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Additive manufacturing for a Moon village

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Abstract

The European Space Agency has proposed a Moon Village as the next step in the human exploration of the Solar System. Considering the cost of sending mass to the lunar surface, the utilization of in-situ resources for building the lunar base is a suitable option to make this mission affordable. Additive manufacturing can play an important role in this context. This paper reviews the state of the art and provides a detailed trade-off of available additive manufacturing technologies that can be used in this mission. Each technology is analyzed in terms of its suitability, its expected performance and the possible required modifications. Accordingly, powder bed fusion has been preliminarily selected. In addition, a test is designed to assess the viability of the chosen option. This work constitutes a first stage for defining an integral system solution to fulfill efficiently all the established requirements.

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Keywords: additive manufacturing; powder bed fusion; Moon Village; regolith; regolith analogues.

1. Introduction

In December 2016, the current Director General of the European Space Agency in its Ministerial Council pushed forward the concept of the Moon Village as the next step in human space exploration [1]. The aim of this project is to establish a Moon colony, which will open a broad field for multidisciplinary research, given that ensuring survivability in a non-terrestrial environment represents a great technological challenge. In fact, a comprehensive design solution of a lunar outpost should involve improving technologies ranging from propulsion to live-support systems. In relation to the last item, one of the most important aspects is to construct a shelter to make human life possible on the lunar surface.

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Building protection structures on the lunar surface is, at the same time, mandatory and highly required due to severe environmental conditions. As it can be supposed, the environmental conditions on the Moon are very hostile: the solar and galactic radiation and micrometeorites are constantly striking the lunar surface and the temperatures can range from -171 to 110 degrees Celsius [2]. For the construction of a shelter for human protection (and other systems that may be damaged), it is required either the transportation of building materials from the Earth or the gathering of materials available in the Moon.

The transportation of materials from the Earth to the Moon is nowadays too costly and lacks the needed immediacy to make life on the Moon sustainable and affordable. One option to prevent massive material transportation to our satellite is the utilization of in-situ resources (ISRU, in-situ resources utilization). This option has been proposed in [3] as an efficient way of fulfilling the expected requirements of a reliable lunar building technology. In this line, additive manufacturing using Moon regolith would play an important role. The cost and complexity of a Moon Village can be lowered by reducing the weight to be carried to the Moon surface by using the additive manufacturing processes, using lunar regolith as the raw material. Nonetheless, the impact that additive manufacturing may have in the Moon Village building will strongly depend on its specific design.

Summarizing, this paper assesses the feasibility of additive manufacturing technology on the lunar surface, using lunar regolith as raw material. A multidisciplinary approach is therefore necessary because it involves a deep understanding on the geology of the Moon as well as a good knowledge of the principles of operation of additive manufacturing and the different technologies available not only in the market but also the ones to be further developed.

Section 2 outlines the different design concepts that have been proposed for a lunar base. Next section reviews the state of the art in the fields of Moon geology and additive manufacturing. In section 4, a test is proposed to further explore the solution sketched in this paper. Finally, in section 5, we draw the conclusions and define the next steps in the research.

2. Lunar base design

The development of the lunar colony is expected to follow three main stages [4, 5]: a first one with prefabricated and pre-outfitted hard shell modules; a second one with an assembly of components fabricated on the Earth; and a third one with large-scale building structures comprised substantially of indigenous materials. A class terminology (Class I, II, and III) is used to define each of the three steps [6, 7, 8]. Autonomous operation of robots on the lunar surface can change this paradigm, making class I (and maybe class II) stages of an actual lunar colony development unnecessary (see [9] for advances in autonomous operation of vehicles on planetary surfaces). In fact, the target of the Moon Village in the actual early stage is building a class II base without human intervention.

According to this three-stages approach, Ruess et al. [10] study the second generation (class II) facilities of the lunar base from the point of view of the structure analysis. For class II construction, inflatable or deployable structures play the role of components to be assembled onsite. For an extensive review of deployable lunar habitation, we refer to [19]. Five different structure concepts are presented and analyzed, namely: spherical inflatable, tuft pillow, lunar crater base, three-hinged arch, and underground construction. All of them are a combination of one or more of key structural concepts: inflatables, cable structures and rigid structures combined with deployable structures.

