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3D PRINTING TECHNOLOGY FOR A MOON OUTPOST EXPLOITING LUNAR SOIL

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In recent years rapid prototyping (a.k.a. 3D-Printing) technologies gained growing interest in the architecture community for their promise to allow direct construction of buildings with virtually any shape. Some of these technologies have the capability to agglomerate inert materials like sand using a special “ink”. This feature is especially attractive for the space community, for in-situ resources utilization related to manned space exploration. In November 2009 the European Space Agency awarded a General Study Programme contract to an industrial consortium formed by Alta SpA, Monolite Ltd., Foster+Partners and Scuola Superiore Sant’Anna. The objective of the study is to assess the concept of 3D printing technology as a potential way to build habitat on the Moon using lunar regolith. The consortium merges knowledge in space technology development, 3-D printing at building scale, complex architectural design, and robotics. In particular, Monolite Ltd. holds the rights for the patented D_SHAPE 3D-printing technology which is, among several different rapid prototyping systems, one of those which is closer to enable full scale construction of buildings. In the initial phase of the study, the physical and chemical characteristics of lunar regolith and terrestrial regolith simulants were assessed with respect to the working principles of D_SHAPE. This work also led to the selection of a novel lunar regolith simulant, made using the ashes of the Bolsena volcano in Italy, which almost exactly reproduces the characteristics of the well-known JSC-1A simulant produced in the US. Tests in air and under vacuum were performed in order to demonstrate that the reticulation process takes place using the regolith simulant. The vacuum tests also showed that evaporation or freezing of the ink can be prevented by adopting a proper injection method. In parallel, the general requirements of a Moon outpost were specified, and a preliminary design of the habitat is underway at Foster+Partners. Based on such design, a section of the outpost wall will be selected and manufactured at full scale using the D_SHAPE printer and the selected regolith simulant. Test pieces of the reticulated “concrete” are going to be manufactured in parallel and will be subject to testing of mechanical properties. Finally, based on the results of the study, the guidelines for future spatialization and automation of the printer and for design and 3D printing of the outpost will be drawn. The study conclusion is currently foreseen by Spring 2011.

I. INTRODUCTION

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

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

Although a complex trade-off would be needed to define the most appropriate concept, the one aiming at 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 serious energetic consequences. Furthermore the structure of the Moon geological system is not fully known.

For these reasons, the European Space Agency (ESA) is exploring the possibility to build infrastructure on the Moon using lunar soil as base material. In November 2009 ESA awarded a General Study Programme (GSP) contract titled “3D printed building blocks using lunar soil”, whose objective is to assess the concept of using 3D printing technology as a potential means of building habitat on the Moon. To do so, it is expected to use a 3D printer of large dimension to manufacture a representative structure using a base material of similar chemical and granular composition as that of Moon regolith. The design and manufacturing shall be then critically analysed to establish 3D printing guidelines for such structures.

I.I. The industrial consortium

The study was awarded to an industrial consortium formed by Alta SpA, by Monolite Ltd., by the Specialist Modelling Group of Foster+Partners, and by the Perceptual Robotics Laboratory of Scuola Superiore Sant’Anna, with Alta acting as Prime Contractor.

Alta S.p.A. of Pisa, Italy, is a small-medium enterprise with a space heritage dating back by more than 30 years, and a large record of participation to space projects funded by ESA, ASI or NASA. Among these, are supply of space systems (e.g. micropropulsion for Lisa Pathfinder), qualification of components for manned missions (e.g. ASIA on ISS Eneide mission) and mission analysis and design for a variety of missions, including interplanetary ones (e.g. ASI’s lunar mission or ESA’s Mars Sample Return).

Monolite Ltd. of London, UK, was set in 2007 by the inventor Enrico Dini (a civil engineer who spent his entire career in the sector of mechanics, automation and robotics) as a patent’s rights holding company on which the D_SHAPE Construction Scale 3D Printing technology and related know- how is based.

Scuola Superiore Sant’Anna of Pisa, Italy, is an autonomous, special statute public university that operates in the field of applied sciences. The Perceptual Robotics (PERCRO) laboratory of Scuola Superiore Sant’Anna, is mainly devoted to design and development of control systems for robotic and mechatronic devices, and to development of software for applications in the field of process control and simulation.

Foster + Partners of London, UK, is one of the largest international practices for architecture, planning and design, led by its founder and Chairman, Lord Norman Foster. Within F+P, the Specialist Modelling Group was created to deal with complex geometrical buildings, bringing F+P towards industrial leadership in the use of rapid prototyping in the architecture and construction sector.

