Innovative design and construction methodologies for in-situ manufacturing of large sensorized structures in future human habitat on the Moon

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Innovative design and construction methodologies for in-situ manufacturing of large sensorized structures in future human habitat on the Moon

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Abstract

Over 50 years have passed since humankind last walked on the Moon during the Apollo 17 mission, but space exploration is still among the most important challenges for our technological and scientific evolution. National space agencies identified Moon colonisation and the development of a sustainable lunar economy as top priorities for their programs. Exploiting in situ resources will be the enabling factor in this scenario for limiting Earth-dependability. Consequently, future outposts will require in situ sourced and processed materials. Furthermore, surface outpost maintenance activities will force settlers to build spare parts, day-use tooling, and safety-critical parts using local resources. Challenges and goals brought by the hostile lunar environment prompt disruptive design methods, and their novelty urges effective monitoring systems.

This paper investigates how large structures of a foreseeable human lunar surface outpost can be realised, such as shells of habitation modules, landing pads, roads, and pavements. They require construction-scaled manufacturing technologies, thus moving beyond laboratory-scaled experiments but keeping robustness, low-power demand, automation, and adequacy to cope with the Moon extreme environment.

The experience gained with compressed earth blocks and polymeric cement in terrestrial applications has driven the development of bricks made from regolith and scarce percentages of an organic phase. This solution has already demonstrated valuable flexural and compressive properties for construction manufacturing, also enabling the production of hollow bricks with inter lockable shapes. Interlocking bricks ease the assembly process and can be mortar-less. Hollows and cavities bring lightweight products, which further ease the assembly of large structures and reduce the amount of material to process; play a significant role in thermal insulation; pave the way towards instrumented and multifunctional parts.

Indeed, the cavities can easily host Fiber Bragg Grating (FBG) sensors that evaluate strains, temperature, and humidity in real-time. This monitoring plays a significant role in safety as it allows constant tracking of the long-term effects of thermal vacuum and enables targeted maintenance. It also enables assessing the occurrence of micrometeoroid impacts on the structure, flagging whether this exceeded the designed impact strength. A reliable, fast, and automatable process for applying the fibres and the architecture monitoring solution is also discussed.

The present research work aims to cast some light on disruptive designing and manufacturing methodologies for constructing smart habitat elements in permanent human lunar surface outposts.

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 last half-century since Apollo 17 has seen considerable advancements in space exploration and technology, with lunar colonization and sustainable lunar economies now being identified as the pinnacles of national space programs [1]–[3]. The future of extraterrestrial habitation relies heavily on In Situ Resource Utilization (ISRU) techniques, driving the development of technologies for manufacturing large-scale structures using locally sourced and processed materials [2], [3]. This paper will describe a detailed examination of how construction-scaled manufacturing technologies can be employed to build critical elements of a potential lunar surface outpost, including habitation modules, landing pads, roads, and pavements, while addressing the unique challenges presented by the Moon's harsh environment [2], [4], [5].

Our investigation involves the use of lunar regolith for the development of bricks, integrated with an organic binder, capable of demonstrating desirable flexural and compressive properties [6]. The proposed design includes the innovative feature of hollow, interlockable bricks, which not only facilitate and easy assembly but also contribute to thermal insulation and overall structure lightweighting [7]. The inherent hollows and cavities also allow for sensor integration, as they can house Fiber Bragg Grating (FBG) sensors, playing a significant role in real-time monitoring of strains, temperature, and humidity [8].

Further will be discussed an advanced evaluation of lunar regolith's thermal conductance using FBG sensors, providing a continuous measure of the long-term effects of the thermal vacuum and space radiation on physical properties, thus permitting targeted maintenance [9]. Notably, the integration of these sensors offers also the potential to detect on real time micrometeoroid impacts on the structure, a critical aspect of safety and structure integrity on the lunar surface [10].