- Spherical inflatable was first proposed by Roberts [12] in 1988. It consists of a spherical pneumatic envelope with an interior structural cage to support the floors, walls and equipment, and to hold up the envelope if the pressure is lost. The main advantage of this concept is the simplicity of the main structure. Nevertheless, the drawback lies in the fact that the weight of the required interior secondary structure is eight times higher than the mass of the main structure.
- "Tuft-Pillow" inflatable structure is a structural concept that consist of quilted inflatable pressurized tensile structures using fiber composites [13]. The weight of the structure is reduced in a great amount, but transportation and construction must be performed with care to avoid damage to the membranes. In addition, composite membranes cannot be produced, in principle, from ISRU, although recent studies start to explore the possibility of curing composites materials on the Moon [14].

- A lunar base cable structure in a crater is a concept that tries to use natural features on the Moon to reduce excavation and the amount of shielding that is needed [10]. A roof structure for the crater has been proposed by Eichold [15] using cable structures, and cover plates or membranes.
- A three-hinged arch main structure is proposed in [10] to cope with the structural requirements in an efficient way. Ruess et al. gather the details of the structural design and sizing and addresses the construction process, the issues concerning the openings, the pressure sealing, and other minor details of the definition of the lunar habitat.
- Lunar lava tubes may provide an alternative to lunar surface construction [2]. The main advantage of a habitat inside a lunar lava tube is that it can be built with an extremely lightweight material [10]. The main drawback, in turn, is related to the quantity of material to manipulate if drilling is required (compared to other techniques as 3D printing [16]).

The criteria proposed by Russ et al. in [10] to evaluate the structure concepts are transportation, ease of construction, experience with the general structural system and materials, foundation, and excavation. With a disclaimer regarding the qualitative and speculative (to a certain extent) nature of the analysis, Russ et al. conclude that the three-hinged arch is the best available option. However, new data coming from the development of related technologies, specifically, additive manufacturing, may modify the above-mentioned conclusions. In this line, Ceccanti et al. [16] explored the possibility of using additive manufacturing technologies to build the habitation modules of a lunar outpost (see Fig. 1).

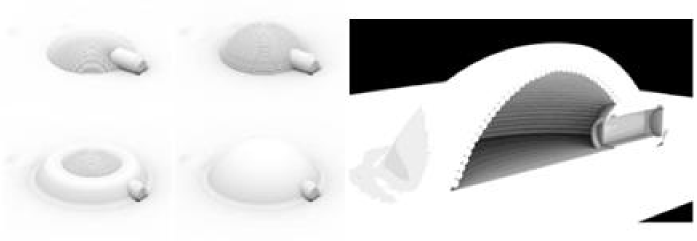

Fig. 1. Inflatable module to construct the lunar buildings. [16]

3. State of the art

3.1. Moon geology and environment

The analysis of the Moon environment is relevant for the definition of the environmental control system, and for the characterization of the available in-situ materials. On the lunar surface, the most abundant is the lunar regolith. As a consequence of the meteorite impacts occurring since the Moon formation, a mixture of components in dust form covers the whole lunar surface, with different depths depending on the region. At the mare area, the thickness of the regolith is around 5 meters, while, on the highlands, it reaches values greater than 10 meters [17]. For the purpose of additive manufacturing only the collection of the regolith from the surface would be required. The characterization of the raw material is essential in order to find the best alternative among the additive manufacturing techniques. The first step consists on performing studies and tests using regolith simulants on Earth, reproducing Moon conditions when possible. One important aspect to validate the results of these tests is the utilization of an analogue simulating the lunar regolith. The term analogue is also used in a broader sense to refer to environments which are resemble Moon conditions. In this broader sense, there are three types of analogues: natural, artificial and mixed between natural and artificial [18]. The natural ones are weather dependent and makes it is not possible to reproduce Moon conditions as vacuum, huge variations of temperature, etc. There have been identified some facilities (artificial analogues) to perform these tests [18, 19] in the ESA's LUNA study. Among them, it has been concluded that the best fitted facility to carry out tests simulating Moon conditions is in Cologne in the DLR installations (Deutschen Zentrums für Luft-und Raumfahrt). In particular, in the EAC, which is the European

Astronaut Center within the DLR plant [18]. Inside the DLR, the facility which will contain the artificial analogue is named ESOL, European Surface Operations Laboratory. The EAC counts with some of the installations already built as the Mission Control/Simulation Control Center. However, others are still to be implemented as the regolith simulant testbed or the gravity off-loading system for humans and rovers [18]. In Fig. 2, one can find a representation of the ESOL facilities.