I.II. Study logic

The study is conducted according to the logic described by the diagram in Fig. 1.

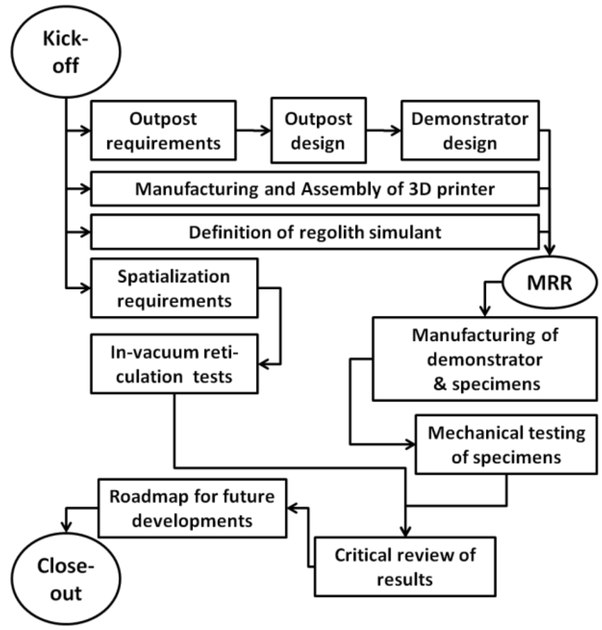


Fig. 1: Study logic.

The outpost design activity follows a preliminary definition of the requirements for the Moon base. The design mainly aims at the definition of the structural shelter made of regolith. One portion of such shelter will be selected to become the *Demonstrator*, i.e. a 1:1 scale block made of regolith simulant, which will be “printed” using D_SHAPE. Ahead of the Manufacturing Readiness Review (MRR) two activities are performed in parallel: the manufacturing and assembly of the large scale 3D printer, and the definition, selection and procurement of the regolith simulant. Also in parallel, the criticalities for the spatialization of the D_SHAPE technology are analyzed, and a test is performed under vacuum to verify that the printing “ink” works properly also in that environment.

After MRR, the demonstrator is printed altogether with some test pieces, which will then be subject to testing to assess the mechanical properties of the reticulated “regolith concrete”. Finally, the results of the performed study and associated tests will be critically reviewed, and a roadmap for the possible in-space application of the D_SHAPE technology will be drawn.

A summary of the status of the study activities as of August 2010 and a description of the steps that will follow is presented in the next sections of this overview paper.

II. OUTPOST DESIGN

II.I. Outpost design requirements

A set of preliminary requirements was laid down to provide the design team a representative scenario and suitable boundaries and constraints, though which a first run of structural optimization could be performed.

Requirements definition took into consideration the environment as well as a possible mission approach.

The first assumption that was made was to decouple the sealing capability (keep-pressure function) from the thermal, mechanical, and radiation protection function of the reinforced regolith structure. It was therefore assumed to use an inflatable module to provide the pressurized shell for the breathable environment of the habitat, while the printed regolith will be used to create an external shell, covering the inflatable. The main functions of the shell would be to shelter the habitat from radiation and micrometeoroids, with thermal insulation and thermal capacitance being a favourable drawback of wall thickness. This assumption is not driven by the impossibility for the final printed regolith structure to have sufficient leak tightness: in fact, the manufactured samples should also be tested and characterized with respect to porosity and permeability. On the other hand, such requirement was not mandatory, as the required performance can be achieved by state-of-the-art lightweight textiles. In addition, internal pressure would create strong tensile stresses in a concrete-like structure which is intrinsically fragile: removing pressure from the internal wall of the shell reduces the loads, and therefore the amount of material to be consolidated, eventually reducing the amount of ink.

A possible building approach was then defined. Although the D_SHAPE technology allows construction scale manufacturing (see sect. IV. below), bringing a huge printer on the surface of the Moon was considered unnecessary, as the construction process can be slow (it can happen well ahead of the arrival of the crew) and it can therefore rely on robots. It was then assumed that a smaller printer (1 to 2 m printing width) on wheels, aided by another rover performing the function of collecting and laying down the regolith, could do the job in a more efficient way. In principle, the construction approach should undergo a trade-off between digging and collecting regolith from the surface. In one possible scenario, the outpost will be partially underground, with the digged regolith being used for construction of the cover above the surface. This scenario was not considered in the study, as for this preliminary stage it will be sufficient to assess the kind of internal structure that would be needed to keep the wall together and the ratio of binder to base material which will eventually define the total mass of construction material to be brought from Earth.

