powders are then manually blended to form a homogeneous mixture, which is placed into a pre-treated mold designed to contain the guided passage for the insertion and position-securing of an optical fiber during the sinterization. The mixture is compacted using a toggle press at 2 kN to enhance its density and structural integrity. The mold, with the embedded Fiber Bragg Grating sensor, is then heated at 220°C for 20 minutes, melting the PEEK to encapsulate the regolith particles and optical fiber. After cooling under standard atmospheric conditions, the solidified composite material forms a cohesive structure. Figure 1 report manufacturing mold, optical fiber integration and a flexural specimen with embedded sensor.



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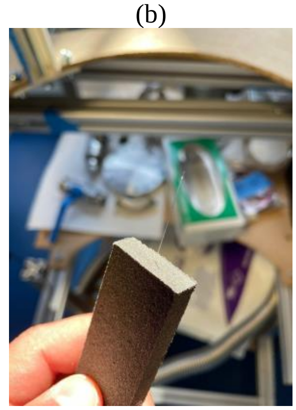

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Figure 1 Manufacturing of Regolith: a) Molding process, b) optical fiber embedded in sintered regolith, c) specimen with optical fiber

2.1 Tile Test Case

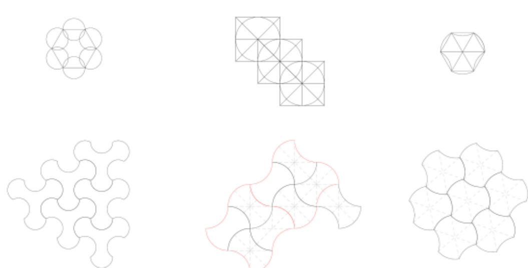
The rationale behind selecting a tile as a test case lies in the importance of a prepared landing pad for the efficient functioning of a lunar outpost over time. While the Apollo landers were designed to land on unprepared regolith, future missions will likely require prepared landing pads to ensure repeatable safe and precise operations, especially as the landing weight is expected to progressively increase with the size of the outpost.

Another driver for the selection of this component lies in its critical nature, due to the fact that it must sustain launching load and touchdown while ensuring structural stability and preventing bending of the lander vehicle or detachment of debris.

It is indeed intended that a key challenge in lunar construction is the minimization of reliance on Earth-sourced materials, exploiting the ISRU design philosophy as much as possible. The tile-based design offered a practical solution, providing a modular and easily repairable surface capable of supporting spacecraft landings while allowing for efficient on-site production. Furthermore, the use of hexagonal tiles was chosen for their geometric efficiency and ability to interlock, ensuring structural integrity under varying loads. Figure 2a report the different shapes selected and tested while Figure 2b and c depicts the interlocking of tiles and the first prototype realized.

Integrating FBG sensors into the tile design offers significant advantages for real-time structural monitoring and long-term maintenance. These sensors enable the continuous tracking of critical parameters, such as strain and temperature, throughout the tile's lifecycle. This sensorization allows for the detection of defects also during production, ensuring quality control and reducing the likelihood of undetected flaws.

Once deployed, the FBG sensors can monitor damage from hard landings, launching, or micrometeorite impacts, as well as degradation due to the Moon's extreme thermal and radiation conditions. By providing continuous data on the structural health of the landing pad, these sensors enable proactive maintenance, ensuring that damaged tiles can be identified and replaced before compromising the overall integrity of the pad. This capability greatly enhances the resilience and longevity of the lunar infrastructure, ensuring safe and reliable operations under harsh conditions.



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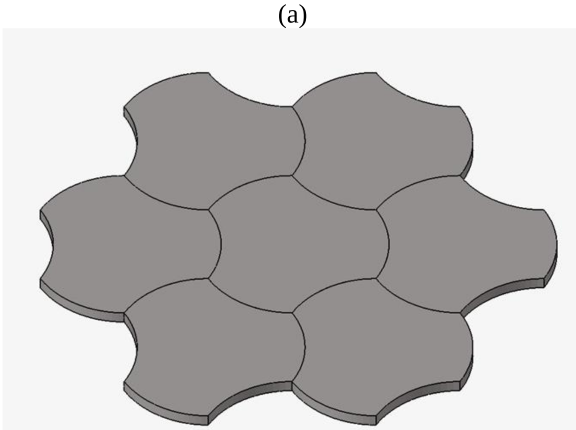