2. From Earth to the Moon: using terrestrial technology for lunar applications

Compressed Earth Blocks (CEBs) have long been at the forefront of sustainable and eco-friendly construction methodologies on Earth. Derived from a mix of dampened soil and compacted at high pressure, these blocks provide a reliable, cost-effective, and green alternative to conventional bricks. Their creation requires minimal energy and relies on local materials, which reduces environmental impact and supply chain complexities. In the context of lunar habitation, the lessons learned from CEBs' production, use, and durability offer promising parallels. The scarcity of resources and the need to minimize energy consumption while maximizing utility makes CEBs a fitting model for lunar construction [11].

The lunar regolith, a fine dust-like material covering its surface, is somewhat analogous to the earth used in CEBs. Thus, understanding how CEBs are manufactured and employed on Earth could pave the way for a similar technology to be adapted using lunar regolith. Moreover, the binding techniques, the applied pressures, and the moisture content of CEBs could inform the methods needed to make lunar bricks robust and resilient.

Polymeric cement is another significant milestone in the journey of innovative construction materials. Comprising of polymers mixed with conventional cement, this compound offers a blend of flexibility, durability, and adaptability. The polymers, typically made of synthetic resins, provide enhanced strength and reduce the risk of cracks, making the resultant structures more resilient to environmental factors. On Earth, polymeric cement has found applications in areas demanding heightened durability, such as roads, bridges, and even underwater constructions. Its unique property of resisting water penetration and the ability to bond with a variety of surfaces has made it a go-to solution for challenging environments [12].

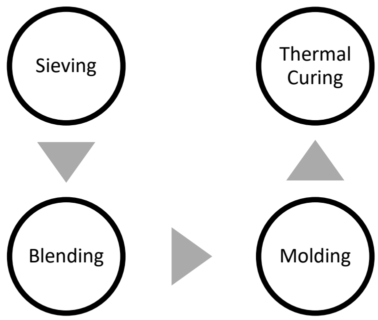
Moon's harsh environment demands materials that can withstand temperature fluctuations, micrometeoroid impacts, and radiation. While lunar regolith itself offers several advantages for construction, the introduction of a polymeric binder (synthesized from available materials on the Moon or delivered directly from Earth) could enhance the strength and resilience of the structures, much like polymeric cement on Earth.

As we delve deeper into the potential of these materials and methods for space exploration, it becomes evident that our rich history of construction innovation on Earth can serve as a foundation for future extraterrestrial endeavours.

2.1 The manufacturing process of regolith bricks

Lunar regolith is predominantly composed of minute fragments of rock, mineral particles, and microscopic shards of volcanic glass. Notably, its composition comprises about 40-45% oxygen, 20-25% silicon, 10-15% calcium, 10-15% aluminium, and trace amounts of various other minerals [10], [13].

Given the regolith's powdery consistency, a preliminary sieving process can be applied to ensure a uniform particle size distribution, which will improve the compressive strength of the resulting bricks. The regolith is then blended with a scarce percentage of an organic phase, which acts as a binding agent. This binder enhances the cohesion and flexibility of the brick, imparting improved tensile strength. Under a predetermined pressure in a specialized mould, the mixture is compacted. Given the lack of an atmosphere on the Moon, this process may require sealed compression chambers or be conducted within a habitat module. The bricks are then left to cure. In the absence of atmospheric moisture, alternative curing processes, such as thermal curing using solar concentrators, can be explored. The manufacturing process is depicted in Fig. 1.



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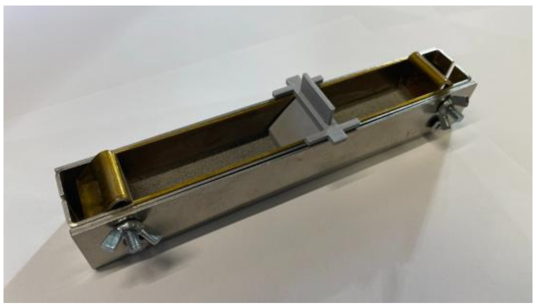

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Fig. 1 Bricks preparation: (a) schematic of the manufacturing process; (b) moulding assembly for the bending test specimen; (c) view of the moulded specimen and the ongoing process

