3D PRINTED BUILDING BLOCKS USING LUNAR SOIL

EXECUTIVE SUMMARY

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ABSTRACT
Sommario

This document is the executive summary of activities performed in the frame of the “3D Printed Building Blocks Using Lunar Soil” study.

KEY WORDS *Parole chiave*: 3D Printing, Moon, Regolith, Executive Summary

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CONTENTS

1 Introduction

1.1 Scope and purpose

Establishing a manned colony on the Moon (or on Mars) will require infrastructure to shelter the astronauts and also many of the scientific instruments from the harsh environment; mainly vacuum, temperature, micrometeoroids, and radiation. For this purpose, several alternative solutions can be envisaged:

- to bring fully functional habitation modules from Earth;
- to build in-situ structures on the Moon surface using lunar soil;
- to dig the habitat under the surface.

Although a complex trade-off would be needed to define the most appropriate concept, the idea of building on the Moon surface using lunar soil presents some advantages:

- compared with the ready-to-use modules, it is not necessary to bring large structures from Earth, maintenance could be performed on site, and efficient radiation shielding could be achieved by manufacturing structures of a sufficiently large wall thickness;
- compared with excavating the Moon, the amount of material to be manipulated is much less with important, positive energetic consequences. Furthermore the structure of the Moon geological system is not fully known.

For these reasons, ESA is exploring the possibility of building infrastructures on the Moon using lunar soil as base material. The “3D printed building blocks using lunar soil” General Study Programme had the objective to assess the concept of using 3D printing technology as a potential means of building habitat on the Moon. To do so, a 3D printer of large dimension had been used to manufacture a representative structure using a base material of similar chemical and granular composition as that of Moon regolith. The design and manufacturing had been critically analysed to establish 3D printing guidelines for future Moon (or Mars) structures.

Purpose of this document is to concisely present activities done and results obtained in the frame of the “3D printed building blocks using lunar soil” General Study Programme.

2 References

2.1 Applicable Documents

AD	Doc. ID	Is.	Date	Title
1	QMM/GSP08/01/LP	1r2	05/03/2009	Statement of Work
2	ALTA_P09_08_3DP	-	05/06/2009	Proposal

2.2 Reference documents

RD	Document Identification
1	3DP-ALT-RS-0001
2	3DP-SSA-TN-0001
3	3DP-MON-RP-0001
4	3DP-MON-RP-0002
5	3DP-FP-RP-0002
6	3DP-ALT-TR-0001
7	Ceccanti F. et al. (2010), *“3D Printing Technology for a Moon Outpost Exploiting Lunar Soil”*, 61st International Astronautical Congress,Prague 2010, IAC-10-D3.3.5
8	3DP-ALT-RP-0001

3 Acronyms and abbreviations

Acronym / Abbreviation	Meaning
3D	Three-dimensional
AD	Applicable Document
ECSS	European Cooperation for Space Standardisation
ESA	European Space Agency
GCR	Galactic Cosmic Ray
ISS	International Space Station
NASA	National Aeronautics and Space Administration
PEL	Peaks of Eternal Light
RD	Reference Document
SEP	Solar Energetic Particles
TBC	To Be Confirmed
TBD	To Be Defined
TDD1	Technology Demonstrator Design (CAD model)

4 Overview of performed activities

To accomplish with the demanding requirements from AD01, a workplan has been organised, in which activities were divided in four main tasks:

1. Verify usability of Moon regolith as building material. This task needed a side activity, that is to select and procure enough regolith simulant to "print" a demonstrator, as required by AD01.
2. Selection of a suitable 3D printing process, and verification of its transferability on a Space environment, and of its effectiveness with regolith simulant.
3. Design of a lunar outpost which could be built -using regolith- with the 3D printing process selected, and print of a significant element of such outpost.
4. Definition of a roadmap to further advance on the goal of "printing" an outpost on the Moon (or Mars).

5 Synthesis of obtained results

From the workplan sketched above, the following results have been obtained:

5.1 Regolith can be used as building material

It is possible to use Moon regolith simulant as building material, providing enough amount of metal oxides are mixed to the simulant itself. As the simulant is concerned, JSC-1A do performed well, as shown in figure 5.1, but its cost was too high to be covered with GSP funds allocated for this project. So, a new simulant has been selected and manufactured, from a volcanic quarry in Italy. The simulant has been named "**DNA-1**". Its chemical and physical characteristics do perform as good as the JSC-1A, at a fraction of the cost of the NASA product. Figure 5.2 show a slice of a curved shape obtained by using the new simulant.