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Figure 2 Tile test Case: a) shape selection, b) interlocking tiles, c) prototype of tile

The tile's hexagonal geometry was purposefully selected to maximize packing efficiency and structural interlocking. This enhanced the load distribution during a landing event and mitigated stress concentrations that could otherwise lead to material failure. This design approach also reduced the need for multiple mold shapes, simplifying the production process. Additionally, critical features such as rounded edges and smooth transitions were incorporated to prevent stress intensification and address the brittle behaviour observed in the material during flexural testing. Finite element simulations validated the tile's ability to withstand the forces generated by the European Large Logistic Lander, with performance dependent on binder content and compaction pressure. Furthermore, the modular design allows for easy repair and redundancy through tile stacking, further increasing the pad's reliability under operational conditions. This methodical approach ensured the tile's suitability for lunar deployment while adhering to the project's stringent ISRU, structural monitoring, and material efficiency goals.

3. Thermal Performance Evaluation

In order to evaluate performance and limits of this component subjected to temperature measuring a simplified test procedure has been developed.

The experimental setup consisted of testing three regolith specimens equipped with three different fiber Bragg grating sensors, each characterized by distinct nominal wavelengths of 1545 nm, 1537 nm, and 1546 nm, respectively. The FBG sensors were labelled according to their corresponding channels on the interrogator, with channel numbers added as subscripts in the labelling to facilitate identification.

The primary goal of the experiment was to establish a thermal calibration curve, λ, for each sensor, using data collected during a series of controlled thermal cycles. These cycles were performed within a climate chamber, spanning a temperature range from -40°C to -10°C with 10°C increments per step and a 30-minute stabilization period for each temperature plateau. The data obtained have been filtered to retain only periods of stable chamber temperatures, ensuring an absolute temperature error of less than 0.2°C. For each stationary temperature step, the mean values of both temperature and reflected wavelength were calculated for each sensor, and the corresponding error was computed.

The climate chamber was programmed to execute 11 series of thermal cycles aimed at calibrating the sensor's response under controlled temperature variations.

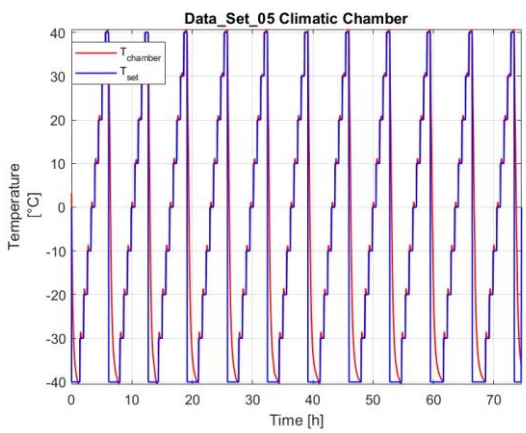


Figure 3 Thermal cycles applied

Although the thermal cycles spanned a temperature range of -40°C to +40°C, representing a shorter range compared to what is typically expected around the lunar outpost location, this compromise was due to the technical limitations of the climatic chamber. The primary objective of this preliminary test, however, was to assess the assembled fiber Bragg grating sensor's ability to endure an 80°C temperature excursion without compromising data integrity. Future testing will involve representative lunar conditions, including exposure to the actual temperature variations expected at the outpost and vacuum environments, ensuring sensor's long-term viability for deployment in the harsh lunar conditions.

The experimental calibration curve, representing the relationship between wavelength and temperature, was obtained by plotting the average reflected wavelength against temperature for each sensor. The resulting data were fitted using linear interpolation, which accounted for measurement uncertainties. The thermal sensitivity coefficients were then derived, leading to the formulation of the calibration equation (1), which was compared to the experimental curve over the temperature range.

$$\lambda = K_t T + \lambda_0 \quad (1)$$

To further validate the calibration, a comparative analysis was conducted by comparing the temperatures estimated using the FBG sensor data with the reference temperatures provided by the climate chamber. The results of this comparison were graphically represented to evaluate the accuracy of the FBGs in tracking the temperature variations.