The location of the outpost on the surface of the Moon had to be fixed, in order to allow the definition of reasonable environmental requirements. A location close to one of the Moon poles, on an elevated position (e.g. the border of a crater) was selected. This choice makes site very close to the behaviour of the so-called “peaks of eternal light” in terms of sun-exposure, i.e. the location is lit almost at all times, with the sun revolving very close to the horizon with an elevation of about ± 1.5 deg. This kind of choice is one of the preferred solutions for outposts which are willing to derive a significant part of the electrical power from solar arrays.[1]

Then, the driving environmental requirements were defined. The main purpose of the shelter would be to protect the crew (and, in the second place, the equipment) from radiation (by keeping the total dose over a typical six months to one year mission within a reasonable level) and micrometeoroids (chance of no penetration of 99% over a mission lifetime of 10 years). These requirements translate into a wall thickness of typically 1 to 2 m (depending on orientation and margins). Such a size also provides for an adequate thermal insulation and a large thermal capacitance of the shield.

In terms of structural loads, three main contributors were identified: gravity, moonquakes and thermo-elastic loads. The former two effects are much lower than the corresponding ones on Earth but it shall be noted that the structure would be a very thin network of consolidated material sustaining the whole mass of a two-meter wide regolith wall. As for thermo-elastic loads, the presence of the Sun, slowly rotating about the outpost in about 29 days, will create a gradient between

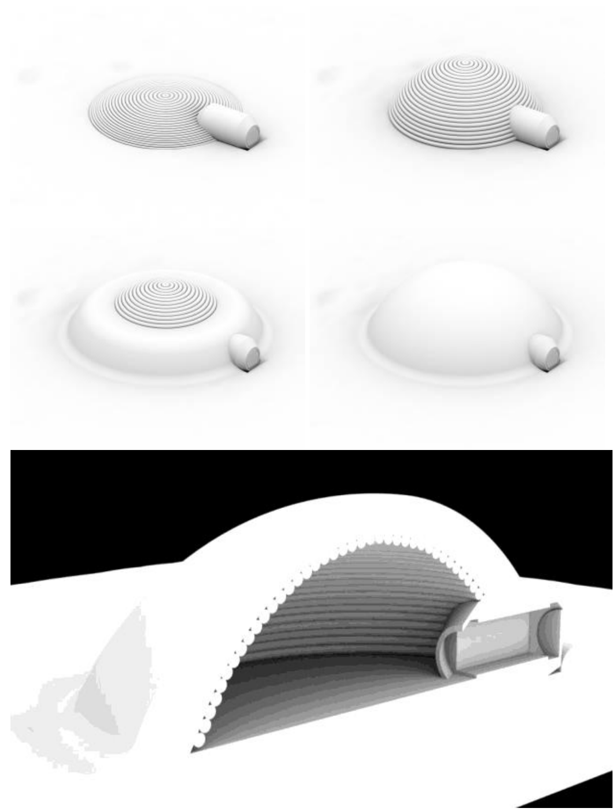


Fig. 2: Building the wall using a temporary inflatable support. Sequence: left to right and top to bottom.

the sunlit part of the shield and the one in the shadow, as well as between the inside and the outside of the wall. The relationship between the coefficient of thermal expansion and the mechanical strength of the consolidated regolith will ultimately affect the ratio between the solid and the powder.

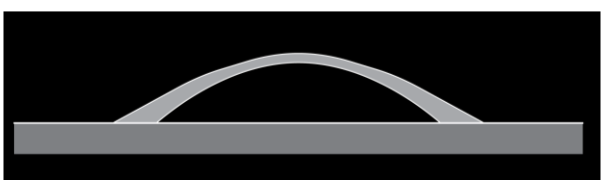
Finally, constraints on the internal volume allocation were derived extrapolating from International Space Station (ISS) experience.

II.II. Preliminary design and optimization

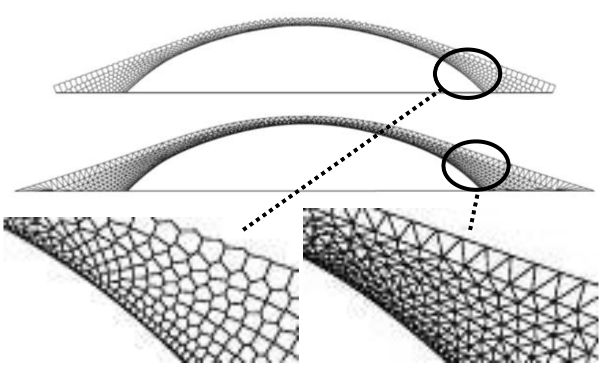
The outpost design work started considering that the overall amount of regolith to be displaced had to be minimized. This can be achieved by considering an intermediate (temporary) inflatable element made of tubes, which will serve as the reference for the internal wall boundary (see Fig. 2 above). Such element can be deflated once the wall is set, and reused if needed for another module. Although this study will focus on the design of a single module, several modules could be constructed and interconnected, in analogy to what occurred for the ISS.