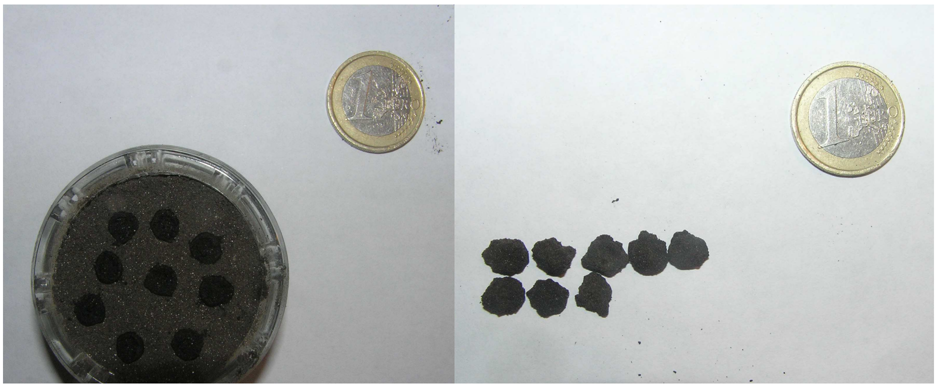

Figure 5.1 - 1 cc drops resulting in Voxels made of aggregated JSC-1A doped with of MgO.

Figure 5.2 – Printing test with D-Shape system and DNA-1.

5.2 The selected D-Shape 3D printing process can be transferred to Space environments

Within the possible rapid prototyping technologies, **D-Shape™** has been selected not only because it is patented by Enrico Dini, Monolite UK CEO, but mainly due to its potential in satisfying Space requirements (such as the capability to print in vacuum).
D-Shape technology relies on a gigantic (6 m by 6 m) frame, in which a "printing head" moves in the x, y & z axes and sprays a certain amount of saline solution on a layer of fine, sand-like substrate.

Figure 5.3 – The D-Shape system (left) and the printing head spraying the "ink" on the layer of sand (right).

In order to preliminarily assess feasibility of D-Shape process in vacuum, a "simplified printing head" (only one spraying nozzle) was prepared and mounted into a Alta vacuum chamber together with a movable container filled with regolith.
Due to the environmental constrains, it has been decided to insert the nozzle under the regolith layer, so to reduce at minimum sublimation processes. The test gave good aggregation results, thus allowing the team to freeze the chosen 3D printing technique.

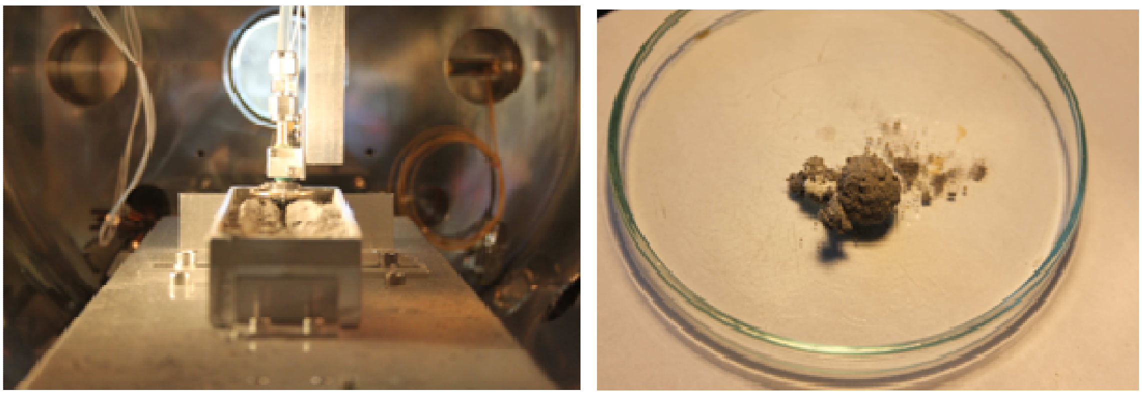

Figure 5.4 – The experimental setup in one of Alta's vacuum chambers (left) and one of the resulting aggregated samples of regolith (right).

5.3 A Moon outpost has been conceived and designed, made of aggregated Moon regolith.

F+P designed a complete outpost, based on an inner inflatable structure which would ensure human crew pressurization and sheltering from vacuum.