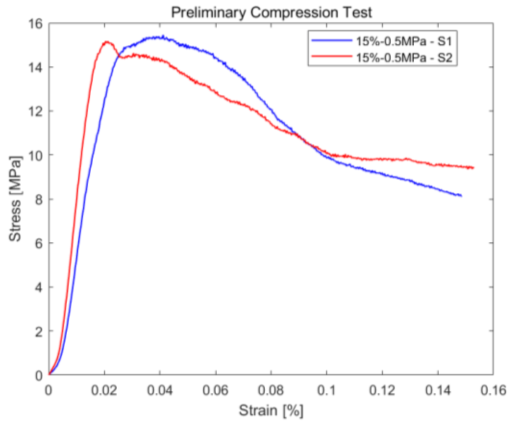
The introduction of an organic phase in the Lunar Regolith Brick (LRB) serves multiple purposes: organic binders offer cohesion to the granular nature of regolith, ensuring the bricks do not disintegrate under stress. Moreover, unlike purely mineral-based compositions, organic components introduce a certain degree of flexibility to the bricks. This is crucial for absorbing impacts, whether from foot traffic, equipment, or even micrometeoroids. Organic components also can reduce the brick's coefficient of thermal expansion. Given the Moon's drastic temperature variations between night and day, managing thermal expansion is crucial to prevent structural thermal fatigue failure.

2.2 Mechanical properties: flexural and compressive test

LRBs, when made with an optimized mixture of regolith and organic phase, showcase relevant mechanical properties:

Preliminary tests have shown that LRBs can achieve compressive strengths comparable to traditional terrestrial bricks, making them suitable for load-bearing structures. Flexural or bending strength is vital for materials used in structural applications. With the organic component's integration, LRBs exhibit enhanced flexural strength, allowing for their use in a variety of construction scenarios, from walls to floors and even ceilings.

Compression test have been conducted with a DoE schematic in order to evaluate the effectiveness of process parameters. Test have been conducted according to ASTM D695 and to ASTM C39 respectively norms for reinforced rigid plastics and concrete. Bending tests have been executed referencing to ASTM D790 and ASTM C293 covering, as for compression, reinforced rigid plastics and concrete. Preliminary results are reported in Fig. 2.



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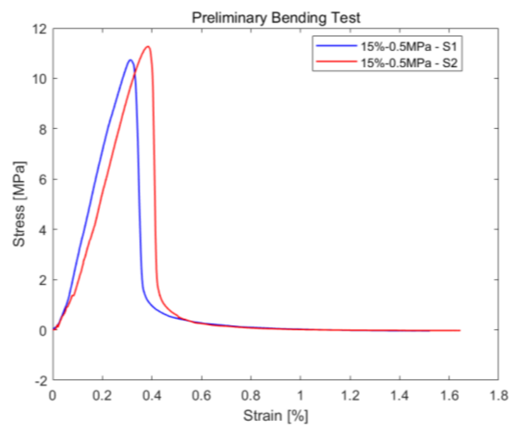

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Fig. 2 Preliminary test: (a) compression test; (b) three-points bending tests

It is crucial to note that while these mechanical properties are foundational, the actual performance of LRBs in a lunar environment may vary in time. Factors such as prolonged exposure to solar radiation, temperature variations, and vacuum conditions can influence the long-term durability and robustness of these bricks.

2.3 Advancements in hollow and interlocking bricks

Lunar construction demands efficiency, resource conservation, and functionality. In this context, hollow bricks (or blocks) offer several advantages. They reduce the volume of regolith required, provide opportunities for insulation, and allow for easy assembly. Hollow moulds designed for the lunar environment, often made from durable metals or polymers, form the backbone of this process. Given the vacuum of space, these moulds need to be particularly resilient.

Fig. 3 Example of hollow bricks [14]

Interlocking bricks represent a step forward in the ease of construction and structural stability. These bricks are designed to fit together like pieces of a puzzle, which provides several benefits:

- The interlocking nature eliminates or reduces the need for additional binding agents (mortar on earth), streamlining the assembly process and saving resources;
- The interlocking pattern provides inherent stability to the constructed structures. This interlocking ensures a more even distribution of stress, reducing the risk of cracks or failures.