The wall thickness and shape is then being analyzed as a function of the following main requirements:

- protection from radiation, which implies the wall is thicker in the directions facing the Sun, as a greater part of radiation is associated to solar flux;
- protection from micrometeoroids, which implies an almost evenly spread minimum thickness;
- the constraint deriving from the slope angle of regolith.



a)



b)

Fig. 3: a) Wall profile obtained by enveloping regolith slope, radiation, and micrometeoroids requirements. b) Optimization of structural elements.

For the internal profile of the wall, a catenary arc was selected, for its optimal performance in terms of load-carrying capability. The combined profile can be seen in Fig. 3 a).

At present, the structural design work is focusing on optimization of the internal elements of the wall structure, with the aim to minimize the ratio between consolidated material and rough regolith. The kind of trade-offs being performed is shown in Fig. 3 b).

III. SELECTION OF REGOLITH SIMULANT

An important task of the study was related to selection of the adequate regolith simulant, both considering chemical and physical properties and economical issues.

About the first aspect, i.e. chemistry, the simulant had to be representative of the lunar soil with respect to the chemical compounds playing a role in the chemical reactions at the base of the reticulation process. The binding ink interacts with the metallic oxides being a natural component of regolith, enabling a crystallization process which envelopes and links the small grains of the regolith powder. While in lunar regolith these metal oxides are available in free form, on terrestrial simulants they are usually in the more inert form of hydrated compounds. For this reason, the regolith simulants have typically to be doped with some metal oxides in anhydrous condition.

About physical properties, the main one is granulometry, as the process quality and the mechanical properties of the consolidated product are influenced by grain size. Granulometry plays an even more important role during vacuum reticulation (ref. sect. V.I.). It is therefore important to ensure that granulometry of the simulant is representative of lunar regolith.

Finally, the cost of the simulant was considered in view of the will to manufacture a demonstrator of sufficiently large size. Since the purpose of the demonstrator is to show the kind of construction complexity that can be achieved with the D_SHAPE 3D printing technology, and the resolution cannot be scaled down (see sect. IV. for resolution values), it is preferred to have a 1:1 scale section of the wall instead of a scaled down model. To have a portion which is large enough to show the features of the printed item, at least a cubic meter of regolith simulant will be needed, meaning the mass of simulant to be purchased is going to be between 2 and 3 metric tonnes. Existing simulants on the market (e.g. JSC-1A from Orbitec of Madison, WI, USA or CAS-1 from the Chinese Academy of Sciences) would cost some 40-50 k€ for that amount, which is unaffordable within the budget limits of this study. For this reason, an alternative source of simulant was identified.

All regolith simulants derive from glass-rich basaltic ashes from volcanic quarries. One of the authors (Dini)

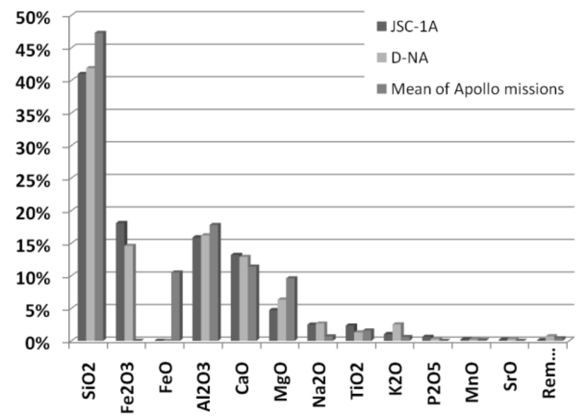


Fig. 4: Comparison of chemical analysis between JSC-1A, D-NA-1, and an average of lunar soil samples from Apollo missions[2].

made a search about Italian volcanic sites and discovered a suitable quarry of pozzolana (a kind of volcanic ash) in the region of Lake Bolsena, a crater lake of central Italy of volcanic origin. Some of the produced pozzolanas were selected and analyzed together with JSC-1A, to compare them. The results of chemical analysis (see Fig. 4) show the composition of D-NA-1 (the acronym for the new simulant) is at least as close as that of JSC-1A to the composition of actual regolith. The main difference between the two simulants and the real lunar soil is in the oxidation state of iron, which is mainly trivalent on the Earth while it is bivalent on the Moon.