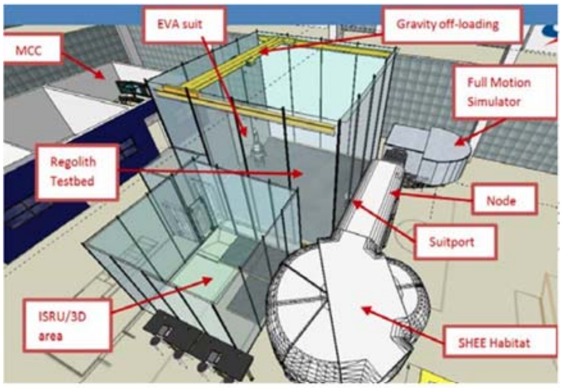

Fig. 2. ESOL installation in the DLR. [22]

Additive manufacturing techniques are required to be tested in analogues, because the Moon environment may affect both its operation and performance. In particular, successful operation in vacuum with reduced gravity (approximately 17% of the Earth's one) is crucial for the installation and later use of the machinery. In addition, the permanent exposition of the building to a harsh radiation environment as well as the micrometeorite striking [20] should be assessed.

With respect to the regolith simulants, the main characteristics to be reproduced for testing are chemical composition, mineralogy, particle size distribution and engineering properties [21]. The lunar regolith is mainly formed by SiO_2 (sand), which corresponds around to 45% of the regolith composition [20] in oxygen weight percent (see Table 1). The composition of regolith has been determined using different Apollo missions' samples. However, its composition is not constant all over the lunar surface and can be also classified in two main groups depending on the content of some elements, the mare regions and the highlands. The mare soil is darker and heavier as it contains Magnesium and Iron. On the other hand, the highlands are characterized by its white colour, having higher quantities of Calcium, Aluminum and Silicon than the mare soil, and, therefore, being lighter [22]. In addition, there are particular sites where high contents of Titanium can be found, which may be of interest for the Moon Village mission purposes.

The composition of some of the samples is summarized in the Table 1. Notice that the values are in oxide weight percentage, which means that some of the compounds may not be presented in its oxidized form.

From the previous description, it is clear that it is not possible to characterize all the diversity of the lunar geology with just one simulant. There exists a standard for producing and using lunar regolith simulants [23]. After some regolith simulant prototypes, the Johnson Space Center in the NASA installations developed the JSC-1 that has been used for several analysis purposes.

In the recent years, some tests have been performed with the JSC-1A simulant, which is a variation of the JSC-1 made in Orbitec (USA) and has more similar chemical and physical properties to the actual lunar regolith. Nevertheless, the main disadvantage is that it is too costly [16], and so other alternatives needed to be found to perform a high number of tests. The D-NA-1 simulant appeared in Italy, developed from the volcanic ashes, having very close properties to the JSC-1A but being much cheaper [16]. In Spain, there are also efforts oriented towards using analogues of lunar material for scientific and engineering purposes [24].

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Table 1. Composition of different regolith samples from Apollo mission, in oxygen weight percent. [20]

	Sample #1	Sample #2	Sample #3
SiO_2	41.3	46.9	47.3
TiO_2	7.5	2.3	1.6
Al_2O_3	13.7	14.2	17.8
Cr_2O_3	0.29	0.39	0.20
FeO	15.8	15.4	10.5
MnO	0.21	0.19	0.14
MgO	8.0	9.2	9.6
CaO	12.5	11.1	11.4
Na_2O	0.41	0.67	0.70
K_2O	0.14	0.41	0.55

ISRU technologies can help providing the needed materials for lunar base construction as well as the consumables for its steady-state operation. Although not within the scope of this paper, it is important to highlight the possible role of these technologies in providing the required water and atmosphere for the lunar outpost. For a detailed review of these technologies, we refer to [25, 26].