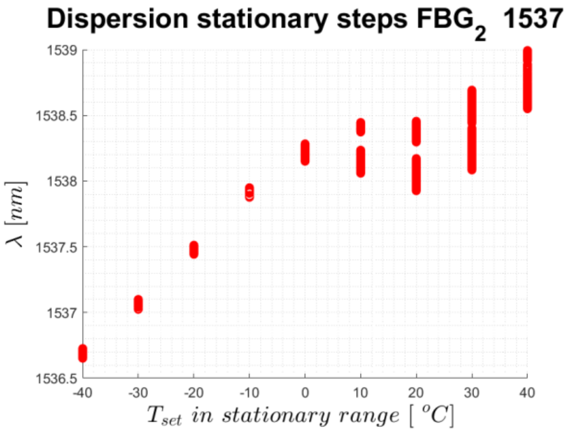
To ensure the repeatability of the experimental procedure, the researchers analysed the dispersion of the reflected wavelengths for each sensor. All data processing, including calibration curve fitting and validation, was conducted using MATLAB.

4. Results

The results obtained from the 11 cycles in the climatic chamber using the three specimens embedded with Fiber Bragg Grating (FBG) sensors reveal an overall stable performance, with some initial deviations. Specifically, in the first two cycles, dispersion was observed at temperatures below 0°C, likely due to the elimination of residual humidity within the specimens. Once the humidity was fully expelled, the FBG sensors exhibited a significantly reduced dispersion rate, regardless of the Bragg wavelength.

However, at elevated temperatures, a marked increase in dispersion was observed, as depicted in Figure 4, along with a noticeable shift in the central wavelength. This shift can be attributed to the thermal mismatch between the optical fiber and the regolith, leading to partial disconnection due to their differing coefficients of thermal expansion. To mitigate this effect, it has been suggested that the selection of an appropriate coating material, one that undergoes sintering at a temperature compatible with the specimen, could provide a robust connection between the optical fiber and the brick, thus minimizing dispersion and enhancing sensor reliability. The subsequent analysis on the variance, whose results are reported in Figure 5 confirm that while the statistical validity remain positive and constant up to 0°C afterwards it explodes with a quadratic trend, showing an unsuitability of the temperature instrument sensor in that range.

The increased dispersion observed at temperatures exceeding 0°C significantly impacts the calibration slope, as shown in Figure 6, rendering the Fiber Bragg Grating (FBG) sensor's predictions unr.eliable due to the partial disconnection between the optical fiber and the regolith.



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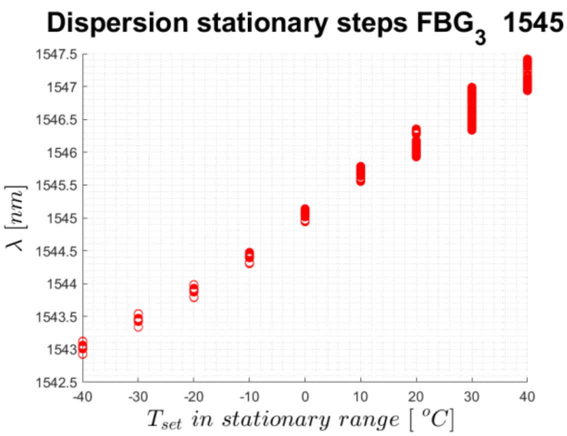

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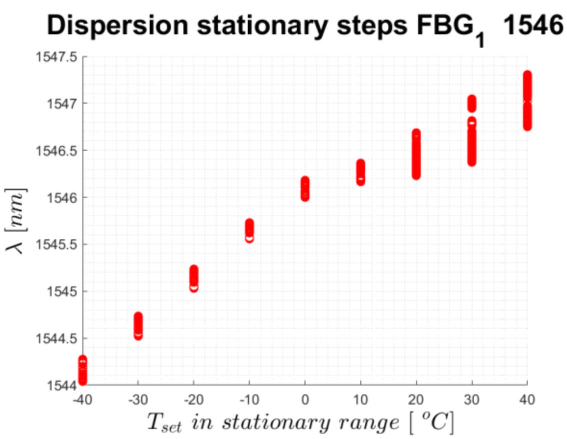

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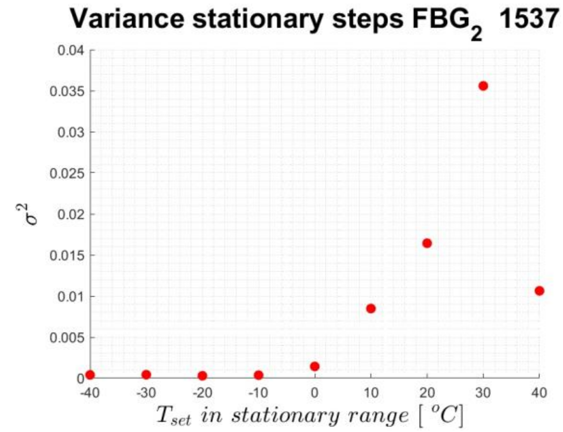
Figure 4 Dispersion vs Temperature: a) 1537 nm, b) 1545nm, c) 1546 nm