With designed grooves and protrusions, robotic assemblers can rapidly construct habitats, ensuring each brick is placed accurately and securely.

Fig. 4 Example of interlocking bricks [7]

The construction process involves several subphases, which also depends on the infrastructure type. It generally starts from the site levelling and preparation since it has to be as plain and regular as possible. Given the lunar complex topography, this step is crucial for the stability of the resulting structure. Starting from a foundation, the interlocking bricks are placed layer by layer. The design ensures that each brick snugly fits with its neighbours, creating a tight and stable bond.

Given the lack of mortar, vertical stability is ensured by the weight of the bricks themselves and the interlocking mechanism. For additional stability, techniques such as "locking" the topmost layer with a different type of brick or sealant can be employed.

The overall infrastructure preparation process is schematically depicted in Fig. 5.

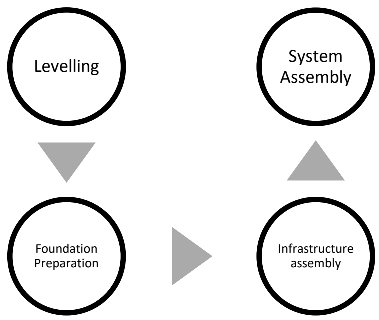

Fig. 5 Proposed infrastructure preparation process

In the endeavour to create lunar habitats, the advancements in hollow and interlocking bricks represent a win-win solution for innovative design with pragmatic functionality.

2.4 Hollows and cavities: the multifunctional advantage

Hollow bricks inherently reduce the amount of material used in their manufacture. This reduction translates to a notable decrease in weight, a quality invaluable for lunar construction.

The temperature variations on the Moon pose a significant challenge to human habitation. Hollow bricks play a pivotal role in mediating this challenge: the cavities within bricks maintain vacuum inside (an excellent thermal insulator); therefore cavities help to maintain stable internal temperatures against the lunar day-night cycle's drastic shifts.

The regolith itself acts as a thermal mass, absorbing heat during the lunar day and releasing it during the lunar night.

Cavities in bricks are not only passive elements; those passage are design to be instrumentalized for various applications. As mentioned earlier, FBG sensors can be hosted in order to monitor strains, temperatures and possible outgassing. This integration ensures that the habitat's health is constantly tracked without invasive procedures.

The hollows can act as conduits for wiring or communication lines, ensuring that the habitat is connected without external exposure of these vital lines. Beyond FBGs, the cavities can be equipped with a range of sensors that monitor the structural health of the habitat, checking for potential damages or vulnerabilities.

3. Integrating FBG sensors into lunar bricks

FBG sensors are a type of Bragg reflector constructed as laser incisions in a short segment of optical fibre that permits the reflection of a particular wavelengths and the transmission of all the others. This property can be used to detect mechanical strain or thermal elongations.

The working principle of an FBG sensor is represented in Fig. 6.

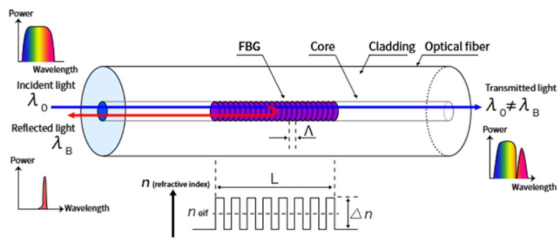

Fig. 6 FBG working principle [8]

Given their miniature size (diameter of 300 μm) and great sensitivity in harsh environment, FBG sensors can be seamlessly integrated into the hollow cavities of the lunar regolith bricks. Some methods for this integration include:

- Embedded design: during the brick manufacturing process, FBG sensors can be embedded within it, thus ensuring they remain protected from external lunar conditions.
- Retrofitted integration: for already manufactured bricks, a specially designed slot can be used to retrofit the FBG sensors, allowing for later upgrades or replacements.

In this research work FBG are directly integrated into the brick automatically during the manufacturing process as shown in Fig. 7.