Crystallographic analysis was performed as well, also showing similarity with lunar samples is not worse that that of JSC-1A. By milling, sieving, and remixing, also the required granulometry can be easily achieved. As said, the new simulant was named D-NA-1, and its cost is going to be about one order of magnitude lower than that of existing simulants on the market.

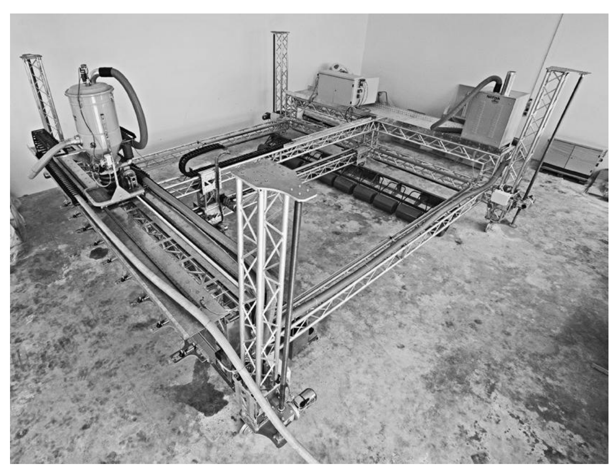
IV. D_SHAPE

Rapid manufacturing techniques derive from the Rapid prototyping systems developed in Japan and USA during the late 1980’s and 90’[3]. Rapid prototyping is defined as an additive process which builds up three dimensional objects, which are going to become end use parts, by the automated curing and/or deposition of successive layers of material. There is a wide range of Rapid Prototyping machines commonly called “3D Printers”, which use different additive processes and materials. More properly, the matter of direct 3D printing of buildings or building blocks falls into the general field of Construction Scale Rapid Manufacturing[4].

The patented D_Shape technology is one among the few which is already capable to build a construction scale artefact through rapid manufacturing, as shown by the 2 meter tall ‘Radiolaria’ demonstrator in Fig. 5 a). The fabrication begins by laying down a thin layer of fine sand approximately 5 mm deep over the entire build area, (the depth of the layer can be adjusted to suit the project depending on the required resolution). A gantry controlled deposition head then moves across the surface and selectively adds an inorganic binder to the sand substrate. This process is repeated as the head returns to its starting position, and then iterated with subsequent layers of sand across the whole build area. During the typical process on Earth an outer shell is also created to hold the unbound material in place; such shell (as well as remaining unbound sand) is removed when the process is complete.

On the contrary, for the Moon process, the structure will be enclosed within two closed and continuous skins, which will be an integral part of it, and which will retain the regolith inside the structural cell, to provide the required protection performance.

a)



b)

Fig. 5: a) The “Radiolaria” manufactured using the D_SHAPE printer. b) The D_SHAPE printer.

V. SPATIALIZATION OF THE TECHNOLOGY

Like for all technologies which were developed for terrestrial application, D_SHAPE shall also undergo a thorough re-engineering before it could be used profitably and safely in space. The architecture and the configuration of parts shall be redesigned to meet the mission objectives, all printer materials shall be reconsidered in terms of mass efficiency, vacuum outgassing behaviour, and robustness to environmental stresses, and all the electrical, electromechanical and electronic parts shall be rebuilt according to space standards (e.g. in terns of radiation hardness, derating, etc.). All these issues are well known, and none of these represents a showstopper for the technology to be successfully validated in space, therefore studying the feasibility of this kind of technology spatialization is not within the scope of this feasibility study.

On the other hand, what is really critical for the application of the D_SHAPE system to the construction of building elements on the Moon using in-situ resources, is the capability of the ink to survive and to reproduce the reticulation process in the lunar environment, namely in vacuum and at a representative temperature. In principle, also these features are not strictly mandatory, as one could reproduce an artificial atmosphere in the surroundings of the element being built, for the required duration*. However, avoiding this need and showing that the technology will work directly in the external environment, will make the system simpler, will reduce the amount of elements, parts and mass to be brought from Earth, and, ultimately, will give it a better chance for selection. As for all chemical reactions, reticulation time is temperature dependant, and it increases when the temperature goes down. Conversely, evaporation will increase with temperature, and there will be a need for trade-off between speed and mass efficiency of the process. Considering the importance of mass in interplanetary transportation, it is believed that the trade-off will push towards a cold and slow process.