3.2. Additive manufacturing

The condition of using in-situ material constraints significantly the material selection. For each option, the pumpability, printability, buildability and open time of the material can be used as a first approach to assess the appropriate method of manufacturing [27]. Earth challenges are scaled-up and the traditional technological solution to deposit material in place must be reconsidered attending to the new scenario. This new way of manufacturing opens a new way of thinking in which optimization must be present in the used means and in the manufactured units.

To select the best additive manufacturing or 3D printing technique among the existing ones, it is necessary to know the processes followed in each of them. The following paragraphs will be devoted to the definition of the different technologies developed up to this moment [28]:

- Material extrusion. The material is deposited through an injector layer by layer in a continuous flow. The injector melts the material at a particular temperature so as to be as fluid and to be easily deposited, but rigid enough in order not to be deformed by creeping. By controlling the temperature and keeping constant pressure, the layers can be bonded without the need of external agents (adhesive, resin…). The common materials used in this type of additive manufacturing process are polymers and plastics.
- Material jetting. For this process, the material is also deposited layer by layer but not in a continuous stream. The nozzle deposits droplets over a platform, working as a common 2D inkjet printer. The platform should be later removed when the material solidifies. The built part is generally cured by employing UV light. As well as for the previous technique, polymers and plastics are used.

- Binder jetting. In this case, there is a binder or agglutinant material employed to compact the different layers. The principal material giving shape to the piece is in powder (solid) form while the binder is in liquid state. The way of working consists in depositing the binder using an injector over a layer of powder, only over the areas where it is intended to building part. After this deposition, another layer of powder is put on top of the already built part. The material employed to build the parts can be either metal, ceramic or polymer.
- Sheet lamination. Sheets of material are placed together, one above the other, to form the desired shape. The use of an adhesive is mandatory, to bond the different layers. If metal sheets are chosen, they must be welded using ultrasonic, for instance. When the pre-final shape is obtained, the unused parts are cut by means of a laser.
- Stereolithography or photopolymerization. The material (liquid photopolymer resin) is cured by employing UV light over it through a laser jet and a set of mirrors and/or lens. The liquid is put inside a vat, where a platform moves the object. When the object is required to be dried, it is extracted from the vat to remove the extra resin.
- Powder bed fusion. A jet of thermal energy is applied to melt the regions of powder selected to shape the piece. The powder, layer by layer, is placed by means of a roller over the last lamina after it is processed with the jet of thermal energy. In this case, there is no need of an agglutinant or resin. Inside this kind of additive manufacturing process, there are several variations: selective heat sintering (SHS), selective laser sintering (SLS), selective laser melting (SLM), direct metal laser sintering (DMLS), and electron beam melting (EBM). The last one is different from the others as it uses a jet of electrons over the material. Depending on the method, the material can be either metal or polymer. SHS commonly uses polymer while the other ones work with different kind of metals as steel or aluminum. Furthermore. the SLS can work with both polymer and metal powder.
- Directed energy deposition. Similarly to the powder bed fusion, a thermal energy jet is used to melt the material, either in powder form or as a wire. However, the difference resides on the fact that the material is deposited at the same time it is melted, as in the material extrusion case. A nozzle is able to move in many directions and with diverse orientations in order to reach any specific part. This is because this method is mostly used to repair parts and not to create one from the very beginning. The materials to be employed are polymers, ceramics and metals. This method resembles a welding process, this is why metals are mostly used.

The basis of this project is to take profit of the in-situ resources that the Moon environment provides, to save weight in the space travel. Therefore, this condition immediately discards some of the possibilities for the mission [29] as it happens with the binder jetting case, unless a type of agglutinate was found on the Moon. For the stereolithography method, it happens the same; a kind of resin would be required, which is not supposed to be found on the Moon.

On the other hand, the sheet lamination technology needs for sheets of material. However, the regolith is only available in powder form, while, under the layers of regolith, it can be found the solid lunar ground that would require drilling mechanisms to extract material.

In tests already performed by the ESA [19], both the directed energy deposition process and the binder jetting method have been successful used to manufacture objects using the lunar regolith simulant as raw material. However, further assessments [29] privileged the powder bed fusion as the solution for the 3D printing to be used in the simulations and then employed in the mission. In particular, one of its variations, as it is actually operating with lasers. For this project, the lasers would be substituted by lens and mirrors to project solar rays [29]. The selection of the powder bed fusion mechanism for the development of the project is due to the fact that this process does not need the addition of other substances or a difficult procedure to deposit the material to obtain the final object [29]. In this sense, simpler machinery would be needed. In particular, the DMLS variation would be used, by introducing some changes.