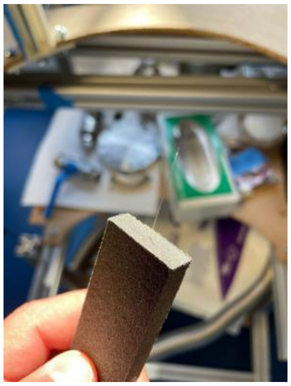

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Fig. 7 (a) Flexural specimen with embedded FBG; (b) optical microscope view of regolith specimen with the FBG highlighted (red circle)

FBG sensors can continuously monitor the strains and stresses experienced by the structure, ensuring that any deviations from expected values are promptly detected.

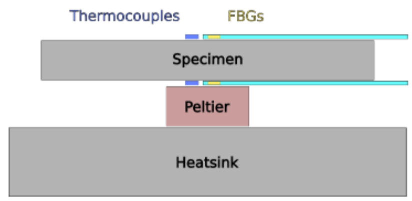
6.1 Evaluating thermal conductivity using FBG sensors

By strategically placing FBG sensors at various depths within a brick, a temperature gradient can be established in real-time. When the brick is subjected to an external heat source, such as lunar daylight or controlled experimental setups, the temperature change at each depth can be monitored. The rate of temperature change and the temperature differences between various depths can be directly related to the brick's thermal conductivity.

Furthermore, the FBG sensors can also detect any anisotropy in thermal conductivity, which means determining if the brick's thermal properties vary in different directions. This becomes particularly important when considering the orientation of bricks in a structure and ensuring uniform thermal behaviour throughout the habitat.

The continuous data stream from the FBG sensors, combined with computational models, can provide a dynamic and accurate profile of the brick's thermal conductivity over time. This not only informs the quality and consistency of brick manufacturing but also aids in predicting and optimizing the thermal performance of lunar habitats. Such real-time evaluations can lead to informed decisions, from habitat design alterations to recognizing the need for supplemental insulation or heat sinks, ensuring the safety and comfort of lunar inhabitants.

In order to evaluate thermal conductivity of lunar regolith and to assess the feasibility of the use of FBG to assess this data, the test bench depicted in Fig. 8 has been used.



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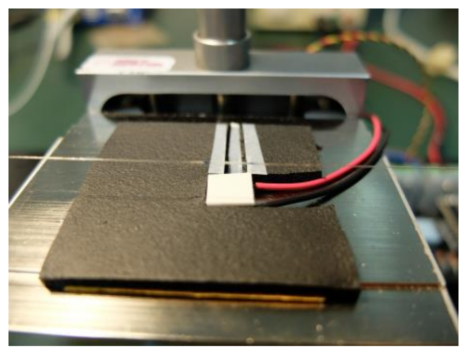

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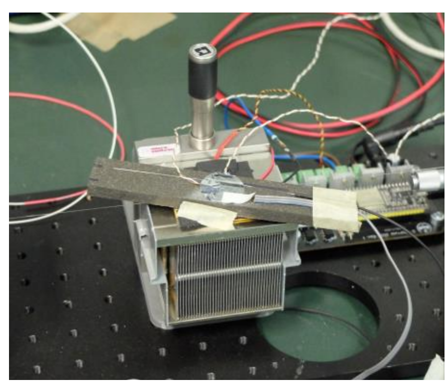

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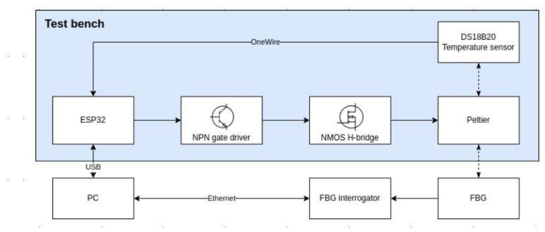
Fig. 8 Thermal conductivity test bench: (a) schematic overview; (b) Peltier cell; (c) test bench with the regolith's specimen

On the specimen realized for bending test two FBG have been glued using cyanoacrylate. Peltier Cell, a thermoelectric system can provide a regular quantity of heat that can be controlled with a Matlab Simulink closed loop control logic, depicted in Fig. 9a. Peltier Cell is controlled using Thermocouples as primary sensor and FBG are used in parallel. In this manner it is possible to compare data evaluated by the new sensor. Thermal loop is reported in Fig. 9b.