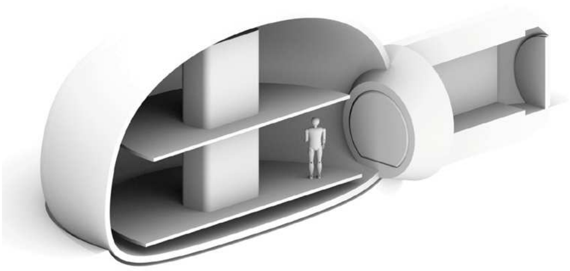

Figure 5.5 – Cutaway axionometry of an inflatable non rigid structure. Courtesy of F+P

Over the inflatable, an external structure made of regolith was designed, which would ensure shielding from meteorites, radiation and thermal gradients. Meteorites shielding is ensured with a high probability (99,8%) with a radial regolith protection layer of 800 mm, to be added on the inflatable.

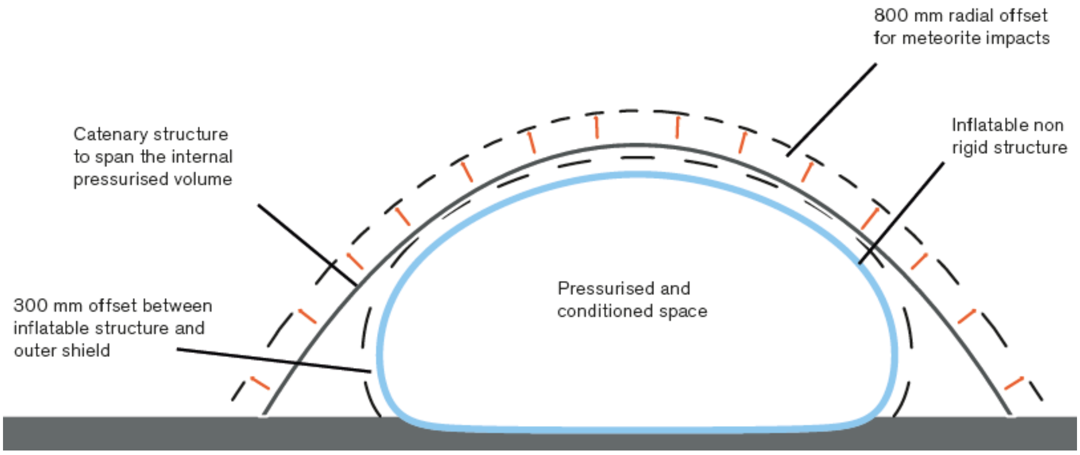

Figure 5.6 – Cutaway of the inflatable non rigid structure with catenary regolith structure for meteorites shielding. Courtesy of F+P

Solar wind, Solar flares and Galactic Cosmic Rays need extra shielding, which means 1500 mm of regolith cover in the dominant direction of rays (in this study we considered a polar location, thus most of the radiation comes laterally wrt the outpost).

Another important aspect is the amount of binder necessary to print the outpost, which shall be minimised (this component has to be brought from Earth). So, a closed foam cells has been selected as an initial compromise between strength, minimisation of binder, and "printability" with the D-Shape system.

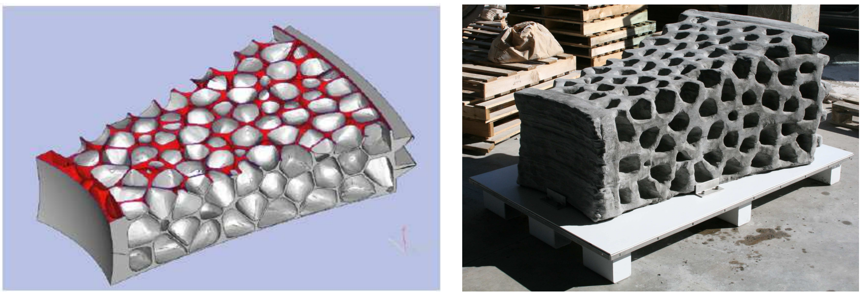

Figure 5.7 –The closed cells structure CAD model of the large demonstrator (left) and the printed block (right). Closed cells do retain loose regolith, thus ensuring shielding from cosmic rays and solar flares.