In a 3D printer of this type of technology, two parts can be differentiated: one that contains the powder and provides new layers to be built and another one where the thermal energy (laser, or in this case, solar rays) acts over the deposited dust. Then, the powder already used but discarded for the net shape is removed. Sometimes, this unused material cannot be reused if it has been already applied energy over it.

The aim of this additive manufacturing process for the Moon Village project is to melt part of the regolith. The powder bed fusion technique commonly uses a laser that would be replaced by a set of mirrors and lens to reflect the solar rays and intensify the thermal energy required to reach the melting temperatures focusing on a point. With solar ray concentrators, the melting temperature of some of the components of the regolith may not be reached. The other components, however, are supposed to be melted over a bed to form an agglutinate and maintain the rest of elements that cannot be melted attached to the mixture [3]. In order for this phenomenon to be produced, it is required that the majority of parts could be melted, in order to have higher quantity of liquid parts than solid ones.

Related to this procedure, an experiment was performed by Markus Kayser in 2010 with successful results [30]. He found in the desert an abundant raw material (sand), and high amounts of thermal energy (solar light). The laser was replaced by sun rays, as well as the intended prototype for the Moon Village Project. Solar ray concentrators were designed to focus them on the desired object. The raw material was crystallized after reaching the melting temperature of the sand.

The promising results that Markus Kayser obtained in the desert are especially relevant for a lunar outpost because of the high percentage of SiO2 (sand) in the regolith, around 45%, as it is seen in Table 1. This percentage in composition is more or less constant all over the lunar surface. Therefore, the determination of the base allocation will be driven by other factors such as other mineral contents [31] (as it can be titanium), or the necessity of solar radiation and high temperatures to obtain energy for the machinery to work.

Then, the place to locate the base will directly depend on the sun illumination periods, in order to reach the needed temperatures for the printer to be driven. This is the reason why the ESA has proposed an area near the South Pole to place the base, where is almost always sun-lighted, and the temperatures can reach the 110 degrees Celsius [20]. This is a great advantage to take into account for a designed of the 3D printing machine based on powder bed fusion technique and solar concentrators.

4. Test design

After exploring the types of additive manufacturing processes and the tests and simulations already performed within this field, it is proposed the creation of a simplified Powder Bed Fusion 3D printer, able to perform the main functions of the DMLS process. However, the main modification would consist on the replacement of the laser by the use of the direct solar light. A design based in [30] of the solar concentrator should be drawn. The objective of the test would be to reproduce the results gathered in [30] within a more realistic simulated scenario of the lunar conditions.

To reproduce lunar conditions, a simulant with characteristics close to the lunar regolith ones would be required to obtain meaningful results. Two simulants have been identified, being the most extended one the JSC-1A. The price of the simulant and the requirement to match closely the properties of the regolith of the lunar base location make advisable to manufacture dedicated analogues for the tests.

It is also known that the presence of an atmosphere may affect the results, obtaining a variation far from the reality. For this reason, the necessity of a vacuum room would be desirable for the performance of these tests. Furthermore, the simulation of the gravity conditions would be worthwhile for a faithful assessment of the additive manufacturing operation and performance.

5. Conclusions

The Moon Village mission aims for the construction of a permanent base on the Moon surface capable of providing life-support for a long mission duration. Additive manufacturing techniques using in-situ resources have been considered an alternative to help the construction of the permanent base, because of the huge cost of sending mass to the lunar surface. The raw material to be used is the regolith, which can be broadly described as the dust obtained after centuries of micrometeorite striking. The Moon Village can be a suitable frame to further develop additive manufacturing, adapting it to solve the new challenges.

This paper provides a detailed trade-off analysis of the available additive manufacturing technologies and the ones feasible for lunar building purposes. The suitability of each technology is analyzed, as well as the possible required modifications and its expected performance. The powder bed fusion process has been selected for the mission, as it is the most promising one for additive manufacturing purposes with lunar regolith. This work constitutes a first stage for defining an integral system solution to fulfill efficiently all the established requirements.

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