For the time being, however, our main concern was to ensure that the ink would not boil nor freeze once sprayed on the regolith in vacuum, and that it would stay liquid long enough to let the reactions of the reticulation process take place. Our starting point was 20 °C, ambient temperature of our laboratories. We did some analysis to devise a method to avoid excess evaporation or boiling-off of the ink, and we then did a test within a vacuum chamber, showing that, indeed, the process works and we can achieve a good reticulation in vacuum. Following sections will describe both the analytical and the experimental work performed so far in this regard.

V.I. Boiling point analysis

The ink properties in terms of vapour pressure and surface tension were analyzed. At 20 °C vapour pressure is lower than 2 kPa = 20 mbar while surface tension is about 0.1 N/m. To avoid boiling and rapid vaporization, which may eventually lead to freezing of the ink, either the process is performed under a bell (pressurized dome) in which a pressure higher than 20 mbar is maintained, which we want to avoid, or ink is constrained in small volumes (e.g. drops or cavities) having an internal pressure (induced by surface tension) higher than 20 mbar.

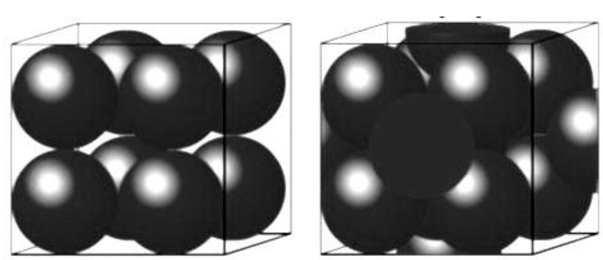
First of all we calculated the minimum (critical) drop radius R_{cr} required to achieve the above condition, then we evaluated the typical size of the cavities within lunar regolith or terrestrial regolith simulants. If the dimension of the cavities (at most) is smaller than $2R_{cr}$ then the behaviour of the drops of the liquid ink is driven by surface effects (namely capillarity), and no boiling occurs. Since the evaporation rate is limited in these conditions, heat transfer is also reduced, and freezing is also prevented if the initial temperature is high enough.

The pressure inside a drop of liquid is given by the well known Young-Laplace law:

$$P_{in} = \frac{2\gamma}{r} \qquad [1]$$

where γ is surface tension and r is drop radius. For the values provided above at 20 °C, the critical radius to obtain a pressure higher than 20 mbar is about 0.1 mm. To avoid boiling (at 20 °C) the size of gaps within the regolith shall therefore be lower than 200 µm.

Radius of gaps within an array of packed spheres is always lower than that of spheres. E.g., for poorly efficient Simple Cubic Packing (SCP), radius of gap is 73% of radius of sphere. Therefore, particles smaller than 200 µm diameter ensure the maximum size of water drops to be lower than boiling threshold, and liquid fills the gaps by capillarity without boiling. To



a) b)

Fig. 6: a) Simple Cubic Packing. Void/full ratio = 48%.
b) Cubic Close Packing. Void/full ratio = 36%.

*We calculated that about 30 kg of water are required to fill a dome of about 2000 m^3 volume at a a temperature of 20 °C and a pressure of 20 mbar, which is more or less the vapour pressure of the ink at that temperature.

guarantee that this actually occurs, there must be enough particles smaller than the limit size above. In particular, this occurs in a packed regolith if the total volume of particles of 200 µm size or smaller is more than 48% (void/full ratio of SCP) of the total volume of construction regolith. Regolith from Apollo 11 samples is such that 73% of mass is constituted by particles smaller than 150 µm, and 81% is smaller than 250 µm, therefore regolith of this kind could be used as-is, with no need for additional milling or sieving: the printing system shall only ensure that the powder is well packed and that the ink is injected directly inside the regolith, with the ink droplets being surrounded by powder all around, and without direct exposure of the ink to the external environment.

The analysis should be extended to assess the whole functional temperature range, in order to provide in-situ operational constraints which will drive the system design and the operations schedule (e.g. with respect to periods of solar illumination). Aspects like variation of vapour pressure and surface tension with temperature and concentration of ink components, as well as