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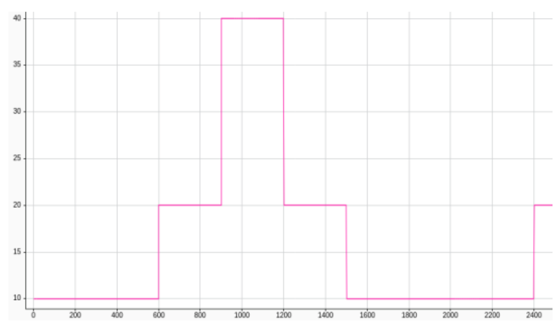

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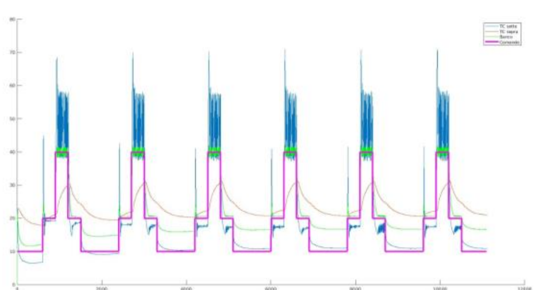

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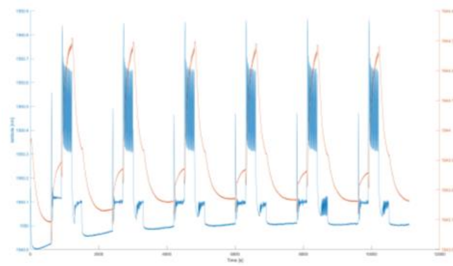
Fig. 9 Thermal test bench: (a) control logic; (b) thermal cycle imposed, (c) thermal evaluation

The FBG sensor data demonstrates a high degree of agreement with thermocouple readings, thereby preliminarily substantiating the feasibility of employing FBG as embedded thermal sensors in regolith-based composites. Moreover, as depicted in Fig. 10c the percentage error on the absolute value evidence less shift for FBG compared to TC and additionally reveals a Gaussian distribution characterized by reduced dispersion. However, due to the high sampling rate of the measuring system, further refinement involving data smoothing and sampling design will be necessary to enhance the quality of the acquired data.



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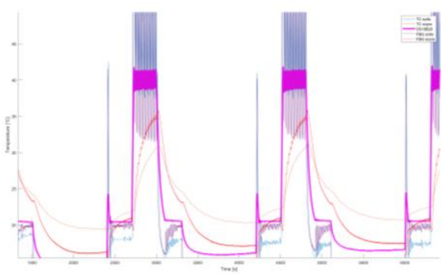

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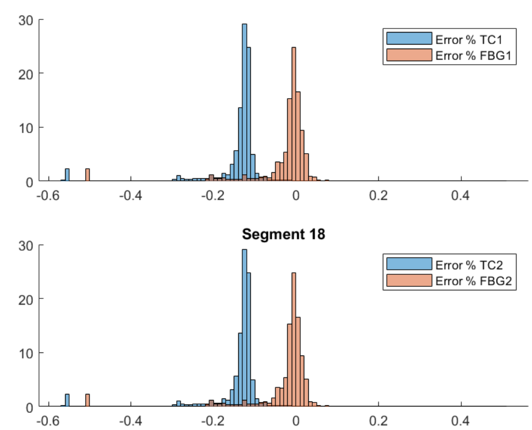

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Fig. 10 FBG thermal data: (a) raw wavelength data; (b) comparison with thermocouples, (c) segment histogram comparison on percentage error

4. Application process for fibres and monitoring architecture

In the extreme and harsh lunar environment, ensuring the safety of structures and their inhabitants is of paramount importance.