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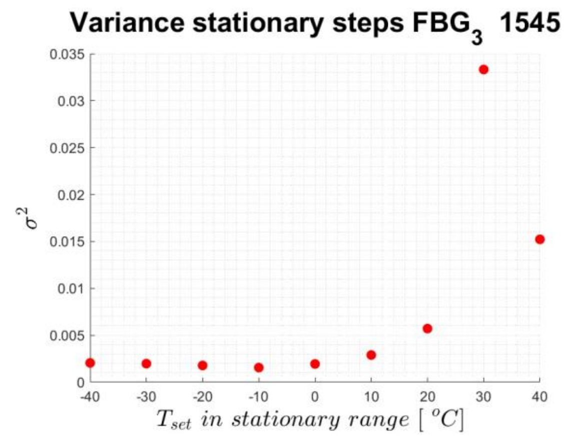

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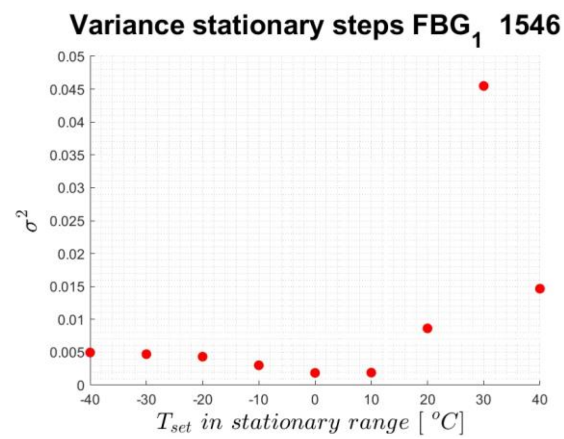

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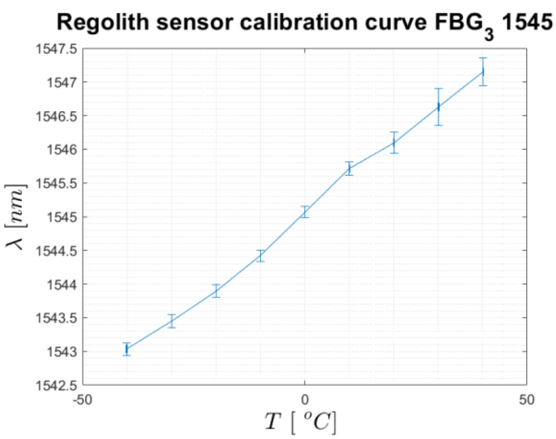
Figure 5 Variance vs Temperature: a) 1537 nm, b) 1545nm, c) 1546 nm

This disconnection is further evidenced by the trend displaying an overshoot in the FBG response compared to the climatic chamber's thermocouple readings, followed by an undershoot before the subsequent temperature step. These deviations highlight the mismatch in thermal behavior between the optical fiber and the regolith, confirming the occurrence of detachment, which disrupts the sensor's ability to accurately track temperature changes.



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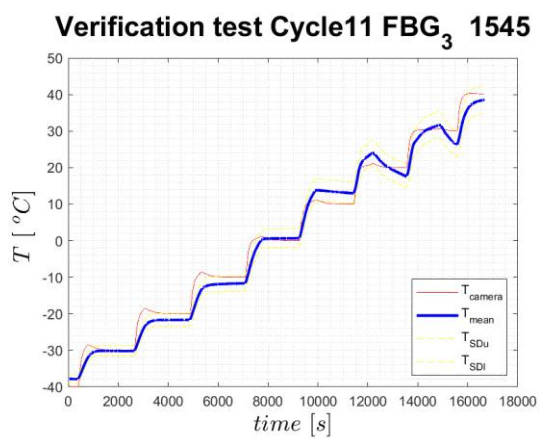

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Figure 6 1545 nm Calibration curve and verification test

5. Conclusion and further developments

This study proposed the integration of Fiber Bragg Grating (FBG) sensors into lunar regolith sintered tiles during the manufacturing process for temperature monitoring purposes. The results demonstrated that this approach provides strong agreement with standard temperature monitoring systems at low temperatures. However, at temperatures exceeding 0°C, the predicted values become unreliable due to the partial disconnection between the optical fiber and the regolith, likely caused by differential thermal expansion. To address this limitation, a potential solution involves substituting the current coating material with a polymer capable of melting and forming a stable bond between the fiber and the regolith during the sintering process, thereby ensuring consistent sensor performance across the entire temperature range.