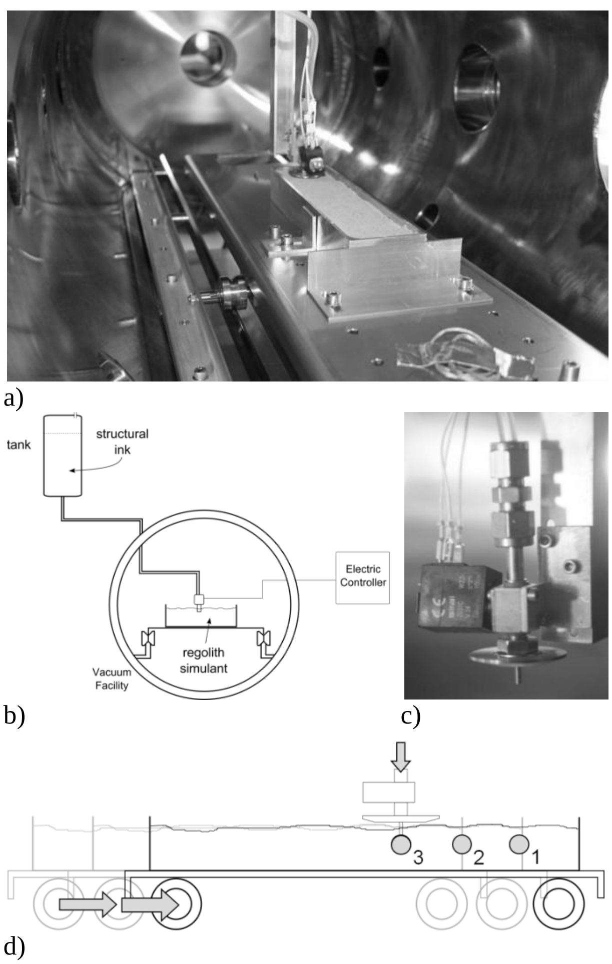


Fig. 7: a) Test setup inside Alta vacuum facility CA-2. b) Schematic layout of the test setup. c) The injector nozzle and valve. d) Injection sequence.

evaporation rate and freezing risk, should be taken into account. This preliminary calculations, however, showed that the process had a chance of success when performed in vacuum, under suitable conditions.

V.II. Vacuum testing

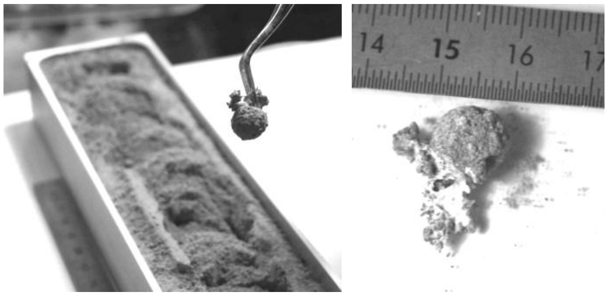
When dealing with a process which occurs in vacuum and involves both chemical reactions and physical transitions, analysis alone does not provide enough confidence the process will work properly. For this reason we performed a “reticulation test” in one of our vacuum chambers. The goals of the test were:

- to verify the actual feasibility of the chemical process in vacuum environment;
- to analyse the behaviour of the structural ink when it is sprayed in vacuum;
- to demonstrate if the direct injection of the ink below a simulant layer can prevent the vaporization of the fluid;
- to measure the size of the reticulated “ball” with respect to the volume of injected ink
- to assess (qualitatively) the solidity of the in-vacuum reticulated compound.

The test set-up is shown in Fig. 7. The structural ink is stored in an external tank in atmospheric pressure. Feeding pressure was therefore about 1 bar in this preliminary test. Lower pressures might be required to improve the accuracy and resolution of the process. To perform more than one injection within a single vacuum cycle a translating carriage (one degree of freedom) was used. The injecting nozzle and fluid management system were fixed, while the box containing the regolith simulant was linked to the carriage and translated in steps of a few cm. The 2 mm outer diameter nozzle was designed with a flat sliding plate, intended to keep a smooth top surface on the regolith simulant during the movement of the carriage. The flow of the ink is controlled by an electromagnetic micro-valve, and the amount of liquid being injected upon every step is regulated by the tank pressure and the duration of the valve opening.

Reticulation test was performed between the 6th and the 10th of August 2010. Two days were required to outgas the powder and achieve a pressure in the 10^{-4} mbar range. Six spot injections were performed with different valve opening durations and, therefore, different amounts of liquid being injected. A small amount of regolith simulant was displaced upon every injection, due to the dragging effect of the nozzle inserted in the powder†. The samples were then kept under vacuum for 24 hours, to allow for completion of

† A future improvement of the injection technique would imply insertion and extraction of the nozzle with a vertical movement, adding one degree of freedom to the test setup.



a) b)

Fig. 8: a) Sample #6 being extracted from the regolith simulant container after the test. b) Size of sample.

the reticulation process and proper outgassing of water, then they were retrieved and inspected.