5.4 A roadmap for improving the process has been indicated

As a result of the activities summarized so far, necessary advancements and weakness points of the process were derived. Here below the main outcomes are listed:

1. *Assessment of the whole D-Shape process in a relevant environment (thermal vacuum chamber), and start of process qualification*. This is a really difficult task, due to dust containment within a vacuum chamber (contamination of vacuum pumps is one of the major concerns); however, recently Alta has designed, manufactured and commissioned an environmental test chamber for Thales Alenia Space Italia -Turin premises- to test some mechanical components for a Mission to Mars. The chamber is performing very well in a dusty atmosphere, so it can be used as a starting point for a test setup for a D-Shape-like printing process. Other problems to face with will be thermal vacuum itself (possible freezing of the binder, closure of the spraying nozzles…), feeding of the regolith simulant, control & automation of the process.
2. *Verification of mechanical and structural features of samples and structures printed in thermal vacuum conditions*. This is another crucial point, which has been only loosely addressed in the frame of the present GSP due to budgetary problems. It has to be tested structural characteristics of the obtained blocks-structures, so to ensure the needed strength and shielding capabilities are retained, even after a series of thermal cycles in vacuum.
3. *Assessment and verification of alternative binders*. Chemistry of the process is today relying on a saline solution, and on mixing a metal oxide to the regolith. It would be of extreme benefit for the process if another liquid would be found, which do not needs metal oxides to be added to the regolith. It is clear the liquid has to ensure thermal and vacuum performances similar to the actually used binder.
4. *Upgrade of the 3D printer D-Shape*. Dimensions and mechanical characteristics of the D-Shape actual printer are one of the main weak points with respect to the use of the system on the Moon. A couple of alternatives were theoretically investigated: to use a “robotized” printhead (which moves on wheels or on legs), supplemented by another robot which lays down the regolith, or to rely on a system which prints with a continuous sweep of a very little printhead on polar co-ordinates instead of Cartesian ones.
5. *Topological optimization of the shape to be printed*. Together with point 3., optimisation might result in a significant reduction of binder, which is one of the components to be brought from Earth. Optimisation of the printing sequence might also bring to a increase in efficiency and a reduction of binder.
6. *Improvement of the control system*. Even if the process is quite simple and can be monitored by a 2D image processing system, an improvement of the software would lead to better

control of shape at the moment it is printed. Using complex artificial intelligence algorithms would be crucial, since the whole process has to be conceived as automatic as possible.

Part of the activities described at point 5 above have been conducted at the end of the project, and resulted in an optimized building block designed by F+P and printed by Monolite UK.

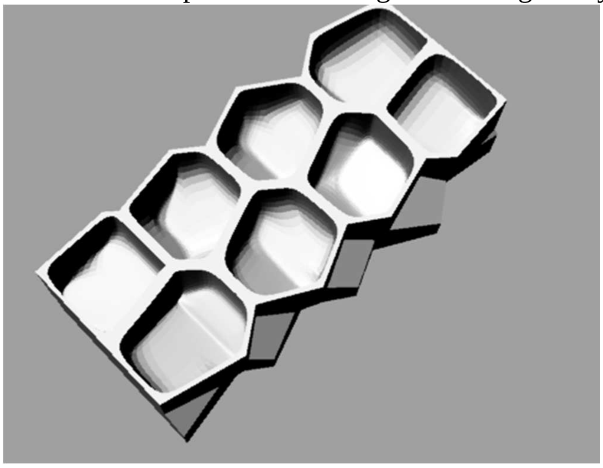

Figure 5.8 – Topologically optimised TDD1 STEP file closed cells structure (left, courtesy F+P) and the printed TDD1 obtained with Monolite UK *D-Shape* system(right)

Table below compares designed features with obtained ones, thus highlighting the actual resolution limits of the D-Shape system:

Comparative Chart TD1 D-Shape versus TD1 F+P					
	Unit	Symbol	A TD1 D-Shape	B TD1 F+P	Ratio A/B
Volume	[mm3]	V	8669476 V=P/ ρb	3140782 (From CAD)	2,76
Area	[mm2]	A	3976662 A=V/t	612995 (From CAD)	0,648
Average Thickness	[mm]	t	21,8 (measured)*	5,12 t=V/A	4,25
Density	[g/mm3]	ρb	1,661 E-3 (measured)	1,661 E-3 (input into CAD)	1
Weight	[g];	P	14400 (measured)	5215 P=Vxρb	2,761

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