The occurrence of micrometeoroid impacts is one of the major threads. While individual impacts might be minute, their cumulative effect or a significant singular event can compromise a habitat structural integrity. The sensitivity of FBG sensors allows them to detect even minute strains on the structure, acting as an early warning system for impacts. The pattern of strain distribution can even give insights into the impact's direction and magnitude. Upon detecting an impact, algorithms could assess if the force exceeded the brick's designed impact strength, thus flagging potential areas of concern.

The lack of atmosphere and the extreme temperature variations on the Moon result in a challenging thermal vacuum environment. Over time, this can lead to material degradation or unforeseen structural responses. By monitoring temperature gradients and cycles, potential threats to the structure's integrity can be identified, such as areas experiencing extreme thermal stresses. Any changes in thermal conductivity or anomalies in temperature patterns can hint at material degradation, enabling pre-emptive measures.

While the Moon's surface is devoid of water in its liquid form, any introduced human habitats will have internal humidity. Monitoring humidity levels is crucial for both human comfort and equipment longevity.

A central monitoring station can be established within the habitat, continuously receiving and analysing data from all FBG sensors. In the event of an anomaly or potential issue, the system can automatically alert inhabitants or remote operators on Earth. With the data from continuous monitoring, maintenance can thus experience a transition from reactive to proactive.

Future lunar habitats might employ maintenance robots that can be dispatched to areas flagged by the monitoring system, ensuring swift responses to potential issues. For tasks requiring human intervention, the system will have to provide detailed data, ensuring astronauts are fully informed and equipped to address the specific issue. Knowing precisely where and what kind of maintenance is needed ensures that resources (tools, materials, personnel) are used efficiently, critical for the resource-scarce lunar environment.

5. Towards disruptive design and manufacturing

Starting from Artemis III mission [15], humankind will return onto the Moon surface after the gold age of the Apollo program. This time, the international endeavours of space faring nations are focused on unprecedented science discoveries [2], [16], where ISRU will play a critical role. The long term vision is the creation of a self-sustaining outpost which can be used as technological test bed for the next giant leap of human kind toward landing on Mars.

Having this final scope in mind, the challenges of lunar construction require an innovative approach that starts from Earth-based methodologies and proceeds beyond conventional.

The first significant constraint on the Moon is the availability of power. The design of the lunar habitat should prioritize energy efficiency starting from manufacturing bricks without compromising structural integrity. Thus, leveraging technologies that can work optimally under low power, is pivotal.

Outpost assembly is another constraint: here automation plays a crucial role in the efficient construction and maintenance of lunar habitats, given the limitations in external continued human labour due to the harsh environment. Machines that can autonomously gather, process, and prepare lunar regolith for brick manufacturing are required as well as robots equipped with advanced AI that can handle tasks from brick laying to intricate assembly processes, minimizing human external exposure. In future, also envisioning habitats that have embedded nanobots or mechanisms to self-repair minor damages, reducing maintenance needs are desirable.

A third constraint could be that every component of the lunar habitat should serve multiple purposes to optimize resources' usage and maximize efficiency. Walls and pavements will have to be sensorized to continuously monitor health status, especially for non-permanent outposts. Regolith layers should also be placed to minimize radiation penetration into habitats and special structures (auxetic, chirals, Negative Poisson Ratio - NPR cells) need to be designed to dissipate energy absorbed from micrometeoroid impacts, ensuring the safety of the outpost inhabitants via a minimization of the damage.

The production of such novel bricks using lunar regolith simulants and an automated low-energy demanding device are currently being tested at the European Astronaut Centre (EAC) laboratories in Cologne, Germany. In the near future, these tests could be performed on a larger scale at the LUNA analogue facility [17], currently developed as a joint project between ESA and the German Aerospace Center (DLR). Apart from the training, operational and technological capabilities offered by the ESA-DLR Moon centre, such disruptive approach could be investigated using novel technology such Virtual Reality [18] in combination with real scale physical mock ups of future surface elements such as the ESA Argonaut lander [19]. The automation process could also be tested against human-assisted operations done by astronauts.

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