References

[1] ‘Managing Activities at the Lunar Poles for Science’, *Space Research Today*, vol. 215, 2022, doi: 10.1016/j.srt.2022.11.013.
[2] J. Thangavelautham, ‘Autonomous robot swarms for off-world construction and resource mining’, in *AIAA Scitech 2020 Forum*, 2020. doi: 10.2514/6.2020-0795.
[3] B. Sherwood, ‘Principles for a practical Moon base’, *Acta Astronaut*, vol. 160, 2019, doi: 10.1016/j.actaastro.2019.04.018.
[4] P. Downing, M. A. Baxter, and E. D. McCullough, ‘Developing a sustainable lunar economy: Expanding the moon base beyond exploration’, in *A Collection of Technical Papers - 1st Space Exploration Conference: Continuing the Voyage of Discovery*, 2005. doi: 10.2514/6.2005-2551.
[5] S. Mohanty, B. Imhof, and P. J. Van Susante, ‘Moon base design concepts for lunar exploration and resource utilization’, in *54th International Astronautical Congress of the International Astronautical Federation (IAF), the International Academy of Astronautics and the International Institute of Space Law*, 2003. doi: 10.2514/6.iac-03-iaa.10.2.08.
[6] K. R. Sacksteder and G. B. Sanders, ‘In-Situ Resource Utilization for lunar and Mars exploration’, in *Collection of Technical Papers - 45th AIAA Aerospace Sciences Meeting*, 2007. doi: 10.2514/6.2007-345.
[7] C. A. McLemore *et al.*, ‘Sustainable human presence on the moon using in situ resources’, in *Space 2008 Conference*, 2008. doi: 10.2514/6.2008-7855.
[8] H. Benaroya, P. Metzger, and A. Muscatello, ‘Special Issue on In Situ Resource Utilization’, *J Aerosp Eng*, vol. 26, no. 1, 2013, doi: 10.1061/(asce)as.1943-5525.0000282.
[9] A. Fernández-Medina *et al.*, ‘Embedded Fiber Bragg Grating Sensors for Monitoring Temperature and Thermo-Elastic Deformations in a Carbon Fiber Optical

Bench', *Sensors*, vol. 23, no. 14, 2023, doi: 10.3390/s23146499.

[10] Y. Wang, C. S. Tjin, T.-K. Lim, P. Moyo, and J. M. W. Brownjohn, '<title>Monitoring of concrete curing process with embedded fiber Bragg gratings</title>', in *Fiber Optic Sensor Technology II*, 2001. doi: 10.1117/12.417409.

[11] A. Aimasso, C. G. Ferro, M. Bertone, M. D. L. Dalla Vedova, and P. Maggiore, 'Fiber Bragg Grating Sensor Networks Enhance the In Situ Real-Time Monitoring Capabilities of MLI Thermal Blankets for Space Applications', *Micromachines (Basel)*, vol. 14, no. 5, 2023, doi: 10.3390/mi14050926.

[12] A. Aimasso, M. D. L. Dalla Vedova, P. Maggiore, and G. Quattrocchi, 'Study of FBG-based optical sensors for thermal measurements in aerospace applications', in *Journal of Physics: Conference Series*, IOP Publishing, 2022, p. 12006.

[13] C. G. Ferro, A. Aimasso, M. Bertone, N. Sanzo, M. D. L. D. Vedova, and P. Maggiore, 'Experimental development and evaluation of a fiber bragg grating-based outside air temperature sensor for aircraft applications', *Transportation Engineering*, vol. 14, 2023, doi: 10.1016/j.treng.2023.100214.

[14] R. Torre, A. Cowley, and C. G. Ferro, 'Low binder content bricks: a regolith-based solution for sustainable surface construction on the Moon', *Discover Applied Sciences*, vol. 6, no. 3, 2024, doi: 10.1007/s42452-024-05717-4.