Surprisingly, considering the limited resources dedicated to analysis and to test preparation, the outcome of the test was very good: reticulation took place (showing the capillary phenomena took the lead as calculated), consistency of the consolidated lumps was hard, concrete-like, and porosity was low (showing that boiling phenomena creating voids in the structure were negligible).

Fig. 8 shows one of the lumps of consolidated “printed concrete” being extracted from the regolith simulant. The picture also shows that, despite some irregular fringes, the core of the lump is quite spherical in shape. The size of the ball is about 1 cm in diameter. Considering that this was the first attempt and that the pressure of the ink reservoir and the valve opening interval can be optimized, it is assumed that reaching a size of 5 mm (more or less equal to current resolution of D_SHAPE) or lower will be feasible.

VI. NEXT STEPS

Some of the activities which are described above still have to be completed. Namely:

- outpost (preliminary) design has to be concluded by defining the optimized internal mesh for the structure, in order to minimize the amount of structural ink (i.e. mass brought from Earth) required to counteract the external loads;
- the mineralogical analysis of the regolith simulant has to be completed and reported;
- analysis of results of the vacuum tests have to be completed and reported. Further vacuum testing has to be agreed upon.

Furthermore, some of the key activities of this study still have to be performed:

- manufacturing of the *demonstrator*, using D_SHAPE and a suitable amount of regolith simulant. Manufacturing will be performed in air, with the main aim to show that the printer can reproduce the structural features (i.e. internal meshing of sufficient resolution and accuracy) which were defined by the design team;
- manufacturing and testing of test pieces, which will be performed as well in air with D_SHAPE (most likely in parallel to the manufacturing of the demonstrator). The test pieces will be used to assess mechanical properties (mainly compression and flexural strength, and Young modulus) and, if possible, thermo-mechanical properties (thermal expansion coefficient, thermal conductivity and specific heat);
- drafting a roadmap for future developments: at the end of the project, a critical assessment of the results will be done, and a first roadmap describing the following steps for 3D printing on the Moon will be produced. Special emphasis will be given to steps to realise a Moon-compatible complete system, and to the necessary autonomous control system. The roadmap will consider short/medium term activities (e.g. the optimization of the process parameters to minimize the mass of materials to be brought from Earth) and medium/long term activities, which shall be conceived as part of a larger framework of international cooperation aiming at interplanetary manned missions.

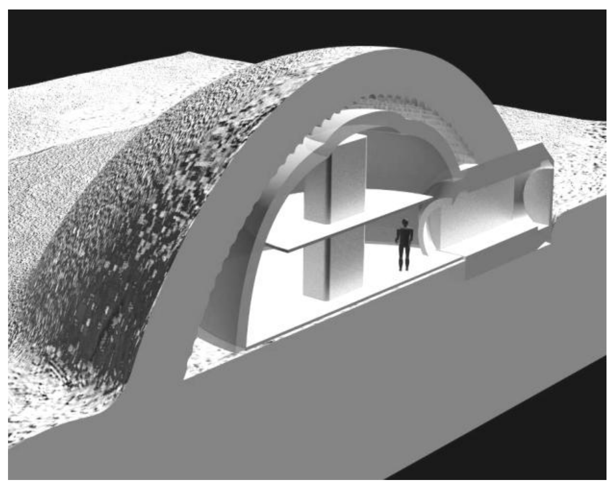


Fig. 9: Artistic view of lunar habitat covered by a 3D printed regolith shelter.

VII. CONCLUSIONS

The European Space Agency is financing a study to assess the feasibility and profitability of 3D printing technology for building infrastructure on the Moon using local regolith. This kind of In-Situ Resources Utilization would be mainly aimed at providing protection from radiation, micro-meteoroids impacts, and thermal environment for a possible manned outpost on the Earth’s natural satellite. The study is still ongoing, but very promising preliminary results were obtained already.

The selected D_SHAPE process was verified to work properly in vacuum and using regolith simulant, by exploiting the natural physical properties (and, in particular, granulometry) of lunar regolith.

In parallel, the definition of a preliminary design for the consolidated regolith shield is progressing, and a demonstrator of representative size (i.e. approximately 1 m^3) will be manufactured using the existing D_SHAPE 3D printer, to show the required structural features can be reproduced.

As a side product of this study a novel regolith simulant, made using volcanic ashes from an Italian quarry, was defined and is going to be marketed as an alternative to existing American and Chinese simulants.

Finally, the use of this kind of technology could eventually be extended to Martian applications, considering the composition of the base material plays a minor role in the working principles of the D_SHAPE process under evaluation.

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